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3D Crane Site Reconstruction with Lifting Path Displaying by a Top-view Camera

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Abstract

Due to the complex working environment, limited vision, and complicated crane operations, the crane operator faces two major problems when constructing with a crane: safety and working efficiency. Every year, numerous accidents occur, the majority of which are the result of the crane operator's inability to acknowledge hidden hazards. Some of these accidents can be effectively avoided through a comprehensive and intuitive display of important visual information to the crane operator. In this research, a 3D spatial map is reconstructed through visual simultaneous location and mapping with a top-view camera. The lifting path is planned on the consideration of both the 3D spatial map and working limit area. These information is displayed intuitively in the top-view image. The lifting path can be successfully and precisely shown in the top-view image in both simulation and field experiments. The augmented top-view image with the planned lifting path can help ensure the operation safety in an efficient way. Based on the proposed intuitive information displaying system, a much more intelligent safety and operation related system which can adjust displaying different kinds of visual information for ensuring construction safety and working efficiency can be developed.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2022.

Keywords: crane, 3D spatial map, working limit area, lifting path, top-view image**.**

1. Introduction

Cranes are widely used in construction, transportation, and other industries [1]. Generally, the crane is operated manually by the crane operator, who sits in a small crane cabin [2]. The operator sitting in such a small cabin can only have a very limited view of the crane's working environment. Hence, the problems of a constantly changing working environment and limited visual information are encountered by the crane operator.

Every year, there are numerous crane accidents all over the world [3-5]. Many researches trying to ensure construction safety and improve working efficiency have been done. Payload lifting should consider all the possible potential hazards which have been discussed in [6]. To help improve the safety and working efficiency of the crane operation, a lot of research concentrating on the automated on-site lifting path planning [7-9], lifting simulation [10-12], and operation management [13-14] are conducted in recent years.

Many researches are done to solve the problem of construction hazards caused by the crane. However, it is ignored that the crane is operated manually by the crane operator with several operation levers. The safety and operation-related information should be displayed in an intuitive way so that the crane operator

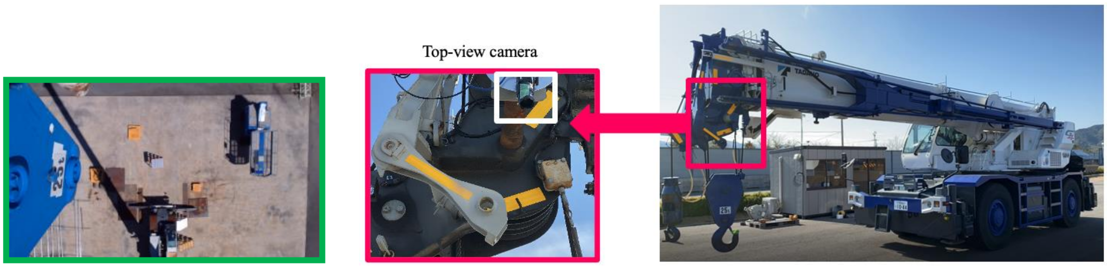


Fig. 1. A top-view camera mounted on the boom head. The optical axis of the camera is always pointing to the

can follow these instructions efficiently and correctly. The lifting path planning is a promising way to improve the crane operation safety and efficiency. Many researches about the lifting path planning is either assuming that the crane's working space is known in advance or making a rough estimation about the crane's workspace [13]. And the planned lifting path is demonstrated to the crane operator with a table of intense numbers.

Thus, it is essential to have a comprehensive 3D workspace reconstruction of the crane's workspace for the better lift path planning and intuitive information display. To achieve the goals, we propose a system for generating a 3D workspace map with planning and displaying the lifting path based on a top-view camera. The top-view camera is mounted on the boom head of a rough-terrain crane as shown in Fig.1. The image on the left is an example of one captured by the top-view camera. The crane operator can get a bird's-eye view of the hook area. However, it is still limited because the top-view camera only provides 2D images of the environment. In addition, in the operation process, the lifted payload can often partially block the view of the top-view camera.

In this study, our proposed system aims at real-time generation of a dense 3D workspace map of the crane's working environment consisting of millions of 3D points from the top-view camera by integrating the real-time visual simultaneously location and mapping(SLAM) approaches Semi-direct Visual Odometry (SVO) [15] and Regularized Monocular Depth Estimation (REMODE) [16]. Compared to the commercial software's and open-source methods such as Autodesk remake [17], Pix4d [18], COLMAP [19] and VisualSFM [20], the

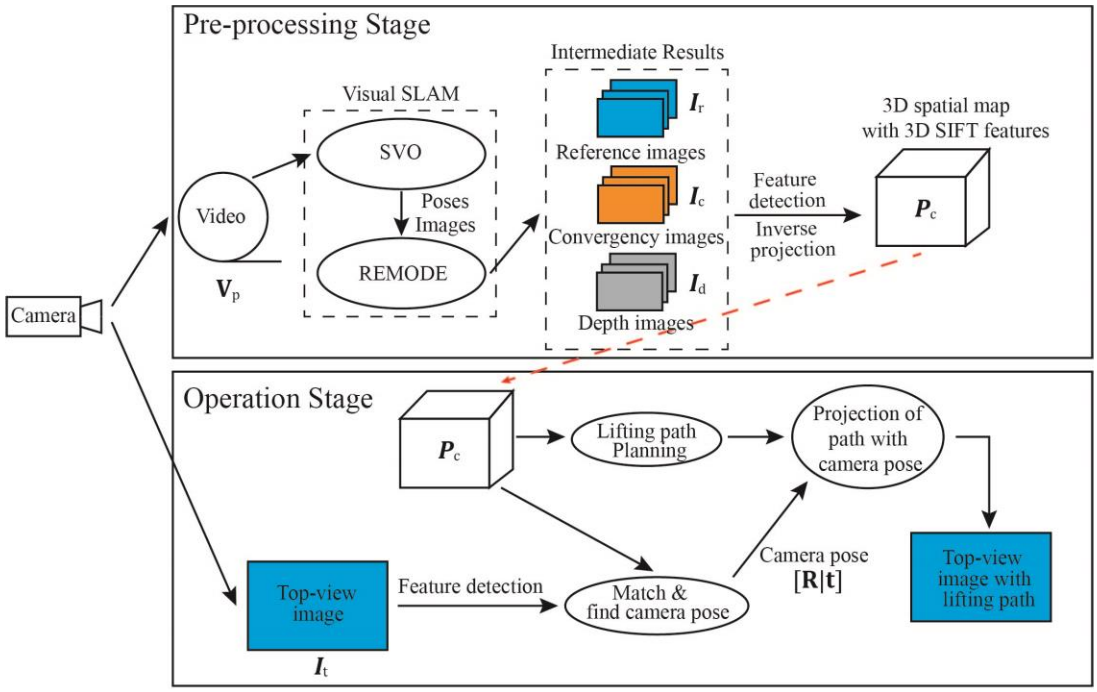


Fig. 2. System overview of the two-stage approach. In the pre-processing stage, a dense 3D spatial map containing SIFT features are reconstructed. In the operation stage, the top-view image with the planned lift path is displayed.

reconstruction can achieve high precision, the combination of using SVO and REMODE can achieve the real-time 3D reconstruction with enough precision and density for more applications.

The flowchart of our proposed approach is shown in Fig.2. It is a two-stage approach consisting of a pre-processing stage and an operation stage. The main goal of the pre-processing stage, as shown in the top box of the figure, is to generate a dense and precise 3D workspace map of the crane's working environment. By using SVO and REMODE, this purpose can be achieved in almost real-time. To achieve our main objective in the operation stage, the feature detection is made for later camera pose estimation. The image captured by the top-view camera is matched against the generated 3D workspace map in the operation stage depicted in the bottom box of the figure to determine its camera pose. In the operation stage with the given lift start point and target point, a lifting path can be planned with the consideration of collision free and working limit area (WLA). The crane operator can see the lifting path in the captured top-view image and hence can have an efficient and safe operation. The proposed system is promising to improve the crane operation safety by avoiding the accidents of crane collisions, overturn, and boom cracks.

2. 3D spatial map reconstruction

The main goal of the pre-processing stage is to make a real-time and dense reconstruction for a 3D workspace map containing features with a top-view camera. In this research, a pipeline achieving both dense and real-time reconstruction is implemented. The reconstructed 3D workspace map also contains many features which can be used for many applications. A live video stream that is a set of continuous images $\mathbf{V}_p$ is used to reconstruct the 3D workspace map $\mathbf{P}_c$.

The reconstruction is achieved mainly by using the algorithms of SVO and REMODE. SVO can estimate the camera pose $\boldsymbol{T}_k$ for every image $\boldsymbol{I}_k \in \mathbf{V}_p$. Meanwhile, SVO can make reconstruction of a sparse 3D point cloud of the environment from which we can obtain minimum depth d_{min} and maximum depth d_{max} for the image $\boldsymbol{I}_k$.

As shown in the top box region of Fig.2, to reconstruct the 3D workspace map $\mathbf{P}_c$, a live video stream that is a set of continuous images, $\mathbf{V}_p$ is recorded by the top-view camera for the reconstruction of the environment in pre-processing stage. To take $\mathbf{V}_p$, the crane moves several rotations and pitchings sequentially to generate $\mathbf{V}_p$. With $\mathbf{V}_p$, $\mathbf{P}_c$ is a dense set of a large number of 3D points with texture information of the environment that can be reconstructed with SVO and REMODE.

There are two major concerns in VSLAM. The first is localization, which is used to determine the camera's pose about its surroundings. The second is mapping, which is geometric recognition of the environment. In addition, they are completely reliant to one another. In our research, we use SVO and REMODE to achieve these purposes separately.

SVO can estimate the camera pose $\boldsymbol{T}_k$ for every image $\boldsymbol{I}_k \in \mathbf{V}_p$. Meanwhile, SVO can make reconstruction of a sparse 3D point cloud of the environment from which we can obtain minimum depth d_{min} and maximum depth d_{max} for the image $\boldsymbol{I}_k$.

REMODE is a probabilistic depth measurement approach for estimating dense and accurate depth maps [16]. Its depth measurement is based on the assumption that the camera pose $\boldsymbol{T}_k$ is known for each image $\boldsymbol{I}_k \in \mathbf{V}_p$. REMODE does not estimate the depth of every image in $\mathbf{V}_p$. It only chooses a few images from $\mathbf{V}_p$ to serve as reference images for $\boldsymbol{I}_r$. The reference images are chosen based on their overlapping relationship, which ensures that they have covered nearly all of the regions shown in $\mathbf{V}_{\boldsymbol{p}}$. REMODE can recover the depth $d_{\boldsymbol{u}}$ for every pixel $\boldsymbol{u}$ of a reference image $\boldsymbol{I}_r$. Hence, the depth image $\boldsymbol{I}_d$ of the reference image $\boldsymbol{I}_r$ can be obtained. However, some of $\boldsymbol{I}_d$ estimated depth values are unreliable. The REMODE calculates the $d_{\boldsymbol{u}}$ uncertainty as well as the depth for each pixel $\boldsymbol{u}$ of the reference image $\boldsymbol{I}_r$. Such uncertainty is represented by the convergence image $\boldsymbol{I}_c$. The region where the uncertainty is low is called a convergent area. In the final reconstruction for $\mathbf{P}_c$, only the pixels in the convergent area will be used.

To make a global camera pose estimation for displaying the lifting path, we extract the SIFT features [21]. The detected SIFT features have been inversely projected to the 3D workspace map as landmarks to globally estimate the camera pose.

The reconstructed 3D workspace map $\mathbf{P}_c$ is a necessary prerequisite for planning the collision-free lifting path. Another necessary prerequisite is the working limit area (WLA) which will be explained in the next section.

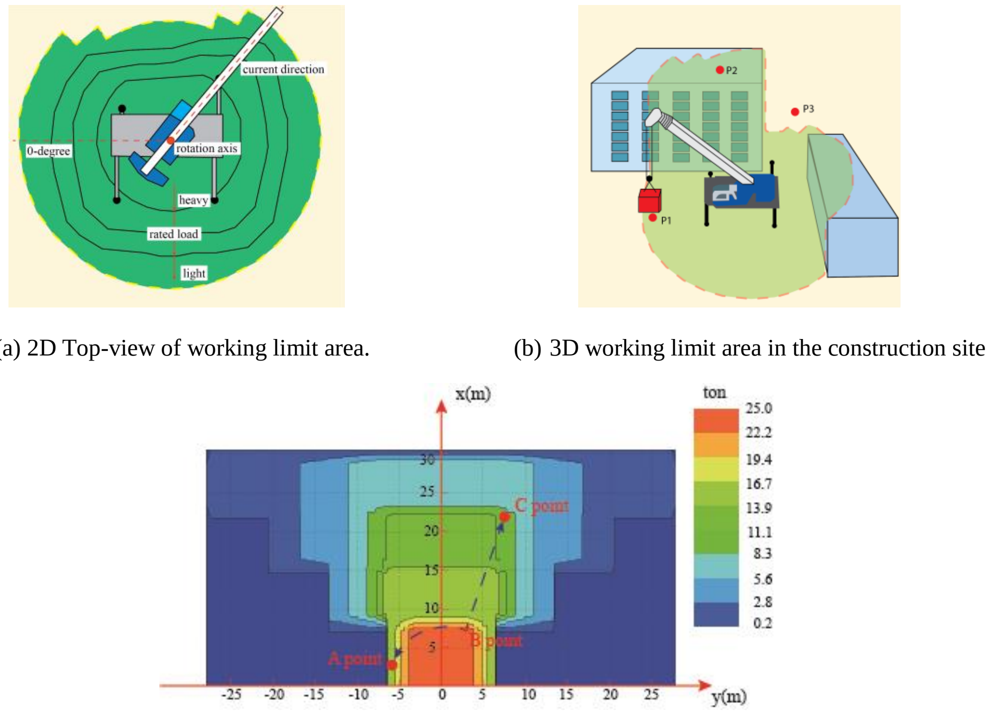
3. Top-view image with planned lifting path

In this research, the lifting path is on the consideration of both the working limit area and the 3D workspace map. To begin, we provide a thorough explanation of how to plan the lifting path with the working area limit and 3D workspace map. Based on that, the procedure for displaying the lifting path in the top-view image is then explained.

3.1. Working limit area

The crane lifting path planning in this research is considered from three aspects which are collision-free, operation preference, and working limit area. Almost all the lifting path planning for the crane takes the consideration of the collision between the crane and the environment. The operation preference is that the crane operator prefers making pitching and rotation in a lifting mission. And it is for the crane with an extensive boom. Unless the crane operator needs to extend the crane boom, the crane operator almost has no preference to extend the boom.

The working area limit is an area that is computed by the structure balance and mechanical strength of the



(a) 2D Top-view of working limit area. (b) 3D working limit area in the construction site

(c) Working limit area map (WAL map)

Fig. 3. Working limit area. For the different payload and crane, the working area limit differs a lot. (a) and (b) are two illustrations for WAL in the 2D and 3D respectively. (c) is a half working limit area map computed through evaluating the crane's structure balance. A simple lifting path is in (c).

crane. As shown in Fig.3 (a), for a different payload from heavy to light, the working limit area increases. Fig.3 (b) is the working limit area in the crane's 3D workspace. It is a complicated area for the mobile crane with some non-regular extended outriggers. Fig.3 (c) is the working limit area of a fully extended mobile crane by computing the mobile crane's structure balance while working.

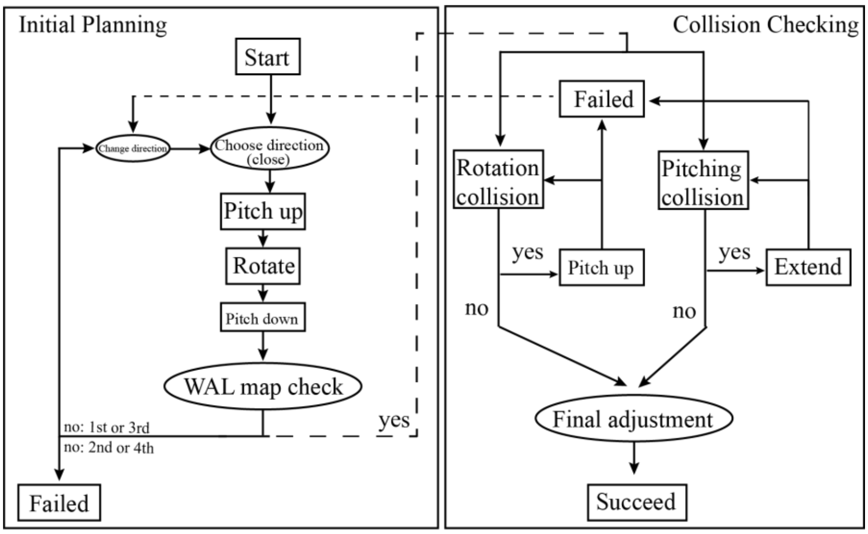


Fig. 4. The lifting path planning pipeline.

3.2. Lifting path planning

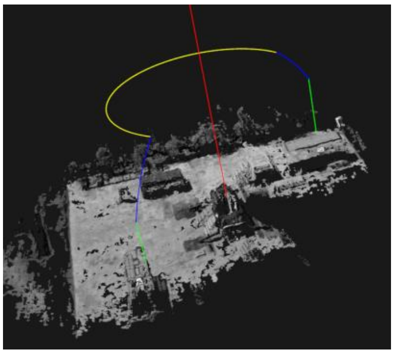
The lifting path planning considers both collision and working limit area. The planning orders is firstly making a plan based only with the working limit area. After that, the planned lifting path will be optimized according to the possible collisions. The cycle of a lift process is generally consisting of a lifting up, several rotations and pitchings, and a lifting down. Hence, the planned lifted path can be divided into 3 sections which are the lifting up section, transferring section, and lifting down section.

To reduce the oscillation, it is required to reduce the distance from the boom head to the lifted payload. Hence, the lifting up section is generally a line vertical to the ground plane. The distance needs to be researched in-depth more. In this research, we decide to set it to one-third of the distance from the boom head to the ground plane. The lifting down section is quite the same as the lifting up section. To improve efficiency, it is better to lift down fast in the beginning. And when the payload is close to the workspace, it should be placed slowly to ensure safety. Hence in the lifting down section, the endpoint of the path is set to one meter above the target point.

The main and most important lifting path planning is the transferring section. An initial lifting path planning is just based on the working limit area. For a known weight of the payload, from the working area limit map, a simple lifting path can be planned which is shown in Fig.3 (c). The lifting path planning process is shown in Fig.4. First, the initial planning process is trying to search for a safe lifting path from the WLA map. For a given payload, we need to first find a maximum radius that which the crane can keep its balance. Then the crane pitches its boom up to the allowed radius. After that, the crane rotates its boom to the target direction. In the last, it pitches the boom down to the target point. As shown in Fig.3 (c), a simple case from point A to point C only needs rotation and pitching.

In the collision checking process, the collision can happen in both the rotation period and the pitching down period. Different strategies are given to avoid these collisions. If the collision is not able to be avoided from the current rotation direction, it is required to go back to initial planning to change the direction.

In the initial planning process, if the path cannot be able to plan in both directions, it will fail to plan a path. It is the same with the collision checking process. The collision checking process will make a final adjustment to reduce operation times. Such as in the collision checking process, if a pitching up operation is required to avoid the collision, this pitching up will be removed from the initial pitching up operation.



(a) The planned lifting path in the workspace map

(b) Lifting path in the top-view image while in operation

Fig. 5. Experiment result of displaying the planned lifting path.

3.3. Lifting path displaying

The lifting path displaying process is a process of displaying the planned 3D lifting path into the top-view camera image while in operation. The planned lifting path can be obtained from the above section. To projective the planned 3D lifting path, we need to know the camera pose first.

The SIFT features were detected and attached to $\mathbf{P}_c$ via inverse projection during the reconstruction process. These characteristics can be used as landmarks to estimate the camera pose of the top-view image $\boldsymbol{I}_t$. First, the SIFT features are extracted from $\boldsymbol{I}_t$ and matched to the 3D SIFT points in $\mathbf{P}_c$. Several 3D to 2D points correspondences can be obtained as $\boldsymbol{X}_i \leftrightarrow \boldsymbol{x}_i$ for $i = 1, \dots, n$. $\boldsymbol{X}_i$ are the 3D points from $\mathbf{P}_c$, and x_i is the image points from $\boldsymbol{I}_t$. Second, the camera pose $\boldsymbol{T} = [\boldsymbol{R} \mid \boldsymbol{t}]$ can be estimated with a PNP approach, which is to solve $s\boldsymbol{x}_i = \boldsymbol{K}[\boldsymbol{R} \mid \boldsymbol{t}]\boldsymbol{X}_i$. s is a scale factor for homography. $\boldsymbol{X}_i$ and $\boldsymbol{x}_i$ are the homography representation of 3D points and 2D points respectively. $\boldsymbol{K}$ are the camera intrinsic matrix that can be obtained through a chessboard calibration.

4. Experiment

The field experiment is conducted to prove the proposed system with a rough-terrain crane. The crane's boom will rotate in a circle around the working area. The boom head is kept at a height of 15 m above the ground in the first field experiment. It is equipped with a PoE camera FLIR with a 24 mm focal length. The resolution of the captured image is 1280×1024.

The results of the experiment are represented in Fig.5. In this experiment, as there is no collision object in the lifting path, this is only a simple demonstration to check the ability of our proposed system. As can be seen from the result, the lifting path is correctly planned in the reconstructed 3D workspace map in Fig.5 (a). In Fig.5 (b), the lifting path is augmented to the top-view image to assist crane operation.

5. Conclusion

In this research, an approach for planning and displaying the lifting path on a real-time 3D workspace map reconstruction is developed. The approach is divided into two stages: pre-processing for the reconstruction of the 3D workspace map and operation for planning and displaying the lifting path. The method is useful for improving operational safety and efficiency.

In the future work, we shall continue to research some more complicated environments which exist in collision in the initially planned lifting path to complete this research.

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A Vision-based Solution for Determining Edge Tiles in Robotic Tiling

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Abstract

With the rapid growth of robot technology, robotic tiling to replace manual work gains increasing attention. However, existing studies may have oversimplified their working conditions in automatic tiling work, where the floor-tiling robot can only tile the middle area in a room, leaving the edge area to be tiled manually. This research aims to provide a vision-based solution for floor-tiling robots to determine the profile of the edge areas, aiming to improve the automation level of the tiling robot.

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Keywords: Edge tiling, Floor-tiling robot, Shape detection

1. Introduction

The construction sector has long struggled with sluggish productivity [1] and a shortage of competent labor [2]. This is primarily due to an aging and retiring workforce that has not been compensated by younger people who are generally unwilling to work in the construction industry [3]. Construction automation and robotics will be able to successfully address the current challenges and defects in the construction industry [4]. With the rapid growth of smart technology (e.g., robotics, sensor, and AI), construction robot technology has progressed significantly in recent years [5]. Many construction robots, such as the rebar tying robot [6], the drilling robot [7], and the brick-laying robot [8], are used to execute specialized tasks on construction sites. The construction sector will benefit from the adoption of robotics to replace manual construction in severe environments.

Currently, during the architectural finishing process, floor tiling is still done by hand using a few simple devices, which is labor-intensive and time-consuming. The tilers must bend over for an extended period of time when paving tiles, which is ergonomically harmful. To ensure that the floor-tiling work is of high quality, the workers must be qualified and have professional abilities. Furthermore, tiling work is a highly repetitive building procedure with consistent tile sizes. Therefore, automatic tiling by robotics to replace manual work gains increasing attention. Tiling robot has a large potential for higher efficiency, better accuracy, and lower cost, as well as ensuring the safety and health of workers [9]. This encourages the development and design of an increasing number of tiling robots, including Semi-automated Floor Tiling Robotic System [10], Tile Placement Robot in complex patterns [11], and the low-cost tiling humanoid [12].

Despite the development of robots and sensors for tiling work, the automation level of existing tiling systems is still limited. One problem is that the existing floor-tiling robot can only tile large areas but leave edge areas to be tiled manually. Therefore, edge tiling with robots is an effective way to improve the automation level of floor-tiling robots. Edge tiling consists of three main steps: determining the shape of the edge tiles, cutting, and laying the edge tiles in the correct place. This study intends to fill in the knowledge gap on edge tiling by developing a vision-based approach for determining the edge shape.

Compared with conventional methods such as using tape to measure the edge area and then cutting the edge tiles, the vision-based method can obviously improve efficiency and reduce the manual work. This research may pave the way for automated tiling entirely by deploying robots in the future.

2. Literature review

2.1. Construction robotics

From the 1970s, robotics started spreading in the construction industry, gradually moving from factories to construction sites [13]. Over the previous two decades, the number of scientific papers focusing on construction robotics and automation has increased dramatically. Conventionally, construction robotics are created to execute specific tasks, such as bricklaying and glass panel installation [14]. On the other hand, new types of robots have been introduced into the building environment, such as drones [15], 3D printing technology [16], and exoskeletons [17]. These robots help to improve the efficiency of construction and address the concerns of labor shortage.

Since a large number of human workers are staying on construction sites, safety problems become a serious concern. Collaborative robots, or cobots, are designed to assist workers with work that may be dangerous or repetitive, as well as create a safer and more efficient workplace. The most obvious difference between cobots and industrial robots is that cobots aim to work together with workers safely, while industrial robots are used to automate the manufacturing process entirely without workers [18]. Afsari et al. [19] discussed the application of collaborative robots in construction. In addition, standard collaborative robots are unable to cover large workplaces, despite many construction procedures necessitating a larger area. Therefore, the mobile platform system is usually equipped with collaborative robots, to allow the robot to move and work on the construction site.

2.2. Automation in tile laying work

The idea on floor-tiling robots dates back to the early 2000s, or possibly before, when Apostolopoulos et al. demonstrated a robotic system for automatic tiling [20]. Navon developed a floor-tiling robot equipped with a computer vision system and proved that the robot can work two to five times more efficiently than a human in tiling work [21]. Khan et al. demonstrated a semiautomatic floor-tiling robot, which required some manual procedures to complete [10]. Schwartz proposed a humanoid robot that can be customized for floor tiling [12], while the efficiency and accuracy are not good enough for actual tiling work. Using a visual measurement method with limited FOV, Wang et al. proposed a robot floor-tiling control approach to complete the high-precision automatic floor tiling [22].

Quality detection of tiles is the prerequisite in high-quality tiling work. Hocenski et al. used the Canny edge detector to detect edges and flaws on ceramic tiles, and it was shown to be quite adaptable to various textures of ceramic tiles [23]. Golkar et al. proposed an automated visual inspection system to detect the quality of ceramic tiles, including edge curvature, thickness, size, and edge crack [24]. Emam and Sayyedbarzani provided a machine vision method for measuring the size deviation of ceramic tiles using two cameras, with a measurement accuracy of 0.06 mm [25].

However, few studies mention edge tiling using robots. Khan et al. [10] demonstrated that requiring robots to conduct edge tiling will significantly increase complexity, which is uneconomical. This problem can be solved with the development of robot and sensor technologies. With the increasing lack of labor, it is imperative to upgrade the level of automation of tiling robots.

3. Objective and scope

One of the barriers to floor-tiling robots, as discussed above, is the lack of approaches to tile in edge areas. The first subtask for robotic edge tiling is determining the shape of edge tiles, which can be addressed by machine vision using an independent camera mounted on the robotic arm, in order to make a trajectory planning for cutting the edge tiles. Therefore, this study presents a vision-based solution for determining edge tiles. A prototype for determining edge tiles in robotic tiling was developed by creating an algorithm to measure the gap between walls and tiles and using trajectory planning and Finite State Machine to allow the robot arm to obtain and draw the edge shapes. The main objective of this research is to provide a proof of concept for determining edge tiles in a prototype environment. The proposed method extends the automation level of floor-tiling robots and has a significant potential for realizing full automation in tiling work. The scope of this research is strictly limited to determining the edge shapes by using the developed algorithm, whereas cutting and locating edge tiles are left for future research. As a result, detailed descriptions of techniques related to actual execution, such as cutting and locating edge tiles in an appropriate way, are not included in this research. Even though real conditions can be different from the developed prototype system, a construction planner can assess the feasibility of adopting tiling robots for edge tiling and the potential benefits that can be achieved by full automation in tile laying work.

4. Methodology

For the robotic arm to determine the shape of edge areas autonomously, it needs to: 1) convert 2D points to 3D points and allow the end-effector to reach the next intended edge area, 2) detect the shape of edge areas, 3) make a trajectory planning to show the edge shape, and 4) develop a control strategy for conducting the above tasks.

4.1. Prototype design of tiling robotic arm

The hardware system consists of the UR5e robot, RealSense D415 depth sensor, pen, teach pendant, and upper computer as depicted in Fig 1. The RealSense 415 depth sensor is fixed onto the end-effector of the UR5e robot and connected to the upper computer via a USB interface, while the lower computer communicates with the upper computer via Ethernet protocol.

Fig. 1. Hardware configuration of the platform

4.2. Coordinate description in the design

The image obtained from the camera is described under the sensor (pixel) coordinate system, from which the actual size of the shape of the non-tiled area and the position related to the robot cannot be obtained directly. Therefore, camera calibration and hand-eye calibration are necessary to convert the sensor coordinate system into the camera coordinate system, and finally into the robot base coordinate system.

Basically, the camera calibration aims to obtain intrinsic parameters and extrinsic parameters of the camera. The transformation relationship between the sensor (pixel) coordinate system and the object coordinate system is:

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = H_{Img}^{Sen} \cdot H_{Cam}^{Img} \cdot H_{Obj}^{Cam} \cdot \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} \quad (1)$$

Where $H_{Img}^{Sen} \cdot H_{Cam}^{Img}$ is the intrinsic parameter of the camera, indicating the transformation from the camera coordinate system to the sensor coordinate system, while H_{Obj}^{Cam} is extrinsic parameters of the camera, describing the transformation from the object coordinate system to the camera coordinate system.

Hand-Eye calibration is aiming to describe the object's position and orientation from the camera coordinate system to the robot base coordinate system, so that the end-effector can reach the intended location. This research used Eye-in-Hand calibration, a process for determining the relative position and orientation of a robot-mounted camera with respect to the robot's end-effector, which assumed that the camera is rigidly mounted on the end-effector and moves with the end-effector.

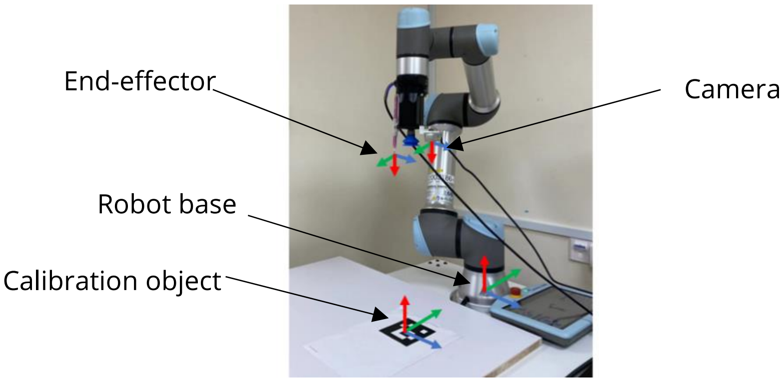


Fig. 2. Hand-eye calibration

The aim of hand-eye calibration is to obtain the object's pose transformed from the camera coordinate system to the robot base coordinate system (see Fig 2). This transformation can be determined by equation (2):

$$H_{Obj}^{Base} = H_{End}^{Base} \cdot H_{Cam}^{End} \cdot H_{Obj}^{Cam} \tag{2}$$

Where H_{End}^{Base} can be provided by the UR5e robot controller, and H_{Cam}^{End} can be determined by the hand-eye calibration. H_{Obj}^{Cam} can be obtained from camera calibration, specifically extrinsic parameters of the camera.

Since H_{Obj}^{Base} is always fixed in every posture of the robot arm, the equation (3) can be obtained, and then convert to the equation (4). To solve this form of the equation, at least two poses of the robot are required, while more poses of the robot can be adopted to improve the calibration accuracy.

$$(H_{End}^{Base})_i \cdot H_{Cam}^{End} \cdot \left(H_{Obj}^{Cam}\right)_i = (H_{End}^{Base})_{i+1} \cdot H_{Cam}^{End} \cdot \left(H_{Obj}^{Cam}\right)_{i+1} \tag{3}$$

$$(H_{End}^{Base})_{i+1}{}^{-1} \cdot (H_{End}^{Base})_i \cdot H_{Cam}^{End} = H_{Cam}^{End} \cdot \left(H_{Obj}^{Cam}\right)_{i+1} \cdot \left(H_{Obj}^{Cam}\right)_i^{-1} \tag{4}$$

Where i indicates the i-th pose of the robot.

The calibration process in this research was done by Robot Operation System (ROS) [26], via capturing a set of images of a static calibration marker of known geometry with a set of different positions and orientations of the robot arm. The intrinsic parameter was provided by the RealSense API, and a ROS package named *easy_handeye* was used for programming, which was based on the calibration method by Tsai et al [27]. Finally, the transformation relationship between all coordinate systems in every pose of the robot arm can be determined.

4.3. Profiles of edge area Detection

The main algorithm for edge shape detection is written based on the OpenCV library [28]. Two common situations in a room are discussed in this research.

4.3.1. Image preprocessing

Measurement tasks are based on the edge features, which can be expressed by the change of the gray level of the image. Therefore, to reduce the amount of operation in the image processing, the image taken by the camera should be transformed into a grayscale image first. Furthermore, image denoising allows for making the details of the image clearer, as shown in Fig.3 (b).

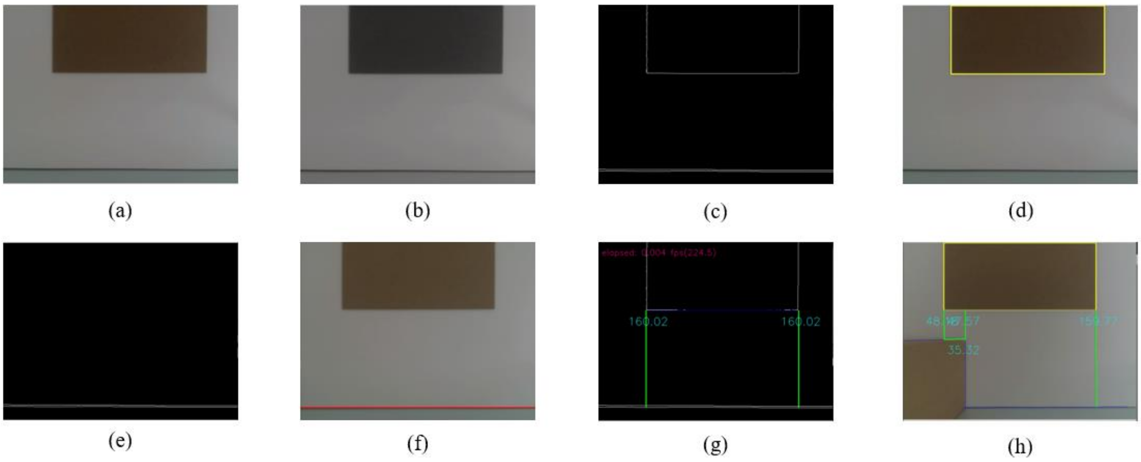


Fig. 3. Edge shape detection process: (a). Original image; (b). Image preprocessing; (c). Canny image; (d). Contour of the tile; (e). Image after masking tiles; (f). Detected wall-floor boundary; (g). Measurement of edge without columns; (h). Measurement of edge with a column.

4.3.2. Canny edge detection

The edge is detected using the Canny algorithm [29], which is an edge detector approach for detecting sharp intensity changes and object boundaries [30]. Ideally, the edge of the tiles and the wall-floor boundary can be obtained after image processing. The Canny function in the OpenCV library is adopted and required the upper and lower thresholds to determine the final edge in the image. In this study, the final gradient threshold is set as the lower limit of 15 and the upper limit of 30, as shown in Fig.3 (c).

4.3.3. Finding the contour of paved tile

Tiles can be detected through size. Due to the limited FOV in the camera, the whole contour of the tile cannot be obtained in one image, but it still has the largest convex contour. Tiles are detected in the following steps: 1) Select the largest contour from all contours detected by the cv2.findContour() function in the OpenCV library, which is the contour of the laid tile. 2) Find two corners of the laid tiles closest to the wall. The contour of the tile is shown in Fig.3 (d). Noted that the tiles are on the upper side of images and the wall is on the lower side of images all the time.

4.3.4. Determining the wall-floor boundary

The contour of the laid tile should be masked to eliminate its influence on boundary line detection before determining the wall-floor boundary, as shown in Fig.3 (e). In order to find the wall-floor boundary, progressive probabilistic Hough Transform (PPHT) [31] is adopted in this study. Compared with traditional Hough Transform, PPHT can detect the line segment with endpoints. However, a line segment that was originally a straight line is detected as a number of tiny line segments. In other words, the detected line segments detected are discontinuous. Therefore, a rule is set: if line segments are almost identical in length and slope, as well as overlap, they should be merged as a single line. Line segments can be merged in the following steps: 1) Convert the line to polar coordinate form (r, alpha). 2) Compare each two lines: if the difference of r and alpha between two overlapped line segments are smaller than 10 and 0.15 respectively, treat them as one line segment. Ideally, only the wall-floor boundary can be detected by PPHT if the threshold is suitable. In this section, only the edge with a straight wall situation is considered. Therefore, the wall-floor boundary is detected by finding the longest line in the Canny image after masking the contour of the tile, as shown in Fig.3 (f). The case of a more complex wall edge is considered in the next.

4.3.5. *Determining the profile of the edge area*

Overall, the profile of the edge area is determined by projecting from the tile edge to the wall-floor boundary. Since laid tiles are not always parallel to the wall, two distances (d1 and d2) from both sides of the tile to the wall should be measured, as shown in Fig.4 (a). The length of the gap can be calculated by following the steps: 1) Make a perpendicular to the wall-floor boundary line through a corner point of the tile, and then find the foot. 2) Transform the corner point and the foot from the pixel coordinate system to the camera coordinate system. 3) Calculate the distance between the foot and the corner point of the tile.

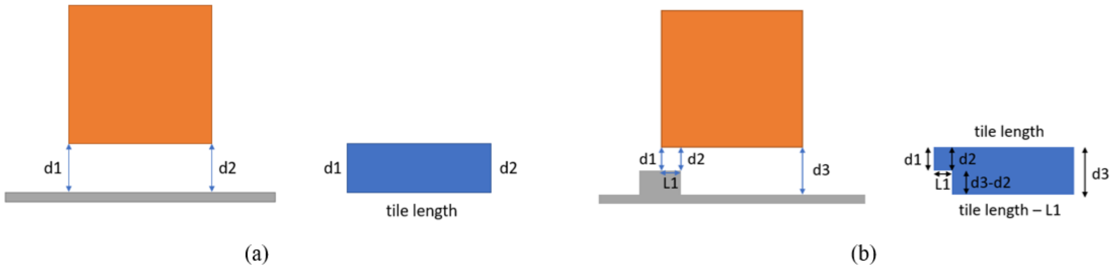


Fig. 4. Edge shape determination

4.3.6. *Improvement for determining edge with a column*

The above sections introduce the technical route of detecting the edge with a straight wall only. However, since the real site has some complex edges, the improved method for determining the edge with a column and a straight wall is introduced in this section.

In this research, only one rectangular column perpendicular to the wall is considered. The wall-floor boundary detected by the program has two horizontal lines and one vertical line. A total of four values should be determined in this scenario, as shown in Fig.4 (b).

Sometimes the program may detect additional line segments such as cracks and the high of the column, which are not conducive to the subsequent gap calculation. Since the wall-floor boundary consists of the three longest lines (two horizontal and one vertical) in the image and intersected each other, two other rules have been set: 1) if the endpoints of the identified line segment are not connected to the endpoints of other segments in the 10-pixel radius space, the line segment should be discarded. 2) If the slope (absolute value) of the identified line segment is greater than 3 degrees and less than 87 degrees, then the line segment should be discarded. As shown in Fig.3 (h), three blue lines are the detected wall-floor boundaries, and four values can determine one edge tile in this edge situation.

4.4. *Edge tiles drawing*

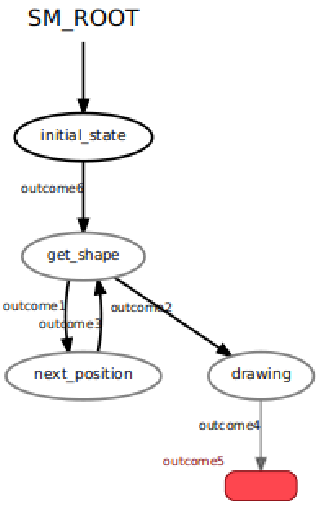
After a group of edge shape analyses, the robot will reach the drawing area. Every tile has the same initial penpoint, which is one corner of a complete tile set in advance. The penpoint will reach a start point first, then draw the edge shape depending on different edge situations. The movement control is based on *Moveit!* modules with a Descartes trajectory.

4.5. *Project implementation*

This section details the sequence of operations for the shape detection for each group of edge tiles.

In order to improve efficiency and reduce repeatability errors, putting several tiles in a group is necessary. The robot first collects information about a group of edge tiles and then arrives at the drawing point to draw the shape, instead of drawing immediately whenever it collects information about an edge tile.

The finite state machine (FSM) is used to combine all modules together. FSM has an arbitrary number of states, but only one is selected at any given moment (current state), and changes in them are triggered by an event or a condition [32]. For combining the aforementioned modules with finite state machines, this research adopted a python library named SMACH [33], which allows users to create and execute FSM. Fig.5 shows the FSM architecture in this research.



State description:

1. initial_state: Reach the first edge position that is set in advance.

2. get_shape: Get shapes for edge tiles.

3. next_position: Move along the wall-floor boundary, which is detected in the previous detecting position and transformed into the base coordinate system, where distance moved is equal to the length of the tile.

Fig. 5. FSM architecture

5. Result and discussion

5.1. Experiments and results

To verify the system, 200 mm * 250 mm planks were laid on a plane, and the gap between adjacent planks was 3 mm. This research has validated two scenarios, edge without columns and edge with a column respectively. Noted that these data were collected from the upper computer, and the deviation has not come from the drawing module.

1) Scenario 1: Edge without columns

In scenario 1, we regarded two planks as a group and repeated 5 times experiments, and finally collected 20 pieces of data for error analysis. The average deviation of Δd is 1.0 mm, while 85% of the measured values have deviations<2.0 mm (see Fig 6 (a)). Noticeably, there is no unusual interruption when testing the edge situation with a straight wall.

2) Scenario 2: Edge with a column

Due to the limited brightness and more complicated context by considering the column, it sometimes fails to identify the wall-floor boundary line well during the testing process, leading to experimental failure. To reduce the difficulty of the experiment, therefore, only one plank was put on the plane in scenario 2, since this study was focused on testing the feasibility of the edge shape determination. We repeated 5 times experiments and a total of 20 gap data have been obtained. The average deviation of Δd in scenario 2 is 1.5 mm, while 80% of the measured values have deviations<2.0mm (see Fig.6 (b)).

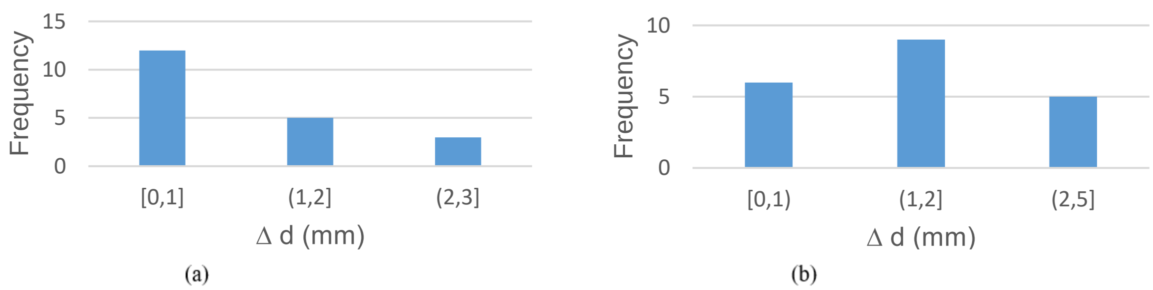


Fig. 6. (a). Result of the edge without columns; (b). Result of the edge with a column

Table 1. Deviation in two scenarios.

Items	Edge without columns	Edge with a column
Average deviation (mm)	1.0	1.5
Standard deviation (mm)	0.9	1.1
Maximum deviation (mm)	2.9	4.6
Fraction of deviations < 2mm (%)	85	80

According to Table 1, the average deviations of the edges with straight walls only and the edges with columns are 1.0 mm and 1.5 mm, respectively, which can meet the error tolerance requirement of 2 mm. However, only 85% and 80% of deviations are less than 2 mm in both edge situations, and the maximum deviation may be unacceptable for tiling work. Furthermore, the more complex the environment, the greater the error will be, and the robustness will also be reduced. The main error came from the insufficient background brightness, which may result in the inaccuracy of the calibration and the result of vision operators such as the Canny operator and the PPHT algorithm. Since depth cameras are sensitive to the light of the environment, providing good lighting conditions can well improve the stability of the depth camera work and reduce error.

5.2. Limitation and future work

Overall, the objective of this study is not to create a commercial robot, but rather to demonstrate the efficacy of the proposed vision-based method for the edge tiling problem. There are several limitations in the research. Firstly, the accuracy of this research is not yet sufficient and robust for actual tiling work. One of the reasons is the inadequate brightness of the environment, which results in the calibration process and the stability of the vision algorithm using a depth camera. Increasing the brightness of the environment during both the calibration process and the experiment testing stage is a necessary measure. Secondly, the visual algorithm in this study relies heavily on thresholds that are set in advance. Both the Canny operator and Hough Transform need suitable parameters to fit the situation. However, tiling conditions such as the brightness and the color of tiles are different in various scenarios. In future research, an edge detector that can adjust to more general illumination conditions and tiles with different patterns should be developed. Thirdly, this research oversimplifies edge situations, only discussing two common situations. In actual work, however, edges are more complex, such as edges with pipes and doors. It is necessary to find a flexible solution to adapt to more complex situations. Furthermore, for future practical applications, the end-effector with laser cutting and the mobile platform should be configured, and collaboration with other robots can be considered.

Although the trend of replacing manual labor with robots has emerged, some processes that are oriented to the corners or edges (e.g., edge tiling during the architectural finishing process) are still difficult to be completed entirely by robots. Following the thinking of industry 4.0, human-robot collaboration has the potential to be a fast and effective solution to the challenges. For edge tiling, the main tasks can still be performed by the robot (e.g., measuring, cutting, and placing), while humans can assist the robot in making decisions when encountering flexible and complex situations, such as determining the measured location and laying trajectory of each edge tile. In the future, it is suggested that the limitations and challenges mentioned in this study can be addressed through human-robot collaboration.

6. Conclusion

This research presents a vision-based solution for determining the shape of edge tiles. This is a first attempt at robotic edging tiling, although neither the accuracy nor the robustness is sufficient to be considered a viable option at present. It contributes to a new horizon in the use of sensors and robots for edge problems, which has the potential to reduce the workload of human workers and make them safer and healthier. Future research is recommended to make robot edge tiling more flexible to accommodate various situations, such as introducing human-robot collaboration.

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An Alignment Object Detection Method for Automatically Erecting Precast Components

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Abstract

In the context of intelligent construction, the alignment of precast components is the key to the automated erection of precast components. This can be divided into preliminary and precise alignment. The alignment process depends on alignment objects on site. The preliminary alignment is based on the control surface, while the precise alignment is based on exact control elements. Traditionally, this requires manual operations and communications to determine alignment objects, thus leading to low efficiency and being prone to accidents. To address this issue, taking the typical sleeve-rebar connection during the erection of precast structural components as an example, this research proposes an alignment object detection method based on computer vision. Firstly, an automatic generation algorithm for the hoisting control surface is established by combining image processing and a precast component model database. Then, an automatic extraction and matching algorithm is proposed to match the extracted control elements (i.e., sleeve centers and rebar contours). Finally, two experiments are conducted to verify the feasibility of the alignment object detection method. It is found that the proposed method can extract the basic alignment information for the automated erection of precast components.

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Keywords: alignment object detection, intelligent construction, precast component alignment.

1. Introduction

Hoisting is one of the most frequent processes on construction sites, particularly for prefabrication housing production (PHP), during which thousands of prefabricated components are transported and erected[1]. In terms of precast concrete components, their alignment is the key to the erection. However, the traditional manual alignment is not only time-consuming but also prone to collision accidents, resulting in tremendous casualties and property losses[2]. That is because drivers have limited environmental perception[3,4], which makes them unable to know the site situation immediately and accurately[1,5]. Existing research focuses on improving the environmental perception ability of crane drivers combined with various sensors to ensure safety[6,7], but neglecting the identification of alignment reference objects, which is very important to the automated erection of precast components.

In practice, different measuring and positioning equipment has been applied to improve the quality and accuracy of precast component alignment. The former enhances the measurement efficiency through total stations, with angle steel locators or positioning brackets assisting the alignment[8], still requiring manual erection and judgment. The latter combines with various positioning devices to measure the real-time distance between alignment objects and lifting components. Zhou[9] carried accurate setting-out to assist in hoisting alignment based on the Global Navigation Satellite System (GNSS), which is still in the experimental stage. Focusing on long-span steel arch bridges, Zhang[10] predicted the trajectory of precast columns to assist in the alignment with deep learning. Wakisaka[11] introduced a comprehensive construction system, in which some positioning equipment was utilized for alignment, but the system is bulky and costly. The above methods provide some reference for the automatic alignment of precast components, but manual assistance and erection errors still exist, thus also difficult in supporting the automated erection of precast components.

Visualization sensors have become widespread in industrial engineering. Yan[12] developed an automated assembly method with an accuracy of 50μm by converting the pixel coordinates of the assembly position into robot coordinates. Qin[13] proposed an assembly method for large-scale objects based on vision and laser sensors, which can detect polygon edges and achieve alignment elements. Based on the surface roughness and reflectivity, Tang[14] established an optical alignment system to identify and extract key edge features to assemble complex three-dimensional (3D) microstructures automatically. Although the alignment scene in construction is different from those in other industries, the above alignment element extraction methods can still provide a reference for the alignment of precast components.

This research aims to develop an alignment object detection method based on computer vision via taking the typical sleeve-rebar connection during the erection of precast structural components as an example. The rest of this paper is structured as follows. The method is first presented in Section 2, then two experiments are illustrated in Section 3, and finally a conclusion is drawn in Section 4.

2. Method

As the prerequisite of component erection, the detection of alignment objects not only determines the position where a lifting component should be erected, but also provides relevant site conditions. According to the erection process of precast structural components, the alignment object detection method involves two parts, i.e., the intelligent generation algorithm of hoisting control surface and the intelligent extraction and matching algorithm of alignment elements. The former is for the preliminary alignment, while the latter is for the precise alignment.

2.1. Intelligent generation algorithm of hoisting control surface

In this research, a hoisting control surface is defined as the vertical projection of a precast component on the erection plane when it is correctly placed. As the reference during component erection, the automatic generation of the control surface is the key to realizing the automatic erection of components. Based on the segmented rebar foreground of the trained Faster R-CNN, an intelligent generation algorithm of the control surface is proposed by combining the image processing algorithm and component database. On the one hand, an automatic generation algorithm for the minimum envelope of rebar is established based on the minimum circumscribed polygon. On the other hand, a screening algorithm is proposed to generate the target control surface according to the rebar arrangement in different envelopes.

2.2. Generation of minimum envelopes

Considering the process that the components are lifted to the top of the in-position location and approach the alignment object from far to near, it depends on the prearranged control lines and points that directly affect the alignment accuracy. Therefore, the hoisting control surface can be determined based on the control points and lines. The minimum envelope of rebar is the basis for generating the hoisting control surface, which contains the original control lines, points, and the steel bar arrangement situation. Fig. 1 shows the generation principle of minimum envelopes, i.e., to find the minimum circumscribed polygon of the points in u-v (two-dimensional (2D) pixel) image coordination. The whole generation process is illustrated as follows.

- Step1: A set P contains plenty of points $p_i(u_i, v_i)$. To find the point with v_{min} in set P (i.e., p_1 in Fig.1.) and add it in a new set P';
- Step2: A line l parallel to the u-axis is created from p_1 and rotated clockwise around p_1 until the line meets another point in set P' (i.e., p_2 in Fig.1.);

- Step3: Line l continues to rotate clockwise around p_2 until it finds another point in set P (i.e., p_3 in Fig.1.), then add p_3 in set P';
- Step4: Determine whether p_2 and p_3 are coincident. If they coincide, the rotating process ends, and the minimum envelop is generated by connecting points in set P' in order; Or, p_3 will be added to set P' and line l will rotate clockwise around p_3. Then, step3 is repeated to obtain points (p_4, …, p_n) in set P' till p_n coincides with p_1.

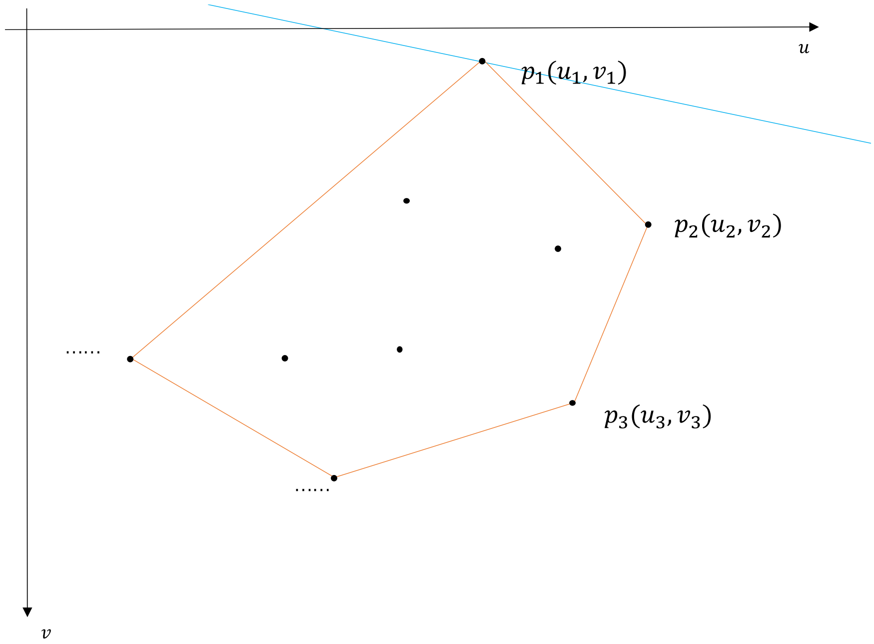


Fig. 1. The generation principle of minimum envelopes

2.3. Screening of minimum envelopes

In the early alignment stage, the overhead camera results in an extra-wide field, which means that multiple components are photographed simultaneously with several minimum envelopes. To solve the problem, an automated envelope screening method is presented by comparing the arrangement of rebar (including the envelope area, the number of rebars, the number of columns, the number of rows, and the spacing of rebar) with the components stored in the database. The entire screening process is illustrated as follows.

- Step1: The area of each envelope is calculated and compared with the bottom area of the lifting component to screen out the nonconforming;
- Step2: The number of steel bars in each envelope is calculated and compared with the sleeve number of the lifting component to screen out the nonconforming;
- Step3: The row and column number of steel bars are calculated and compared with those of the sleeves to screen out the nonconforming;
- Step4: The spacing of rebar is calculated and compared with that of the sleeves to screen out the nonconforming;
- Step5: According to the edge information (e.g., the distance between the sleeve and the bottom edge) stored in the database, the screened minimum envelope is further expanded into the hoisting control surface of the lifting component, providing a reference for intelligent hoisting (see Fig. 2).

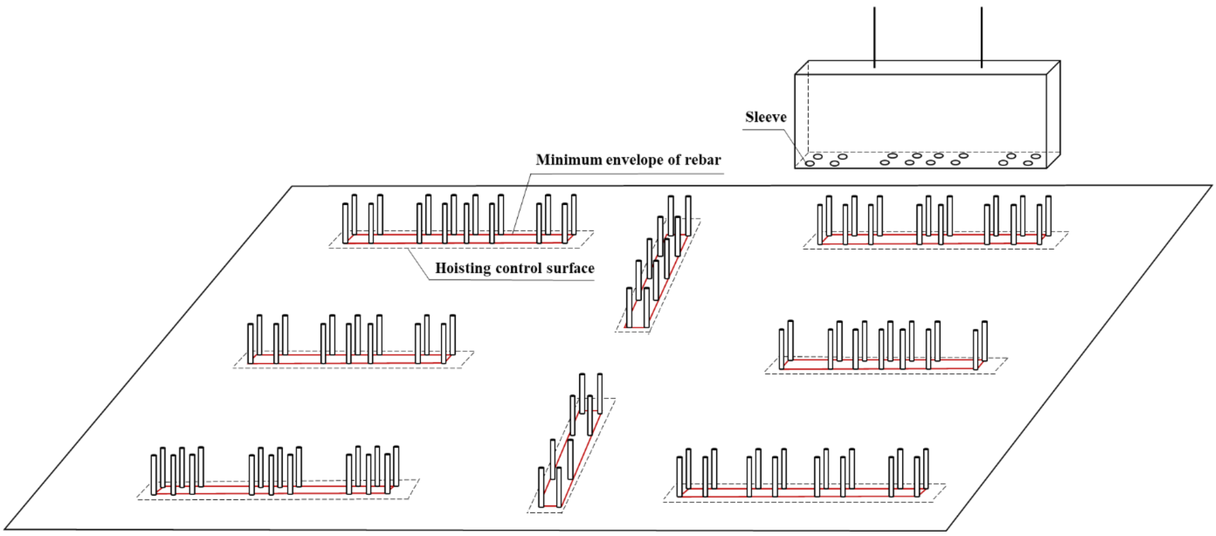


Fig. 2. The screened minimum envelope and the expanded hoisting control surface

2.4. Intelligent extraction and matching algorithm of alignment elements

According to the generated control surface, the lifting component can approach the target position and stops above the control surface. More detailed information about the alignment elements, such as the sleeve and rebar, is required to realize precise alignment. An intelligent extraction and matching algorithm for precise alignment elements is proposed based on image processing algorithms and technologies.

2.5. Transformation of precise alignment

Precise alignment in this research can be defined as follows: all rebar should be inserted into the corresponding sleeves when the lifting component is erected correctly. According to the theory of solid geometry that three non-collinear points can determine a plane in 3D space, the problem of precise alignment can be transformed into that of determining three non-collinear sleeves in the component. Considering that the final steel bars pass through the corresponding sleeves, this problem can be further transformed into the alignment of three non-collinear sleeves and steel bars (see Fig. 3).

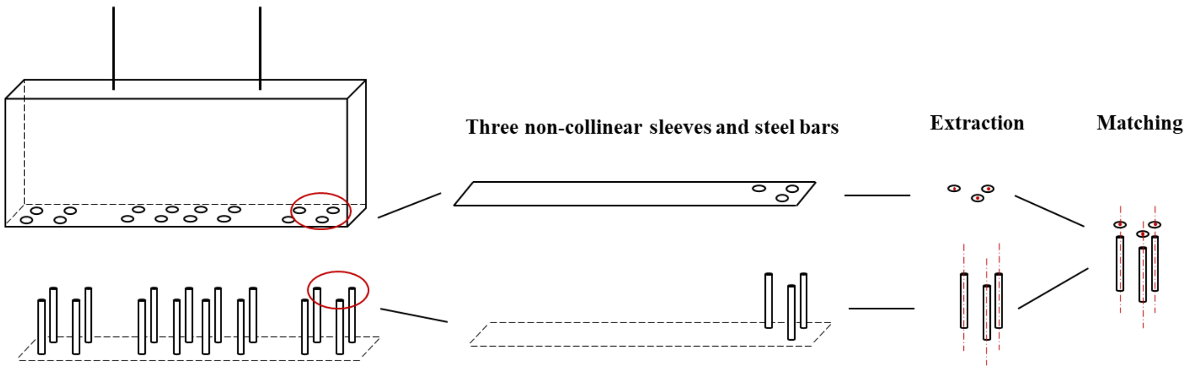


Fig. 3. Transformation of precise alignment problem

2.6. Alignment element extraction and deviation calculation

According to the transformation of precise alignment problem, two kinds of element information are needed, i.e., the fitting straight line of rebar and the sleeve center. For the former, the discrete contour points of rebar are extracted from the foreground by Canny Detection and then fitted as a line through Hough Transformation. For the latter, the extraction of the sleeve center is elaborated, especially the detection of the ellipse corresponding to the sleeve in a 2D pixel image (represented as a u-v coordinate system). Based on the segmented sleeve foreground, Canny Detection is also used to extract the discrete contour points of sleeves. In a pixel image, an ellipse can be parameterized as:

$$Au^2 + Buv + Cv^2 + Du + Ev + F = 0 \tag{2}$$

Therefore, any ellipse can be uniquely determined by the above five parameters. In addition, an ellipse can also be represented by another five geometric parameters, i.e., the center of the ellipse (u_c, v_c), the major and minor axis of ellipse (a, b) and the rotation angle ρ of the major axis to the u axis. The above two ellipse representations can be converted to each other, as shown in Equations (3) - (6) [15,16].

$$u_c = \frac{BE - 2CD}{4AC - B^2} \tag{3}$$

$$v_c = \frac{BD - 2AE}{4AC - B^2} \tag{4}$$

$$a = 2\sqrt{\frac{-2F}{A + C - \sqrt{B^2 + \left(\frac{A - C}{F}\right)^2}}} \tag{5}$$

$$b = 2\sqrt{\frac{-2F}{A + C + \sqrt{B^2 + \left(\frac{A - C}{F}\right)^2}}}$$

$$\rho = \frac{1}{2} tan^{-1} \frac{B}{A - C} \tag{6}$$

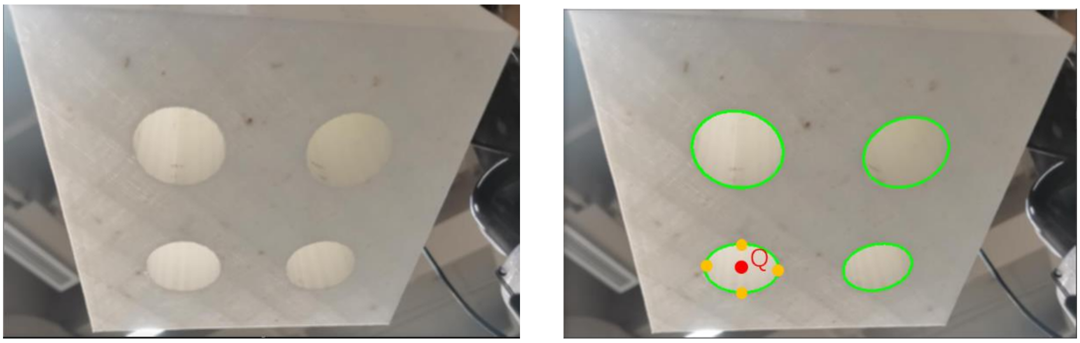
As the most commonly used method for ellipse fitting, the least square uses the maximum likelihood to achieve an optimal estimate to minimize the square root of the measurement error, assuming that the random error is normally distributed. The least square minimizes the distance between the measurement point and the true ellipse by a set of parameters. $f(u_0, v_0)$ is the algebraic distance from the measurement point (u_0, v_0) to the curve $f(\mathrm{u}, \mathrm{v}) = 0$. Assuming that $P_i(u_i, v_i)(i = 1,2, \dots, n)$ represents n (n≥5) measurement points on the ellipse contour, the objective function is described as:

$$f(A, B, C, D, E) = \sum_{i=1}^{n} (Au_i{}^2 + Bu_iv_i + Cv_i{}^2 + Du_i + Ev_i + F)^2 \tag{7}$$

Each coefficient is determined by minimizing the objective function. According to the extreme principle, the first derivative of zero is a necessary but insufficient condition for the extreme value point. Therefore, if the value of the objective function $f(\mathrm{A}, \mathrm{B}, \mathrm{C}, \mathrm{D}, \mathrm{E})$) is minimized, there must be:

$$\frac{\partial f}{\partial B} = \frac{\partial f}{\partial C} = \frac{\partial f}{\partial D} = \frac{\partial f}{\partial E} = \frac{\partial f}{\partial F} = 0 \tag{8}$$

A system of linear equations can be obtained, and the values of the equation coefficients A, B, C, D, E, and F can be obtained after solving the equations. Fig. 4 shows the ellipse fitted by the least square, with the ellipse center further extracted. Although the ellipse center (u_c, v_c) has been elaborated in Equations (3) and (4), its 3D coordinates cannot be directly obtained. This is because the ellipse center point in 2D image coordinates corresponds to the inner wall of the sleeve in the point cloud data (the center point Q of the ellipse is shown in Fig. 4). Therefore, this research calculates the image coordinates of the ellipse's major and minor axis vertices based on the above equations.



(a) Original picture of sleeves (b) Ellipse fitting results

Fig. 4. The fitting ellipses for sleeves

The image coordinates of the four vertices of the major and minor axes of the ellipse are described as follows:

$$(u_c + a * \cos\rho\, , v_c + a * \sin\rho) \tag{9}$$

$$(u_c - a * \cos\rho\, , v_c - a * \sin\rho) \tag{10}$$

$$(u_c - b * \sin\rho\, , v_c + b * \cos\rho) \tag{11}$$

$$(u_c + b * \sin\rho\, , v_c - b * \cos\rho) \tag{12}$$

Then, the 3D coordinates (x_0, y_0, z_0) of the sleeve center can be obtained by taking the average of the four endpoints. After extracting the alignment elements, the deviation between the sleeve center and the fitting line of the rebar can be calculated, which is exactly the distance *d* from Point Q to the corresponding Line L. The distance *d* can be calculated according to Heron's formula. When *d* is less than the value required by the standard, the sleeve and the steel bar can be aligned.

3. Experiment and test

Two experiments were designed to validate the feasibility of the proposed method. Experiment 1 was for the generation of minimum envelopes, and experiment 2 was for the extraction and matching of precise alignment elements. In experiment 1, the minimum envelopes of rebar were generated based on the segmented rebar foreground, as shown in Fig. 5. Rebar_area2 was selected by comparing the arrangement of rebars (including the envelope area, the number of rebars, the number of columns, the number of rows, and the spacing of rebar) with the components stored in the database.

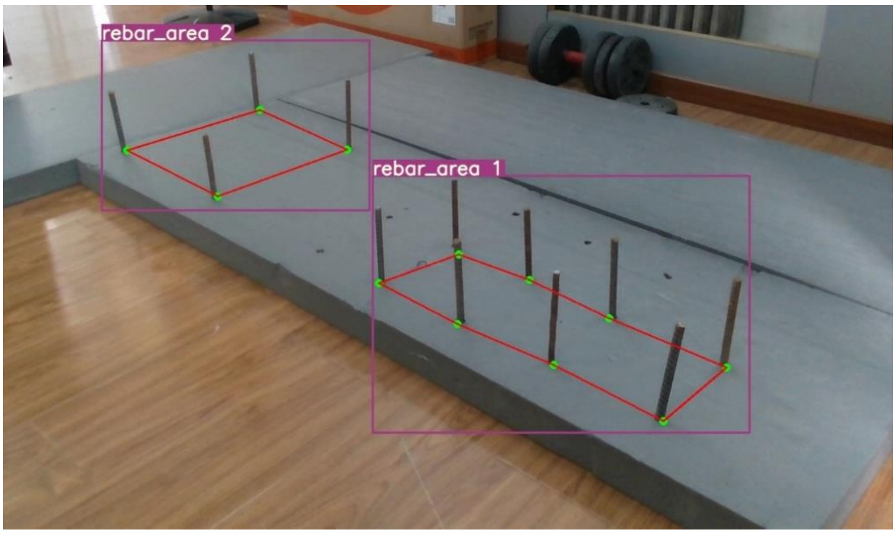


Fig. 5. Generation of the minimum envelope

In experiment 2, two 3D models represented the rebar and sleeves, respectively, and the accurate elements were identified and extracted (see Fig. 6). From left to right, the extracted lines are l_{12}, l_{13} and l_{14}, and the corresponding centers are Q_{12}, Q_{13} and Q_{14}, whose pixel coordinates and 3D coordinates are shown in Table 1. Each extracted line was calculated based on two random points on them. Finally, the deviation distance between Q_i and l_i (i=12, 13, 14) was calculated based on Heron's formula, whose results are shown in Table 2. The average error of the offset is 0.003m, which is acceptable.

(a) 3D Model (b) Alignment element extraction

Fig. 6. Sleeve-rebar alignment element extraction based on 3D models

Table 1. Extraction results of sleeve-rebar alignment elements

Alignment elements	u	v	x	y	z
Q_{12}	400	409	0.0890469	-0.0157684	0.338143
Two points on l_{12}	396	328	0.0883307	-0.0400191	0.33
	390	159	0.287529	-0.0142995	0.548636
Q_{13}	536	536	0.0441957	0.0670145	0.380333
Two points on l_{13}	538	398	0.0325581	-0.00991643	0.2855
	536	296	0.0317233	-0.0236569	0.273
Q_{14}	696	696	-0.0197086	0.0670236	0.346364
Two points on l_{14}	680	388	-0.0135481	-0.00818422	0.3422
	684	368	-0.01442	-0.0540234	0.328333

Table 2 Sleeve-rebar alignment deviation calculation

	Q_{12} and l_{12}	Q_{13} and l_{13}	Q_{14} and l_{14}
Deviation calculation	0.024	0.019	0.019
Actual deviation	0.029	0.019	0.015
Absolute value of error	0.005	0.000	0.004
Average absolute value of error		0.003	

4. Conclusion

To enable the automatic erection of precast components, this research proposes an alignment object detection method. An intelligent generation algorithm of the hoisting control surface is developed to realize the preliminary alignment by extracting and screening the minimum envelope of rebar, while an intelligent extraction and matching algorithm is proposed to achieve precise alignment by extracting sleeve-rebar alignment elements and calculating their deviation distance. It is shown from experiments that the proposed method is feasible and efficient. However, the tests are conducted in a laboratory environment, and it is assumed that the rebars are not bent. Thus, the method can be verified in real construction scenarios in the future.

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Bricklaying Method for rolLock or Soldier Courses with 4DOF Robotic Arms

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Abstract

Bricklaying is one of the traditional construction technologies that can be easily automatized in case of some circumstances. There are many attempts already to lay bricks with robotic arms or with other kinds of automated systems. Typical lifting and automated systems in the construction industry apply four degrees of freedom: movement along the three axes and turning around the vertical one. The automated construction of regular straight, curved, or even special brick courses is not challenging anymore. However, elements changing their typical horizontal position in the pallet to a vertical or to an inclining one during the bricklaying process need more freedom of movement hence a somewhat different toolset for automatization. Among traditional decoration techniques of the brick walls, the so-called rollock, or soldier courses, are frequently used as closing features of the fare-faced brick walls. Still, the 4DOF equipment systems are not applicable for this feature without further extensions. With the help of 5-6DOF robotic arms or an end-effector that provides turning around a horizontal axis, it is easy to overcome this problem. In this paper, an additional option is analyzed. A simple tilting tool is tested for enabling a given 4DOF system to change the horizontal position of the bricks without further extension.

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Keywords: bricklaying, construction methods, construction automation, degrees of freedom, robotic arm

1. Introduction

Many research projects have been conducted for bricklaying with robotic arms or other automated systems, solving many issues [1-9]. However, there are still many to be solved.

The construction industry's typical lifting devices and manipulating frames usually have four degrees of freedom (e.g., robotic arms, overhead gantry cranes). [10, 11] The most commonly applied robotic arms typically have four, five, or six degrees of freedom. In the case of less complicated manipulators, there is a better chance for a lower price and higher reliability, which is a lower chance for failure.

In the case of four degrees of freedom manipulators (overhead gantry cranes, 4DOF robotic arms, cable systems), we usually have movements along the x, y, and z-axis and a turning around the vertical axis (yaw). These four degrees of freedom enable most construction activities, but not all of them.

It is a known fact that prismatic joints are easier applicable and more practical in the construction industry, where we need to move relatively high weights. However, the number of more vulnerable joint types like hinges is typical for most equipment of the automatized tasks. [10] The application of simple tools provides a cost-effective but adequate solution to reduce the number of the more vulnerable joint types, which can be an advantage. Developing specialized elements for automated systems could be a possible way to handle some issues in the construction industry in the near future. In this paper, an attempt is demonstrated how a simple tool like that can be applied.

2. The problem

Most robotic arms with four degrees of freedom can move construction elements in three directions and are also able to rotate them around the vertical axis. In the case of horizontal palletizing, which is typical at bricks, the four degrees of freedom support many automatized bricklaying tasks, like straight or curved wall constructions, and even special features that can be created by the rotation of the bricks around the vertical axis (yaw). [5,9,10] However, it is not ideal when tilting/turning of the brick is needed around any horizontal axis (roll or pitch), like placing a brick vertically in the structure or for the tasks of building vaults. [8]

The simplest case of the ones mentioned above is the so-called rollock (rowlock) course or the soldier course, when a series of standing bricks (halves or full bricks) are applied as a decorative course, mainly at the bottom or on the top of the wall.

This change of position is possible with a five or six degrees of freedom robotic arm, or it requires a specially designed end-effector (that enables a further degree of freedom, namely a turning around a horizontal axis), but a more straightforward method can be used as well: a tilting tool (Fig. 1.). On the one hand, it should be noted that in contrast to the other two solutions, the application of a tilting tool interrupts the placement activity and increases the required time; on the other hand, it is considered to be a cheaper solution that can be an advantage too.

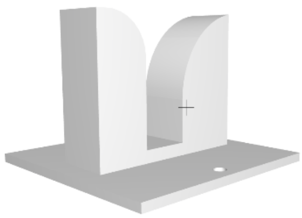

Fig. 1. The tilting tool

3. Method

In this research Dobot Magician 4 DOF robotic arm and a connected sliding rail were used for modeling bricklaying tasks. For the handling of the robotic arm, a python code was written. The application of a model environment enables many rapid tests for construction situations with relatively low cost.

For the purpose of laying soldier course with a 4 DOF robotic arm, a specially designed 3D printed tilting tool was created (Fig. 1,2).

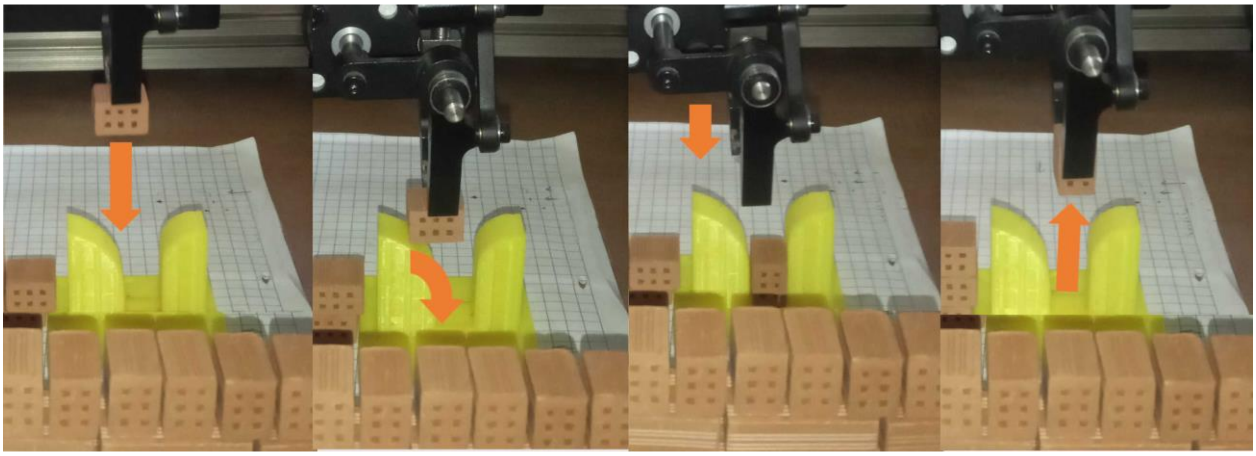

Fig. 2. The tilting sequence

This tilting tool is a simple tool that can change the position of the horizontal bricks to vertical by placing the bricks into the tool, letting them turn, and grabbing them again with the gripper in their new position (Fig. 2).

With the help of the demonstrated tool, the bricklaying activity of the rollock course was done in the established model environment, and the python code automatically measured the time of the activity. The calculated gross time was a little more than 5 minutes for a course of 14 bricks.

Two additional tests were conducted to estimate the difference between the possible options of constructing the same rollock course. In the first case, the position of the bricks was changed before the manipulation process. Namely, instead of normal palletizing, the bricks were stored in a transverse (vertical) palet, that is to say, all bricks were turned to a standing position in the pallet. That kind of thinking would not be typical in the case of a real construction environment; however, that action enabled us to calculate the net bricklaying time without the application of the tilting tool. This net time was around 3 and a half minutes. The two test pallet types are presented in Figure 3.

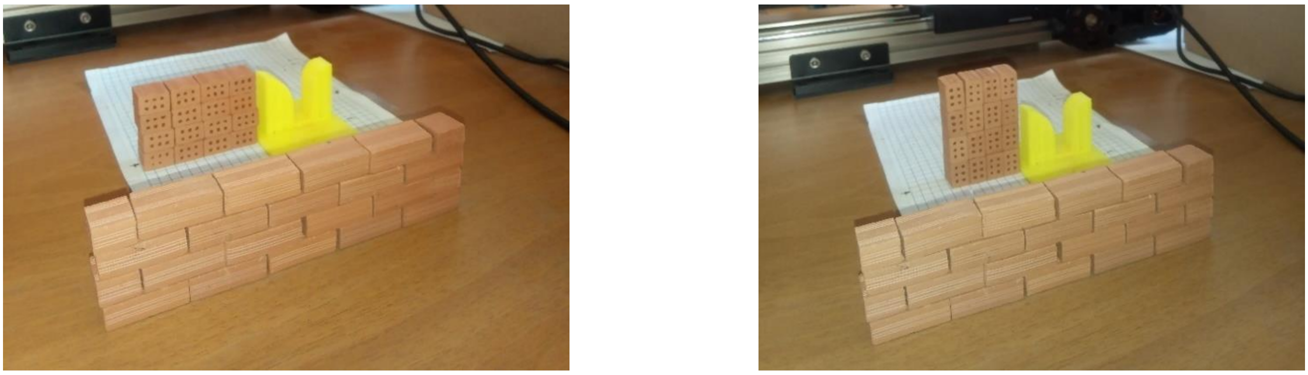

Fig. 3. (a) Normal pallet; (b) Rearranged pallet of standing bricks

We also calculated the difference between the application of the tilting tool and an estimated time of the hypothetical case if the elements would be tilted by an end-effector that enables the required further turning around the horizontal axis. In this case, it was assumed that the turning needs a further servomotor in the end-effector. Hence the measured time of two servo movements per brick was added (57.75 sec as a sum) to the net time of the previous case.

The measured net time of the movement was 14.74 seconds per brick, the theoretical time with the end-effector was estimated to be 18.87 seconds per brick, and the measured time in the case of the application of the tilting tool was 22.22 seconds per brick. The times are summarized in Table 1.

Table 1. Calculated bricklaying times

Bricklaying task	***Palletizing mode***	***Total time***	***Time/brick***
Soldier course with tilting tool	normal pallet	5min 11.05 sec	22.22 sec
Soldier course without tilting tool	rearranged pallet of standing bricks	3 min 3.26 sec	14.74 sec
Soldier course with end-effector (estimated)	normal pallet	4 min 24.21 sec	18.87 sec

4. Summary

The main goal of this investigation was not to give a final solution for the problem but to take one step forward to map the possible challenges in the case of applying simpler manipulators for the automation of the construction processes.

Both simple tools or special end-effectors can be used for the extensions of 4 DOF construction automation systems. The above-demonstrated bricklaying times clearly show that the process with the application of a simple tool is slower and results in around 20% more running time. Still, the use of servo-based end-effectors requires further development, and it is definitely more expensive, so in the case of some circumstances, when rapid, on-site solutions are required for a similar problem, the application of simple tools could be considered.

5. Possible extension of this research

In this paper, only one single case has been investigated, but a categorization of various construction works seems a logical spread of this single examination, namely mapping the requirements of each construction activity in case of automatized manipulation for possible simple tools. With a similar approach, many tools could be developed for various lifting and placing activities in the construction industry.

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Decentralized Maintenance Supply Chain System for Highly Sensitive Assets: 'Blockchain of Things' (BCoT)-based Solution

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Abstract

Due to existing challenges of operating supply chain for the highly sensitive assets (i.e., nuclear power plants) such as delays, disconnection between asset components' elements performance evaluation and supply chain process, lack of digitisation, etc. Therefore, The International Atomic Energy Agency (IAEA) as agency that manages highly-sensitive assets proposed the development of proactive management systems of operating supply chains in order to deal with mentioned challenges, as well as, enabling all parties to collaboratively interact in an integrated system nationally and internationally. Blockchain is a proven technology to enable (1) automating supply chain process in some leading industries (i.e., automotive industry); (2) minimising fragmentation in supply chain, (3) enhancing the trust among suppliers. Moreover, Industrial Internet of Things (IIoT) sensors can be used to track performances of power plants' elements to enable performing maintenance in the right time. As such, coupling blockchain and IIoT can enable developing the highly recommended proactive supply chain system by IAEA. In this research, A solution is developed to build the structure and the high-level architecture of the proposed proactive supply chain-based blockchain and IIoT. Moreover, a smart contract is developed to demonstrate the needed functions to manage the entire supply chain process for highly-sensitive assets such as nuclear power plants for energy production.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2022.

Keywords: Blockchain, Industrial Internet of Things (IIoT), Proactive supply chain system, nuclear power plant, maintenance supply chain challenges, International Atomic Energy Agency (IAEA), Asset and facility management

1. Introduction and conceptual background

Evidence shows that the transformation of the construction industry towards industry 4.0 relies on integrating advanced technologies like blockchain and the Internet of Things (IoT) as a necessary prerequisite to automating value-added tasks and data-acquisition systems [15,23,37]. Blockchain is defined as a distributed ledger technology characterised by decentralised operations across a consensus mechanism network (i.e., peer to peer) [38], where all data is stored as blocks that are immutable once joined and authenticated in a chain [19,33]. During the last few years, workable solutions-based blockchain in construction was developed, such as (1) automating financial transactions and securing interim payment [5,7], (2) minimising fragmentation in the supply chain, tracking resources and efficient shipment management [13,14,36], (3) Enhancing the quality information management based on hyperledger-fabric as a decentralised system [31]. However, the construction industry is still behind compared to other leading industries (i.e. automotive industry). The IoT is an evolution of the internet that integrates billions of smart objects [17]. It is also a process of interrelating several computing devices and digital machines through unique identifiers (UIDs) to exchange data among devices without requiring human interactions [32]. Furthermore, value-added services are added to internet devices by integrating IoT sensors, such as securing the privacy of shared data among network users [4].

The integration of IoT and blockchain has been discussed in previous studies regarding the technological potential and challenges [2,3,26,30]. Studies have also discussed different integration use cases for different industries like food and automobiles, among others, as Ourad *et al.* [25] proposed a blockchain-based solution using Ethereum smart contracts that provides authentication and secure communication to IoT devices. However, no available study has yet considered the potential use of integrating these two within the construction domain [12]. Researchers like Li *et al.* [21] and Perera *et al.* [27] provide a holistic view of the potential uses of blockchain in the construction industry and conclude that blockchain has significant potential in construction. This is mainly due to the transformation in the industry regarding procurement combining the change of onsite to offsite construction. As for IoT, extant literature is, for the most part, comprised of conceptual frameworks or is focused on creating point solutions for technical issues [6,20,28]. Given that there is ample opportunity for the integration of IoT and blockchain [2,35], such as automated tracking of project resources, managing supply chain processes, solving the disconnectivity issues in complex projects, managing equipment remotely and supporting the transformation to smart cities. Combined with a conspicuous gap in the literature on this point, gaining a full understanding of various aspects of integrating these two technologies within the construction industry is much needed.

Miraz [22] identified the Blockchain of Things (BCoT) as integration of blockchain technology and Internet of Things (IoT) to leverage the advantages of each individual technology, for example, blockchain can improve the security for IoT system. The BCoT is introduced to the construction industry by Elghaish *et al.* [8] to assess the potential of its applications to improve the delivery of construction projects. Blockchain is a proven technology to improve the transparency and trust among project parties through using its 'Peer to Peer' (P2P) technology to automate many processes [2,7]. Moreover, IoT can be used in the construction industry to automatically collect real-time information either from sites or facilities [8].

Given that IEAA [16],Oliver and Matheus [24] mentioned that there are several challenges of managing supply chain for highly sensitive assets such as nuclear power plants for energy generation such as the lack of finding qualified local suppliers, lack of collaboration among international suppliers, the lack of proactive material management. Given that the BCoT technology comprises blockchain and IoT advantages in terms of detecting real-time performance of elements using IoT sensors [18,30] and automating supply chain processes including ordering, purchasing, carrying and inventory automatically [1,8,9,11,34].

With all above in the mind, a solution of a proactive and automated supply chain system-based BCoT is developed to combat key revealed challenges of supply chain for highly sensitive assets such as nuclear power plants for energy production. A smart contract is developed to perform all functions such as 'requesting offers from suppliers', 'receiving offers', 'delivery' and 'checking and updating inventory level'. Therefore, the asset operator will be able to perform all supply chain tasks automatically, as well as, checking the national inventory level of specific critical elements via the created blockchain and smart contract. Moreover, A high-level architecture of IoT system to detect and provide real time information for asset operator to proactively plan the required items is also developed.

The outcome of this research will help asset owners/operators of highly sensitive assets to proactively plan their needs and avoid any interruption in the operation of their assets, as well as, enabling them to optimize the Total Material Cost (TMC) on the long-term.

2. Methodology

The literature review was used to highlight the existing challenges of supply chain process for the high-sensitive assets such as nuclear power plants for energy production. The literature review is a robust method to highlight the existing knowledge gap for specific topic or practice [9,10]. The development of a framework can help researchers to investigate relevant variables of a phenomena and develop a solution in a structured way [29]. As such, a framework will be developed to provide a solution for revealed key issues I the literature review. Figure 1 shows the logic and steps of conducting the research and fulfill the aim of this research.

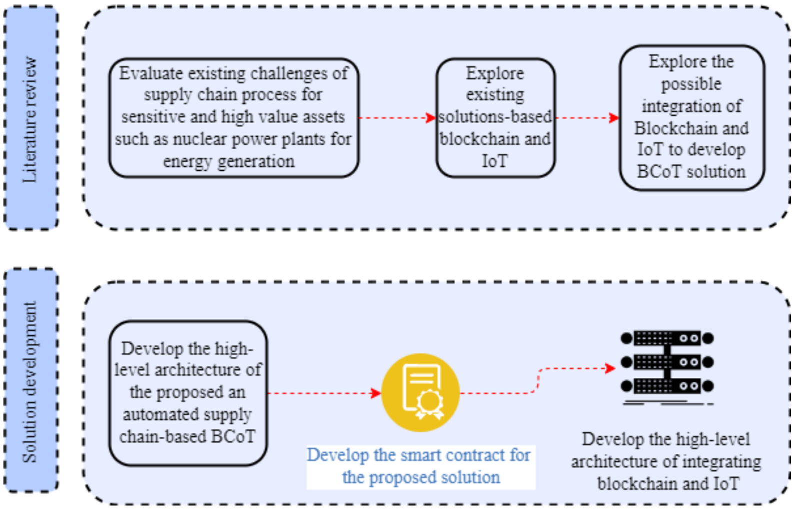

Fig 1. Research logic and steps of development

3. Conceptual Solution Development

3.1. Decentralized supply chain system-based Hyperledger fabric

Given that there should be a proactive supply chain system for the highly sensitive assets such as nuclear power plant, the road to this proactive supply chain is to automate its processes and tasks. Blockchain and smart contracts are proven technology to develop decentralized system that depends on pre-agreed consensus mechanism to transfer and endorse information. This study proposes using Hyperledger fabric and chaincode to develop a proactive decentralized supply chain system for highly sensitive asset such as nuclear power plant to combat issues that are published by The International Atomic Energy Agency (IAEA).

Figure 2 shows the high-level architecture of the proposed supply chain process-based Hyperledger and chaincode. It can be seen that the decentralized supply chain-based BCoT process is divided into three main stages, the first stage is the prediction of the need to replace items, this process will be conducted using IoT system. A set of IoT sensors should be installed to detect the performance of key facilities for the nuclear power plant, and rules are developed to determine based on received real-time data if the item needs to be replaced or not. This can be undertaken through developing an endorsement policy in the Hyperledger fabric to determine if the item needs to be replaced or not according to given ranges in the endorsement policy. The second process is to automatically select the suppliers using the pre-agreed endorsement policy, for examples, rules can be agreed to accept offers between specific cost ranges, and if offers of more than one supplier meet this range, then the nuclear power plant operator can check received blocks (offers) in the asset operator blockchain node and make the decision. A set of functions in the chaincode should be developed to enable all stakeholders (asset operators and suppliers) to undertake all tasks, namely, items to be replaced, offers from suppliers, payment, Items in inventory. Once the supplier is selected either using the automated endorsement policy or by the asset operator if more than one offers are valid and meet criteria, the order will be placed, and a block (information) will be added to all nodes according to the designed ordering policy. For example, information from selected supplier should be only registered in the nuclear power plant operator and other suppliers should not have access to such information. The third process in the proposed Automated and Decentralized Supply chain (ADSC) system is to record all information for future usage. Given that managing the inventory is one of the main critical tasks to maintain the operation of most sensitive assets such as nuclear power plant, therefore, all new purchased items should be automatically added as new blocks to the inventory node in the blockchain network. Therefore, the asset operator can keep the inventory level at the optimal value to avoid any interruption of the operation. The chaincode enables to record all types of information, therefore, the power plant operator can send and receive documents as blocks via the blockchain network. This can facilitate recording signed off invoices, etc.

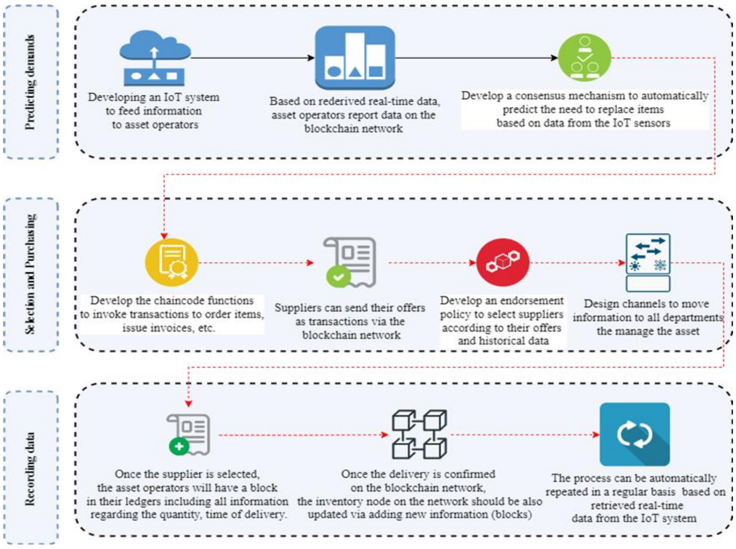

Fig2. High-level architecture of the BCoT supply chain system

Figure 3 shows the design of the proposed channels for ADSC system-based BCoT. There should be three main channels, the first channel (C1), which can be used to send information to all registered suppliers such as items that needs to be replaces—call for offers. The second channel (C2), which can be used to send offer acceptance letter and invoices between operator and selected supplier. The third channel (C3), this is for internal information sharing, for example, operator can use it to share information with inventory manger to add the new items to the inventory node in the blockchain network.

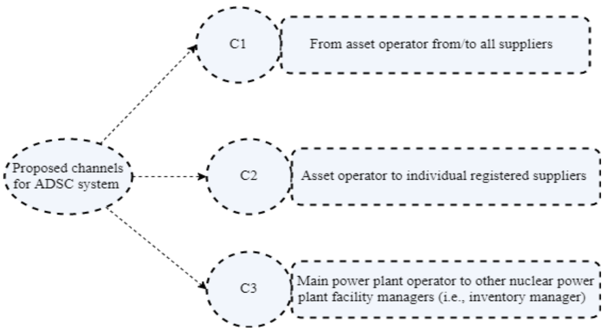

Fig3. blockchain channels design for ADSC system

3.2. *Chaincode functions development*

Figure 4 shows the structure and functions of the smart contract to manage all supply chain tasks on the blockchain network. As it can be seen from figure 4 that there is main four functions in the smart contract to manage supply chain for a nuclear reactor power plant, these functions are 'items to be replaced', 'offers by suppliers', 'payments and invoices' and 'update the inventory statuses'. All these functions are linked with the asset (nuclear power plant) in the smart contract, therefore, if there are more than one plant, asset operator can create another asset in the smart contract and link same functions to the new asset (i.e., nuclear power plant (20), etc.). Therefore, a national blockchain and smart contract can be developed to serve and cover all power plants in the country. This can help to check the national inventory level for the most critical items to avoid any interruption in the operation and the supply of energy from nuclear power plants. Asset operator and suppliers will be able to share documents in the blockchain network, for example, specifications of required items can be sent and recorded in the right blockchain nodes.

Figure 4. the smart contract for ADSC system

3.3. *Blockchain and IoT integration*

As a forementioned that BCoT relies on integrating IoT and blockchain to detect and collect real-time information, as well as processing and recording this information using blockchain technology. This research proposes developing an IoT system to detect and provide a real-time information to the nuclear power operator and the blockchain and smart contract will be used to automatically manage the supply chain process. Figure 5 shows the integration of the IoT system and blockchain to develop the BCoT for ADSC system. According to the survey that the nuclear power plant facility managers do, a set of sensors should be selected for all items and facilities that needs to be monitored regularly, then a set of microcontroller or raspberry pi needs to be connected with IoT sensor in order to process the data and transfer it directly to the main server and shows all the data in a smart monitor. For example, if the degree of temperature of item A is higher than degree (n), therefore, a warn will be showed in the monitor to the power plant operator to take an action for replacement.

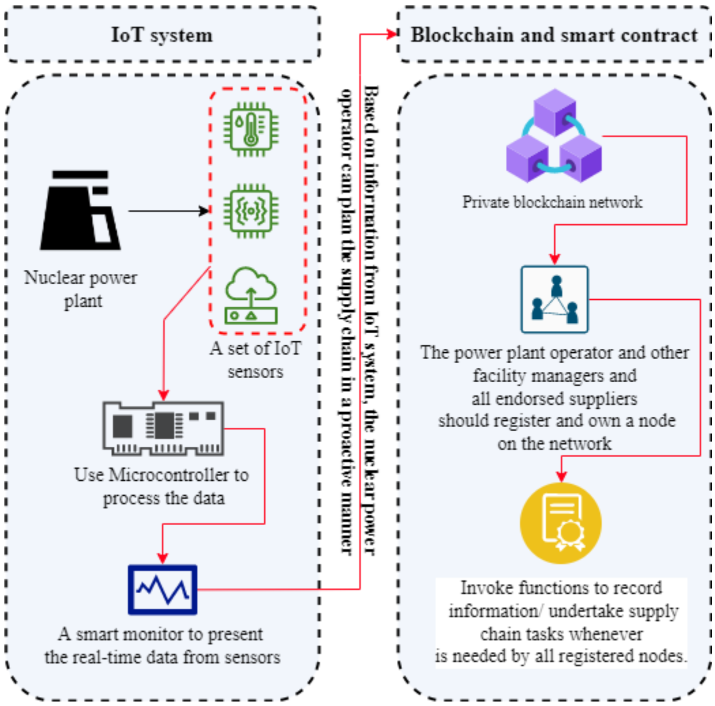

Fig 5. High-level architecture of integration IoT and blockchain

4. Discussion, significance and limitation

According to Oliver and Matheus [24], there are challenges that face the current practices of supply chain for nuclear power plants for energy generation in Europe such as difficulties in finding suppliers, Unuse of non-nuclear components that meet the criteria of safety, especially components that have lower level of nuclear safety. Therefore, there is a need for cross-border collaboration among European nuclear agencies. Moreover, IEAA [16] asserted that a proactive supply chain system is highly needed for nuclear power plants to combat failures of structures, systems or components to perform their planned function, or deal with the poor performance, which can negatively affect the global economy. As such, the proposed solution proposes the usage of BCoT to develop a proactive and automated cross-border supply chain system for nuclear power plants for energy production. The proposed solution provides the following features to manage revealed supply chain challenges in the literature review:

Integrating IoT into blockchain to automate the process of identifying the need to replace components and start the supply chain processes including ordering, purchasing, carrying and inventory. All mentioned processes are integrated into a proactive approach.

Supporting the national and international collaboration among nuclear suppliers via registering all valid supplier who provides components that meet the national and international quality and safety standards in a blockchain network and enable them to see any request for offers to supply elements, as well as, submitting their offers using the proposed smart contract.

The proposed solution will enable power plant operator (i.e., facility manager) to automatically check the national inventory for all components since there is a n inventory function in the smart contract to update the inventory level of specific items once new lot is received from suppliers. As such, this can minimize the existing fragmentation in supply chain process.

Adopting the concept of circular supply chain in nuclear power plants, especially for elements that have no negative impact on health and safety can raise the salvage value and maximize resources. Therefore, employing the proposed solution can enable a wide range of suppliers to collaboratively buy the items that comes out from maintenance process to enter in recycling or re-using them if possible.

The outcome of this research can be used as a point of departure to develop more functions for the created smart contract to expand the function of the proposed ADSC system.

Given that the proposed solution is conceptually presented, and a smart contract is developed, however, a full simulation is required to test the entire applicability, validity and reliability of the solution and participants such as asset operators and suppliers should be involved in the evaluation process.

5. Conclusion

This research proposed a proactive solution to deal with supply chain challenges for sensitive assets such as nuclear power plants that needs an automated monitoring of the performance of its critical components and zero delay in its supply chain. A proactive supply chain system-based BCoT is developed to link between the process evaluating the need to order items using IoT system and the other tasks in the supply chain process such as purchasing, carrying out and inventory management.

Given that there is an endemic issue to manage the inventory for large-scale asset using traditional independent material management approach, this research proposed an automated and integrated approach using blockchain and smart contract to reflect any new purchased items on the inventory level automatically. Moreover, all similar facilities in a country can be managed through one blockchain network to link between all inventories to optimize the Total Material Cost (TMC).

The outcome of this research can be extended in future research to implement it in a real-life case study to measure its applicability, workability, and scalability under different settings. Moreover, targeted stakeholders such as facility mangers and suppliers should be involved to evaluate the usability of the solution.

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The Analysis of Risk Management in Healthcare Construction Projects

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Abstract

Realization of construction projects is a very complex process, which is accompanied by potential risks, shortcomings and challenges. Energy consumption for buildings represents 30–45% of global energy use. The realization of Health Care Buildings is a great challenge due to the size of the facility, the complexity of the required installations, the need for specific equipment, qualified trained workforce, implementation and / or installation of specific systems and commissioning. Buildings such as residential, education, office, healthcare, and industrial are emerging as critical consumers in energy consumption. The problem of exploitation of the building after the realization motivates that during the process of realization and construction of the building, the total costs and energy consumption are reduced to a minimum. The idea is to observe all the phases of a project at the same time, because the realization of a project is as important as its exploitation. By applying automation during the execution and realization of the construction project, many risks can be predicted and prevented, but also by applying automation when using the building the energy consumption of the building can be directly affected. It is important to recognize risks in time and manage them. With large projects, all types of risks are much higher and more pronounced. Risks related to the occurrence of unforeseen costs are very high on the scale of large construction projects. That is why the idea arises to find a way to recognize and manage risks in time during the realization of health-care building. The research deals with the risks that are most common in realization of health-care buildings. The idea is to investigate all potential risks, make a classification and hierarchy from the largest to the smallest with factor influencing the project and propose an approach to solving and manage them.

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Keywords: automatization, construction projects, healthcare buildings, risk management.

1. Introduction

The construction industry is one of the most important economic sectors across the world. [1] The spending in construction represents between the 9%–15% of GDP in most countries and up to half of nation's investment can be allocated to the built environment. [2] Risk management is the process of measuring or assessing risk and developing management strategies. A management strategy begins with identifying risks, measuring and determining the size of risks, and then finding ways to handle those risks. Systematic analysis of safety risks and the impacts of them on the objectives of a project (time and cost) can lead to better planning and scheduling. Planning, identification, quantitative and qualitative analysis, responding, controlling and inspecting on risk along the project are the key steps of risk administration. The main challenge of risk management is the accurate estimation of probabilities or uncertainties of the future. [3]

1.1. Healthcare facilities - Risks

The main step in the process of risk management is risk identification. [4] There are many types of healthcare facilities and hospital buildings, which are one of the most complex buildings. The focus of this study is configurations of Emergency hospitals and Clinical Center that provide around the clock service and contain high-tech equipment for patient diagnosis, treatment and care. Deficiencies in hospital buildings are therefore not uncommon [5]. There are few construction standards specifically for healthcare buildings. Instead, applications and adaptations are made based on general standards for buildings. Configurations based on digital data analysis from similar facilities may reduce deficiencies and create standards by evaluating buildings through their lifecycle [6].

There are different types of risks, risks have a level of classification such as:

- High Risk
- Significant Risk
- Medium Risk

The level of risk based on events is high risk, which consists of aspects of price and cost and is related to the aspect of views. Following the impact of risk is significant risk, the most important aspect of which is location, but also material, equipment, finances, weather aspects, planning aspects and safety and health. Medium risk has aspects of production management and administration, human resource management and socio-cultural aspects.

Table 1. Classification of risk level and interpretation guide

Risk Level	Value (Weight)	Degree of Risk	State	The Ideal Required Action
I	0.1-0.2	Extremely low	Low external pressure	Good condition, needs to be maintained
II	0.2-0.4	Relatively low	Less external pressure	Good condition, vigilance required to avoid further disturbances
III	0.4-0.6	Medium	Environmental state is changing with external pressure	Need to work on the changing state
IV	0.6-0.8	Relatively high	Poor state with large external pressure	Immediate action and management programs required at all levels of the system (DPSIR)
V	0.8-1.0	Extremely high	Serious damage due to great pressure	Dangerous environment for animals and human living; rehabilitation programs are urgently required

Table 1. shows classification of risk level that can be applied on every type of buildings and construction projects. During the execution of construction works on medical facilities, changes and alterations often occur. Deficient availability and transparency of information regarding changes preclude sufficient control over changes, increasing the risk for configuration deviations. This may be a contributing factor for problems insufficient performance of the end-product in healthcare construction projects [5]. However, detailed information about changes enables prevention of negative impacts on building performance [7]. The deciding factors for the success or failure of the project were of great interest to both academics and industry experts. Most of the identified factors focused on project execution rather than organizational success [8]. Although the project management literature does not illustrate great corporate success, there are both direct and indirect links [9]. Organizational efficiency depends on successful project management [10]. The success of the project brings beneficial changes in the organization and vice versa [9]. Organizational efficiency is directly related to all risks and skills. It is important to recognize risks in time and manage them in a timely manner. In large projects, all types of risks are much higher and more

pronounced. Risks related to the occurrence of unforeseen costs are very high on the scale of large construction projects.

1.2. Healthcare facilities – Identification of Risks

According to the above classification, risks can be defined according to the impact they have, the most common risks in the implementation of construction projects are the risks of injuries. That is why it is very important how the construction site is managed and the realization of construction projects. Since it has already been said that Healthcare facilities are very complex and require requirements, the risks are also very complex and can be said to be much more significant and greater.

Table 2 shows consolidate plan of activities and safety risks after the specification of strategies and the execution of corrective actions.

Table 2. Risks ranking

Risk Symbol	Risk description	Score	Rank
R1	Working at heights	95	1
R2	Safety crane and forklifts	95	2
R3	Lifting and handling glass materials	80	3
R4	Working condition	80	4
R5	Fatigue	80	5
R6	Lack of safety equipment for the glass transition	50	6
R7	Stress	50	7
R8	Working in confined spaces	50	8
R9	Mists and vapors e.g. spray paint	50	9
R10	Difficult to use personal protective equipment at heights	20	10
R11	Workplace physical factors (light temperature and thermal stress)	20	11
R12	Fumes e.g. repair welding for installation glasses on the structure	20	12

In addition to all the above, the risks that arise due to changes during the project should be added. Modifications of projects during execution are perhaps the most common in this type of project, especially due to the specific purpose of the facility, technology and diagnostics equipment that is rapidly changing and improving. The biggest cause of design changes is the equipment, which is planned to be installed, the type of equipment and performance are often unknown, and the most common information that is needed is determined too late. Changes increase the risk of inadequate functionality that affect patient care [5], increased costs and/or prolonged construction times [11]. This leads to changes in the project and adaptation to the needs of the equipment. This is often the result of demolition and re-construction of the work, but even this is not a huge problem, such as the capacity to be met (electricity, ventilation, specific ventilation, separate sewerage, etc.).

Control of changes requires both detailed information and systematic management. As expected, the data from the object models contained more details about changes than the manual logs. However, the significant differences between the IFC files and logs indicate that the projects did not have sufficient information about changes to ensure intended functionality. This increases the risk of insufficient performance at delivery [12].

1.3. Healthcare facilities – managing risk

Incoherent change control in construction projects induces more changes to correct insufficient performance [13]. All stakeholders in a construction project should obtain information about configuration changes to avoid redundancy and/or contradictions [14]. Hence, transparency is important regarding information about changes. Digital building model data has the potential to provide detailed information about configuration changes, but this requires standardised input data to enable accurate analyses [15].

The IFC schemas for object model data provides standards and exchange formats that facilitate interoperability [16]. This improves the reliability of change information [17] and enables predictions and proactive measures [12].

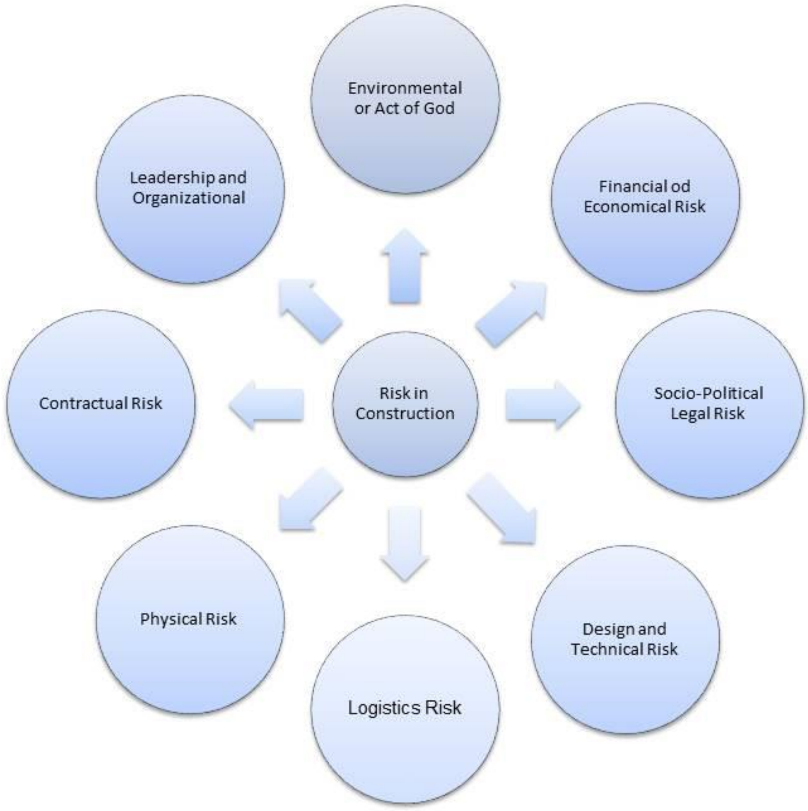

Fig. 1. Risk in Construction Project Management

In Figure 1 we can see the risks that occur when managing construction projects, these risks can be linked to the execution of construction projects. Risk management is a very complex part of the project, because it is necessary to identify and influence them in time. Changes in the project are almost considered inevitable in construction projects. Most change research often focuses on reactive action research rather than prevention. More precise control over changes in health care construction projects can prevent unnecessary changes. Most change research often focuses on reactive action research rather than on prevention or detection of risks / potential project changes.

2. Healthcare facilities – managing risk during the realization of project

The greatest influence on the execution of works in medical projects actually has radiological equipment and nuclear medicine equipment. Especially, reason for that is because the law and regulations can be supplemented and have some changes. The process of building medical facilities is often a long process, and regulations may change during its construction. Which further implies that it may happen that just before the completion of the facility, an entire part of the facility may be adapted to the new requirements and restrictions of the applicable regulations. Insufficient details about changes preclude informed implementation decisions and increase the risk for deviations from intended functionality. Even the slightest risk, if not recognized and affected in time, can have a catastrophic impact on a construction project. There are risks that cannot be foreseen, as is the case with equipment that has yet to be selected and installed, but just knowing that this problem exists gives room to prepare for that risk as much as possible. A way to prevent or reduce the impact of this risk is for designers to try to go one step further when designing a hospital project and anticipate as many changes as possible that may occur.

2.1. Managing risk – Decision maker changes

Often the risks that are unpredictable become even greater and more pronounced because the moment they appear, they do not react in time. The problem is with decision making and who is responsible for making the decision. In figure 2 is present the decision - maker process. In practice, we often encounter problems in making decisions on time. The clients were to a small extent involved in the change decisions in the logs. Although, four out ten of the respondents considered them responsible for decisions regarding changes to the configuration. Instead, the project managers made change decisions as responsible for costs. The deficient management of configuration changes in the cases increases the risk of the configuration deviating from the client's intentions regarding functionality [18].

Fig. 2. Decision - maker process

3. Conclusion

Project management is a very important part of any project, especially in construction projects where as a product we have a facility that uses a large number of people. It is important to meet all the required criteria and prevent all possible risks in a timely manner. In medical projects, the risks are diverse and much more serious than in a residential or building project. Starting the project with a solid plan and clearly communicating to stakeholders will place the team on a path for success. The process to get the team aligned requires time and preparation from the Project Team Leader to validate the approach, deliverables, resources, and timeline. In this way we can reduce potential risks to a minimum. This venture does not require any financial investment, but only the good will and ability of engineers and managers.

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A Mobile-based Application for Performing Assembly on the Construction Sites in a Decentralized Manner

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Abstract

The culture of morning assembly in the construction sites in Japan is in practice for a long period of time. The traditional morning assembly of the construction site is the gathering of all the construction workers in one place before starting the work of that day and listening to the information delivered by the site manager. The site manager explains the work, safety declaration, disaster's information, emergency exit, etc. using the bulletin board. Morning assemblies in construction sites are crowded, unorganized, unproductive, and pose a significant challenge for the management team. The problem of forgetting the assembly contents, not paying attention to the manager, unable to listen to the contents of the assembly are the major problems of traditional morning assembly. Besides these, the morning assemblies are known to be hotspots of Coronavirus infection as well. So, with the aim of making the morning assembly safer, organized and to aid boost of workers' productivity, we propose an application that can be used to organize the morning assembly in an organized and decentralized manner. This application can be used by the construction workers to check the morning assembly information on their own smart devices. The application includes all the information about the assembly and the user can access the application inside the site whenever they want to recall the assembly information. The application is developed in such a way that fake access to the site's information is avoided by using the QR code scan tool linked with the GPS data. The application was tested at multiple sites, and we receive various comments from the construction sites which prove that it will be possible to improve safety and productivity compared to the existing morning assembly.

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Keywords: Construction, COVID, GPS, morning assembly, site management, smart device.

1. Introduction

The morning assembly known as "Chourey" in Japanese is the first task to be performed every day on the construction sites before starting everyday work. At the construction sites, everyone who works in the construction sites gathers at a place in the early morning and listens to the tasks, safety measures, emergency routes, disasters example, safety declarations, etc. explained by the site manager before starting everyday work.

The traditional morning assembly scenery is shown in Fig.1 [1]. The traditional style of morning assembly was conducted by gathering all the construction workers at a place where the construction site manager stood in front of all the workers and give instructions using the bulletin board and displays. In the current situation of the COVID 19, it is necessary to avoid the gathering of many people in the same place for controlling the risk of infection [2].

In addition, the traditional style of morning assembly was not so effective and the problems like "difficulty in listening and understanding the morning assembly contents", "difficulty in seeing the morning assembly bulletin board", "forgetting the assembly contents during work", "going to the bulletin board area for checking the contents", "leakage of sites privacy", "data collection problem on user access and safety declaration" [3] etc. These types of problems are also one of the factors for decreasing the productivity of the construction management works [4].

To overcome these problems, the construction sites were always in need of a system that will solve the above-mentioned problems and difficulties. Therefore, we came up with a "Smart Morning Assembly" application that allows the construction workers to check the contents of the morning assembly within the working time and anywhere at the construction site range. This type of application will be used on a smart device which results in the operation of diversified morning assembly, reduction of gathering time, and the productivity of the entire workplace will be improved [5].

The application consists of various security functions for protecting and maintaining the privacy of every site. In this paper, we will be describing the "Smart morning assembly" application's features, technical ideas, high-security features, and its implementation and testing in various construction sites. We will show the testing results and the effectiveness of this application for increasing the productivity of construction sites.

Fig.1. Construction site manager briefing to site worker during the morning assembly

2. Application Overview

The "Smart Morning Assembly" application is an application for performing every day's morning assembly via smartphone. In this application, the individual e-site can be created for every construction site. The person who creates the e-site is the site-admin of the e-site, who has the authority to upload the contents of the morning assembly using a PC or smartphone. The contents created by the site-admin are made visible to the users using the smartphone at the designated time zone and range from the designated construction site. The site-admin can upload the contents like images, text, videos, and PDF files in the site-admin mode as shown in Fig. 2.

The site-admin will create a QR code for the designated construction site which will be scanned by the users (construction workers) via smartphone while entering the construction site to view the morning assembly contents uploaded by the site-admin as shown in Fig. 3 [6].

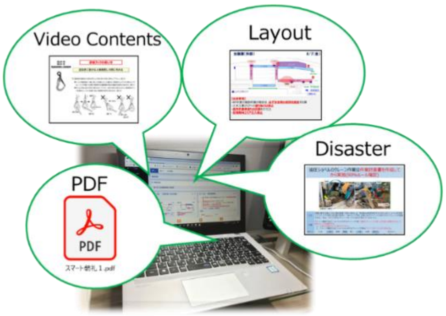

Fig.2. Contents type to upload on assembly app. Fig.3. site worker (user) scanning the QR code using the smartphone.

The QR code is used for security purposes as well. The information can only be accessed after scanning the QR code of the respected e-sites within the designated browse range from the construction site and the designated time [7]. To avoid the fake access, the application consists of a function where the site- admin can change the QR code at any time.

3. Application

"Smart Morning Assembly" is a solution that distributes the venue and time of the morning assembly by consolidating the morning assembly activities on e-site into one smartphone. As an effect of the application, we can expect diversification of morning assembly operations, reduction of personnel transportation time, efficiency of information transmission, and improvement of productivity of the entire workplace.

The problems related to the morning assembly in the construction sites along with the merits of using "Smart Morning Assembly" application are shown in Fig. 4. The special features of this application are described as follows.

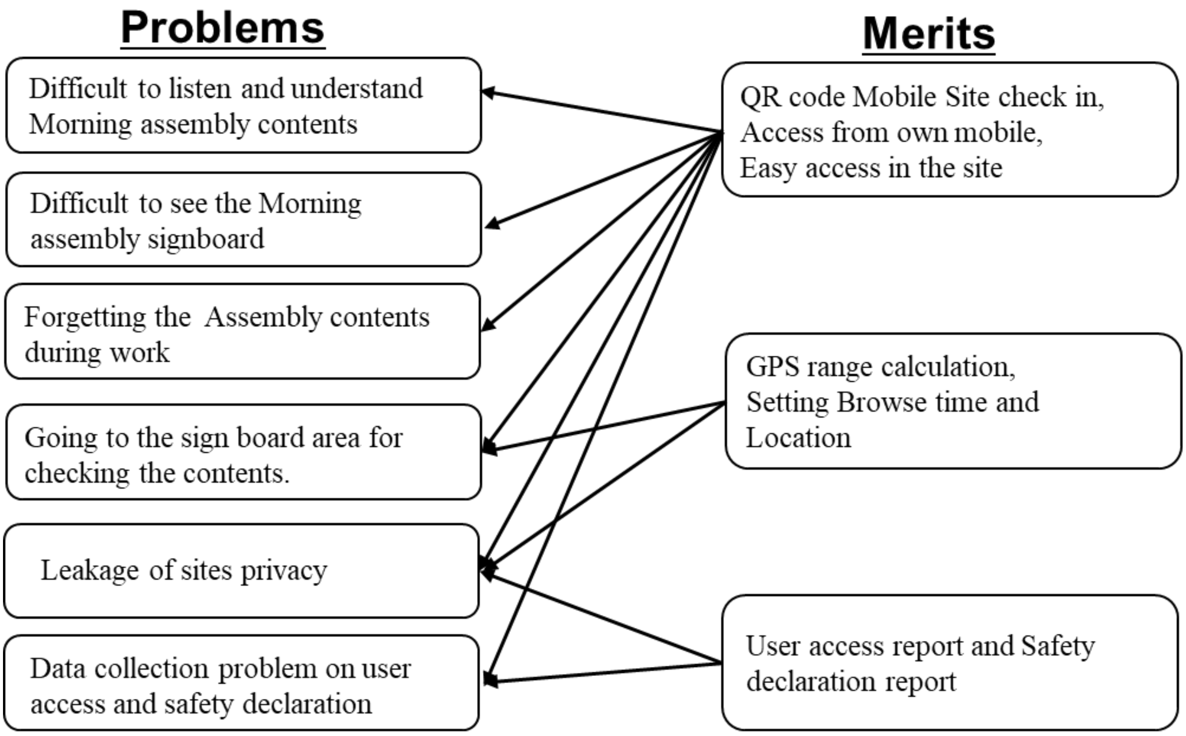

Fig.4. Relation of the Morning assembly problems and the merits of using Smart morning assembly app.

3.1. Designated Roles

This application consists of 3 designated roles, they are user, site-admin, and sub-admin. The description of the designated roles is as follows.

3.1.1. User

The users are the construction workers who work on the construction sites. Anyone who creates the account in "Smart Morning Assembly" application by setting the email address and password becomes the user. The user can log in to his application page by his login details, after the user is logged in to the application, the QR code button appears, and the user has to click the QR code button to scan the QR code for the specific sites and access the site information. The image showing the login page, and user screen before and after scanning the QR code are shown in Fig.5.

Fig.5. Login Screen, User screen image before and after QR code scan

3.1.2. Site-admin / Sub-admin

In this application, the user can create a new e-site by getting the authorization key from the system administrator. After inputting the authorization code, the user will input the required field such as site name, construction period, GPS Range (browse range), browse time, and site address to create a new e-site. The site-admin has the right to perform overall tasks related to the smart morning assembly application.

Similarly, the site-admin has the authority to generate and update the QR code to be used in the construction sites. The system flow of the site-admin role from creating the site profile to QR code printing is shown in Fig.6. It is possible to edit the related information of the e-site whenever the changes are required. All the information related to the e-site including the site name, construction period, browse range, browse time, site address, and the QR code can be edited whenever it is required. The application uses the cloud server for saving all the related data and information of the e-site.

The content updates in the sites are carried out in shifts, so it was necessary to assign site-admin privileges to multiple admin etc. The site-admin can assign the sub-admin in the sites for doing the reltaed works on behalf of site-admin.

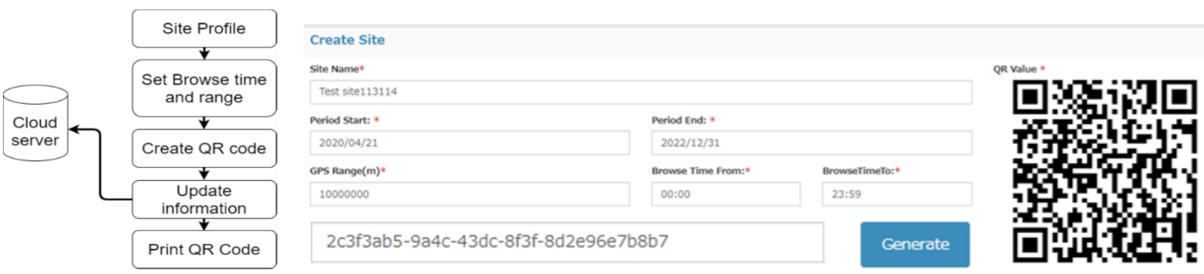

Fig. 6. System flow of the site-admin role from creating site profile to QR code print.

4. Proposed algorithm

The structure of our proposed algorithm for the user to access the smart morning assembly application and view the morning assembly contents is shown in Fig. 7.

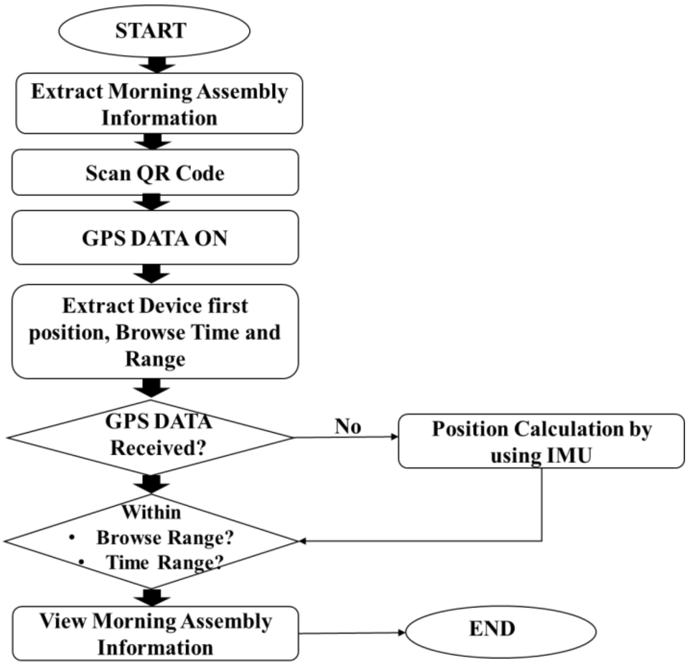

Fig.7. Proposed algorithm for the smart morning assembly application

The user (construction worker) whenever enters the site, they login to their account and scan the QR code on the site. When the QR code is scanned, the system checks whether the GPS data is enabled or not, if not then asks to enable it. In Parallel, the system detects the position of the device while scanning the QR code. Then, the system checks the browse range and browse time set by the site-admin, if the browse range and browse time are within the set values by the site-admin, the user will be able to view the morning assembly information. To maintain the privacy of the sites, we used this tool by calculating the latitude and longitude of the device using the GPS [8].

The algorithm is designed in such a way that, when the GPS is lost suddenly, the system uses the IMU of the device (smart device) for calculating the position of the device and the distance from the scanned QR code. We are using a simple IMU algorithm for this system which is why the accuracy is not so good [9].

5. Testing and Evaluation

We tested the “Smart Morning Assembly” application daily in multiple construction sites for more than 6 months. Depending on the sites, the morning assembly contents vary, some sites were using only the videos, whereas some sites were using a lot of images and some sites were using both images and videos.

This app can also count the number of users, where and who scanned the QR code and get access to the site. The aggregated data is saved in CSV format. This CSV data can be used to identify who has accessed the site and who has checked the safety declaration. The graph showing the user access data for 6 months in a site with 300 workers is shown in Fig. 8.This application is a new trend for conducting the morning assembly via smartphone, Construction workers are not familiar to such types of applications thats why the user access decreased from 52% to 40% in the second month but after the announcemnet for users to use the smart morning assembly application every day, the access ratio of the application increases gradually to 92%. The remaining 8% are the ones who are not used to smartphones or don’t have smartphones.

We found that continuous announcements are necessary to secure the number of access for each person. We also took an interview with the site managers regarding the usage of morning assembly application and received the comments stating the reduction of time and effort required for preparing the morning assembly contents.

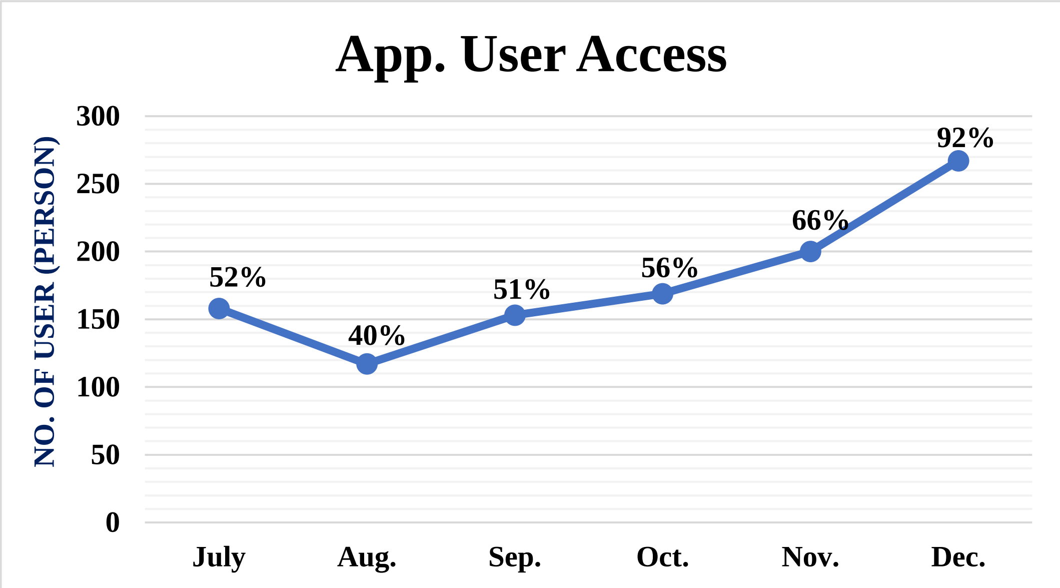

Fig.8. No. of users accessing the application for morning assembly contents.

5. Conclusions

The Smart morning assembly still have some issues to be solved but the application seems to be effective for increasing the productivity of the construction sites and bring a change in the morning assembly trend of the construction sites. This application has made it possible to convey information in real time without having to gather at the site, which was difficult until now."

This application solved the problem of protecting the secured information of the sites by using the QR code and accessing the GPS data for determining the location and position of the device within the range of the construction sites. In the future, by providing a work style that allows workers to mange thier time freely , we would like to improve productivity and attract a large number of human resources.

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Atmospheric Corrosion of Structural Steel and Hot Dip Galvanized Structural Steel in Saraburi, Chonburi and Songkhla, Thailand

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Abstract

The investigation of corrosion for structural steel grade SS400 and hot dip galvanized structural steel has been conducted in 3 different provinces in Thailand, Saraburi for the rural agriculture environment, Chonburi for the industrial environment, and Songkhla for the coastal environment. The exposure period of specimens was 3 months, 6 months, and 12 months from March 2020 to March 2021. Environmental conditions such as temperature, relative humidity, and rainfall were monitored monthly averaged. Pollution parameters such as chloride and sulfur dioxide were monitored 6 months averaged. The corrosion rates are calculated by the weight-loss method. The result showed that SS400 structural steel has a significantly large value of corrosion rate than hot dip galvanized structural steel in 3 provinces. The specimens in the coastal environment showed more corrosion rate than in industrial and rural agriculture environments. The life cycle cost of the steel structure constructed with these two materials was compared, and the result can be used for material consideration and service life design of steel structures.

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Keywords: atmospheric corrosion, hot-dip galvanized steel, structural steel.

1. Introduction

Structural steel design mainly considers only member strength. However, to carry the same member design strength throughout the design service life is less likely discussed. The common major problem is atmospheric corrosion which causes thickness loss of steel. Therefore, the structure that had been built for an extended period of years faced questions of structural safety.

Atmospheric corrosion is the degradation of material surfaces by physical and chemicals in a different atmospheric environment. [1] For atmospheric corrosion of carbon steel and hot-dip galvanized steel, their primary corrosion comes from several environmental parameters such as temperature, rainfall, relative humidity, Cl^- and SO_2, as proposed by several researchers.

In Thailand, environmental parameters are unique compared to other countries. Therefore, other countries' atmospheric corrosion data cannot be used to estimate the corrosion of material in Thailand.

This paper aims to investigate the corrosion magnitude of SS400 steel, and hot-dip galvanized steel in different environments in Thailand as they are common structural steel used for steel construction buildings.

4. Experimental Program

4.1. Specimen preparation

In this paper, the materials used for the study are SS400 and hot-dip galvanized steel. SS400 is the steel grade by JIS G3101 standard, which stand for general steel. Hot-dip galvanized steel in this study is SS400 hot-dip galvanized under ASTM A123/A123M standard. The chemical composition of SS400 steel shows in Table 1. The hot-dip galvanized steel coating of special high-grade zinc, chemical composition shows in Table 2, with a coating of approximately 110 µm. SS400 steel specimens were sandblasted, rubbed by sandpapers, rinsed with distilled water followed by acetone, hot-air dried, weighted, and placed inside desiccators. Hot-dip galvanized steel specimens were rubbed by sandpapers, rinsed with distilled water followed by acetone, hot-air dried, weighted, and placed inside desiccators. Both steel specimens are 100 mm x150 mm x4.5mm in size.

Table 1. Chemical composition of SS400 steel

Steel	Chemical Composition % by weight										
	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	Nb
SS400	0.058	0.191	0.595	0.014	0.009	0.038	0.008	0.036	0.010	0.112	0.001

Table 2. Chemical composition of hot-dip galvanized steel (HDG)

Steel	Chemical Composition % by weight					
	Zn	Pb	Cd	Fe	Cu	Sn
HDG	99.995	<0.003	<0.001	<0.001	<0.001	<0.001

4.2. Exposure Test

Specimens were distributed to exposure sites and placed on the site exposure racks in which facing south or the closest sea direction. Exposure sites are located at Saraburi, Chonburi, and Songkhla. In Saraburi, the exposure rack is placed on a ground elevation, and the surrounding environment is an agriculture area at a coordinate of 14°29'03.6", 100°53'34.4". In Chonburi, the exposure rack is placed on a ground elevation, and the surrounding environment is an industrial estate at a coordinate of 13°04'19.9", 101°05'18.3". In Songkhla, the exposure rack is placed on the 13th floor on top of the building elevation, and the surrounding environment is a sea coastline. The exposure test was conducted from March 2020 to March 2021.

Environmental parameters were collected and presented in Table 3. For Cl^-, they were collected by the dry gauze method and SO_2 by the lead cylinder method. The two methods stated are listed in ISO 9225. Other parameters were collected by the on-site weather station.

Table 3. Environmental parameters collected from each exposure sites

Exposure Site	Annual average temperature	Annual average relative humidity	Annual Cumulative rainfall	Annual Cl- deposition	Annual So2 deposition
	°C	%	mm.	mg/(m^2 day)	mg/(m^2 day)
Saraburi	28.5	76.2	927	1.68	9.30
Chonburi	27.0	83.7	1471	3.18	10.22
Songkhla	28.7	80.0	3288	10.95	8.75

5. Result and discussion

5.1. Thickness loss

Commonly, the corrosion rate of steel by atmospheric corrosion is calculated based on the weigh-loss method and put in the term of thickness loss. The equation to calculate the thickness loss is assuming uniform corrosion and show in Eq 1.

$$Thickness\ loss\ (\mu m)\ = \frac{w}{\rho \cdot A} \times 10^4 \quad (1)$$

Where w = mass loss (g), ρ = density of steel (7.86 g/cm3) / hot dip galvanize coating (7.14 g/cm3), and A = specimen exposure areas. Fig 1 and Fig 2 show the thickness loss of SS400 and HDG from 3, 6, and 12 months at different exposure sites. Thickness loss of SS400 steel at different exposure sites from 3 months, 6 months, and 12 months is shown as follows: Saraburi: 6.26, 8.91, and 13.46 μm, Chonburi: 7.85, 11.80, and 19.77 μm, Songkhla: 6.75, 12.53, and 23.76 μm. Thickness loss of HDG steel at different exposure sites from 3 months, 6 months, and 12 months is shown as follows: Saraburi: 0.12, 0.22, and 0.33 μm, Chonburi: 0.26, 0.42, and 0.68 μm, Songkhla: 0.36, 0.46, and 1.17 μm. From the thickness loss at 12 months, HDG steel shows better performance than SS400, about 40 times in Saraburi, 29 times in Chonburi, and 20 times in Songkhla.

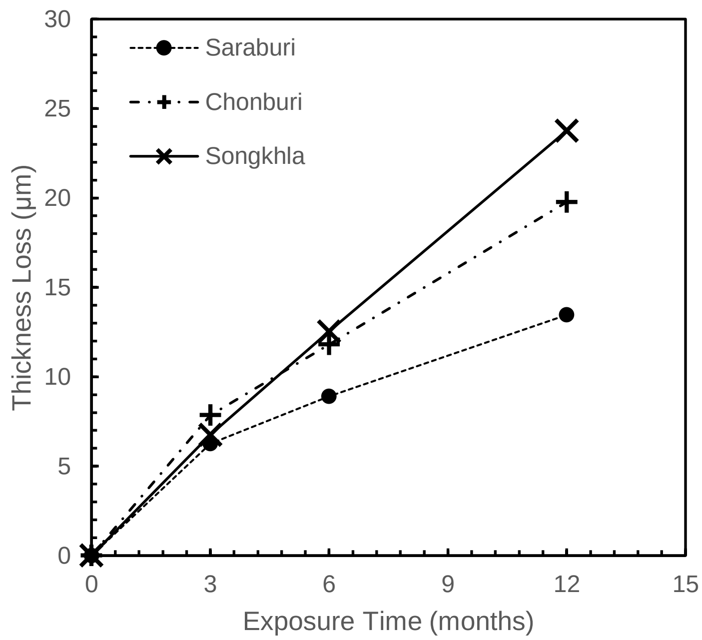

Fig. 1. Thickness loss of SS400 at different exposure sites

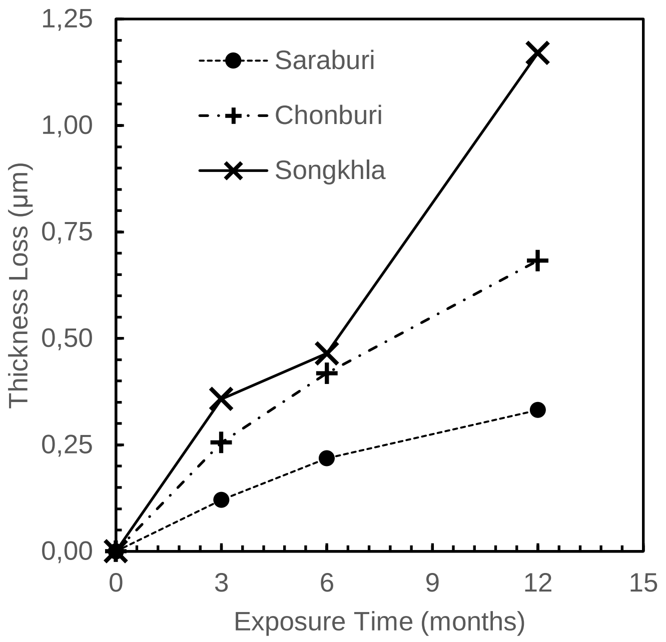

Fig. 2. Thickness loss of SS400 at different exposure sites

5.2. Project thickness loss

Thickness loss prediction equation due to atmospheric corrosion, which several researchers proposed. [2,3,4]

$$Project\ thickness\ loss\ (\mu m)\ = At^{b} \qquad (2)$$

Where A and b are constants obtained in fitting curve analysis, t = extended exposure time (months). The b value is considered a growth rate of corrosion product on steel surface related to environmental corrosion effect of different locations to different steels and usually < 1. When b < 0.5, it is considered that corrosion products had formed some rust protection layers, which become compacted and reduce corrosion rate in longer exposure time. For b > 0.5, It is believed that corrosion products had formed some rust protection layers which become compacted but did not significantly protect steels or did not become compacted at all [5]. The constant value of each steel is presented in Table 4. For SS400 and HDG, the b value at Songkhla is the highest, representing the harsh corrosive environment due to high present of Cl^- and rainfall. Therefore, the corrosion activity is high in Songkhla than in Saraburi and Chonburi.

Table 4. Constants values from fitting curve of SS400 and HDG steel

Steel type	Exposure site	A	b
SS400	Saraburi	3.37	0.55
	Chonburi	3.71	0.66
	Songkhla	2.48	0.90
HDG	Saraburi	0.056	0.73
	Chonburi	0.117	0.71
	Songkhla	0.135	0.85

5.3. Life cycle cost

Life cycle cost is the estimated cost for feasibility analysis of the project. The main parameters are starting cost and service cost that may occur. In this paper, SS400 and HDG steel were analysed as construction materials. The life cycle cost for a steel structure service life of 20 years, according to data analysed from Eq. 2 and Table 4 is shown in Table 5. This calculation was only performed in Songkhla as the location had the highest corrosion rate in this paper. The calculation is based on a commonly used steel section, WF150x150x7x13x31.5 kg/m, for an outdoor low-rise steel building column of 3.00 meters. The unit cost of materials was observed in Thailand in 2020. The cost was converted from THB to USD using 34 THB to 1 USD. The result shows the total cost over 20 years of HDG is very high compared to SS400 about 74%. This is because the starting cost of HDG is very expensive. However, if the starting cost is neglected, HDG steel shows a lesser cost than SS400 steel about 39% at 20 years of service life due to the very low corrosion rate of the materials.

Table 5. Life cycle cost of SS400 and HDG steel in in Songkhla for 20 years of service life design.

Steel type	Starting cost	Service life cost = w x A x Unit cost				Total cost
		Weight loss	Exposure area	Unit Cost	Service life cost	
		w	A			
	USD	kg / m^2.	m^2.	USD	USD	USD
SS400	**84**	2.85	2.65	0.89	**6.72**	**91**
HDG	**153**	0.96	2.65	1.62	**4.07**	**158**

5.4. Durability of design strength

Durability design is the design of a structural member to maintain structural design strength throughout the expected service life of a structure. After the life cycle cost of the material was analyzed, the durability of strength also must be verified throughout the expected service life of a structure. The durability problems are usually ignored as the construction industry is very competitive. Most of the steel members are very optimized in design strength to achieve the lowest price in a construction project bidding possible. The steel column made of SS400 and HDG steel as analyzed in Table 5 were used to compute a structural design strength in Fig. 3 when considered an effect of thickness loss due to atmospheric corrosion for 20 years of service life design. The standard to determine the column strength is based on Allowable Strength Design (ASD) 1986 code with effective length factor, k =1.20. At 20 years, the results show SS400 steel loses the structural design strength about 15% compared to its original design strength value at the beginning. This is due to a high project thickness loss of 362 μm in which the gross section area of the steel column is reduced during service life period. For HDG steel, it does not lose structural design strength throughout the service life as it has hot-dip galvanized coating as a corrosion protection in which the project thickness loss is only 13.4 μm out of the initial coating thickness of 110 μm. In term of maintaining a structural design strength, HDG steel show a better performance than SS400 steel.

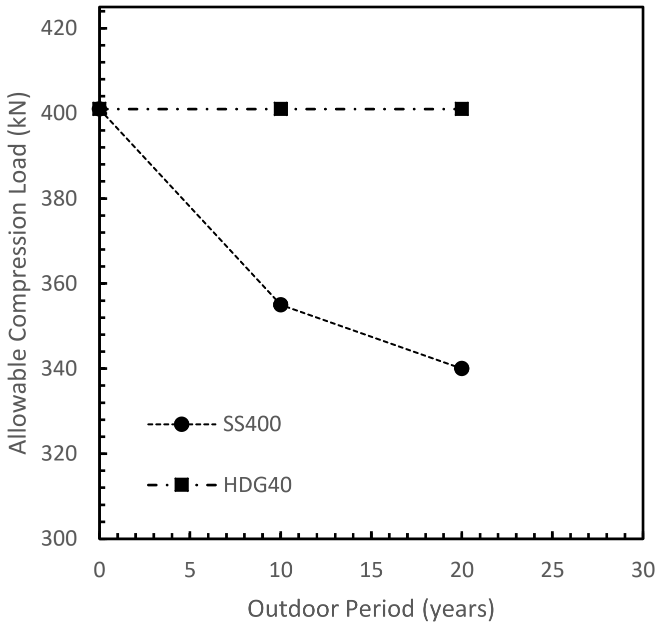

Fig. 3. Allowable compression load of SS400 and HDG steel in Songkhla.

6. Conclusion

Atmospheric corrosion cause steel to lose thickness. Saraburi, HDG Steel, shows better corrosion resistance about 40 times than SS400 Steel for the lowest corrosive environment in this study. Songkhla, HDG steel shows better corrosion resistance about 20 times for the highest corrosive environment in this study. In terms of project life cycle cost of 20 years, SS400 steel shows a cheaper cost than HDG steel. However, when it comes to the durability of design strength, HDG steel shows better in maintaining design strength throughout 20 years, while SS400 steel loses 15% from the initial design strength. Only not the cost must be concerned, but the safety of a structure should be considered as well, whether it is still capable of resisting the design load or not. This led to more considering of choosing materials for construction when atmospheric corrosion factors are considered.

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Characterization of Concrete Exposed to Marine Environment

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Abstract

Concrete can be found in various types of environments during its service life. Marine environment is one of the most aggressive and complex due to its diverse actions and variable nature. Achieving designed service life with the least embodied energy for materials production, construction and maintenance of marine structures is an important task. To meet the criteria of economy and environmental protection, concrete is made of locally available cements and aggregates. Additional benefits to reduce energy consumption but also to prevent landfills can be achieved if part of the cement is replaced with by–products of other industries. A research project entitled *"Concrete development for sustainable construction in the marine environment"* aims to develop an optimized concrete mixes for Adriatic marine environment. This paper gives the overview of activities planned to achieve that goal. The project focuses on the design of the composition of the concrete mix, striving for an optimally sustainable solution between service life, energy consumption and environmental impact.

Keywords: concrete characterization, marine environment, optimization, sustainable construction.

1. Introduction

Concrete can be found in various types of environments during its service life, and one of the most aggressive and complex is the marine environment. The mechanisms of degradation in such an environment are numerous, and the most pronounced is the corrosion of reinforcement caused by the action of chlorides. The intensity and interaction of degradation mechanisms depend on the local specifics of each region - (micro) climatic and weather conditions, chemical composition of water, presence of local pollutants from industrial plants or seaports, changes and flow rates, use of maritime structures, etc. Typical salt content in seawater is about 3.5% (salinity of the Adriatic Sea is approximately 3.8%), and the majority are NaCl and $MgSO_4$. Sea water also contains dissolved gases (O_2, CO_2, H_2S) and numerous living organisms (mollusks, shellfish). Seawater temperature varies from -2°C (freezing point) in colder regions, to 30°C in tropical areas [1]. In warmer water, degradation of concrete is the result of chemical action, i.e., changes in the composition of cement caused by chlorides and sulfates. In colder water, the chemical action is less pronounced, and the main damage is caused by temperature fluctuations between water and air, which affect the moisture content and growth of marine organisms [2]. Concrete is exposed to cycles of wetting and drying, heating, and cooling, and freezing and thawing (colder climates) during high tide and low tide. Dissolved salts penetrate deeper and deeper into the pores of the concrete during the wetting and drying cycle. Winds, storms, and earthquakes can create high power waves. Structures exposed to waves show concrete degradation caused by erosion, abrasion, and cavitation, which manifests as surface wear of the material. It is important to mention sea dust, i.e., seawater particles formed by breaking waves and carried by the wind over long distances [1]. Degradation of concrete in the marine environment is caused by physical and chemical influences. Physical ones occur due to pressure due to crystallization of salt which creates cracks and opens the way to chemical influences, i.e., water penetration and initiation of chemical reactions of dissolved substances with hydration products of cement or aggregate [2]. Table 1 lists the most common participants in chemical reactions between seawater and concrete and their consequences on the durability of concrete.

Concern for sustainability is constantly posing new challenges in the areas of resource management and thus in the cement and concrete industry. The desire to reduce energy consumption for the construction and production of construction materials imposes the need for the most rational use of raw materials. Therefore, it is necessary to encourage the use of locally available materials and reduce the share of Portland cement in concrete at the expense of replacing part of the cement with by-products of industry. The use of by-products of other industries simultaneously protects the environment because it reduces the amount of deposited material and reduces the likelihood of environmental pollution. The implementation of these activities in the construction of structures located in the marine environment is a challenge for the concrete industry. This is the theme of the project entitled *"Concrete development for sustainable construction in the marine environment"* (RBOGMO) funded by the European Regional Development Fund. Research within the project is being conducted for the Adriatic coast of the Republic of Croatia. The project aims to include various parameters that are important for sustainable construction, such as local climatic specifics, identification of locally available aggregates, cements and secondary raw materials, their characterization and optimization of concrete composition. This paper presents the planned course of activities within the said project.

Table 1. Participants in chemical reactions between seawater and concrete, and their influences [2].

Reactants - seawater	Reactants - concrete	Products	Influence
$MgSO_4$, $CaSO_4$, K_2SO_4	C_3A, CH, C-S-H	$Ca_6Al_2(SO_4)_3(OH)$ x $26H_2O$, $Mg(OH)_2$, $Al(OH)_3$, $CaSO_4$, SiO_2 x nH_2O, M-S-H	Leaching, expansion, cracking
CO_2, H_2CO_3, Na_2CO_3, K_2CO_3	CH, $Ca_6Al_2(SO_4)_3(OH)$ x $26H_2O$	$CaCO_3$	Local softening, disintegration, leaching, corrosion (carbonation)
K_2O, Na_2O	Silica or carbonate constituents of the aggregates	Na_2SiO_3, K_2SiO_3	Alkali-aggregate reaction, expansion, cracking
NaCl, $MgCl_2$	C_3A, CH, $Fe(OH)_2$	Chloraluminates, Fe_2O_3 x H_2O	Corrosion of reinforcement

2. Research methodology

The activities envisaged by the research within the project are shown in Fig. 1. In the first phase of the project, data were collected on locally available sources of mineral admixtures that remain as a by-product of other industries, and their use in concrete is justified. In addition to mineral admixtures, data were collected on the types of cement produced within the nearby region. After the analysis of available raw materials, those materials that will be used in further research on the project will be selected, for which the possibility of contributing to the improvement of concrete properties will be assessed. Detailed characterization of selected materials by standardized and advanced test methods was performed to assess their suitability for use in concrete. In addition to the characterization of the material, a literature review was conducted aimed at investigating the interdependence of properties and composition of concrete and the resistance of concrete to actions from the marine environment. To properly select the materials to start with designing the composition of concrete and optimization, additional data collection (sampling and their characterization) was carried out from real existing structures built in the marine environment. The research is focused on structures for which data on the properties and composition of concrete and applied construction technology are known. In the final phase of the project, the collected data will be implemented in a database that will also be the basis for computer-aided design of concrete compositions.

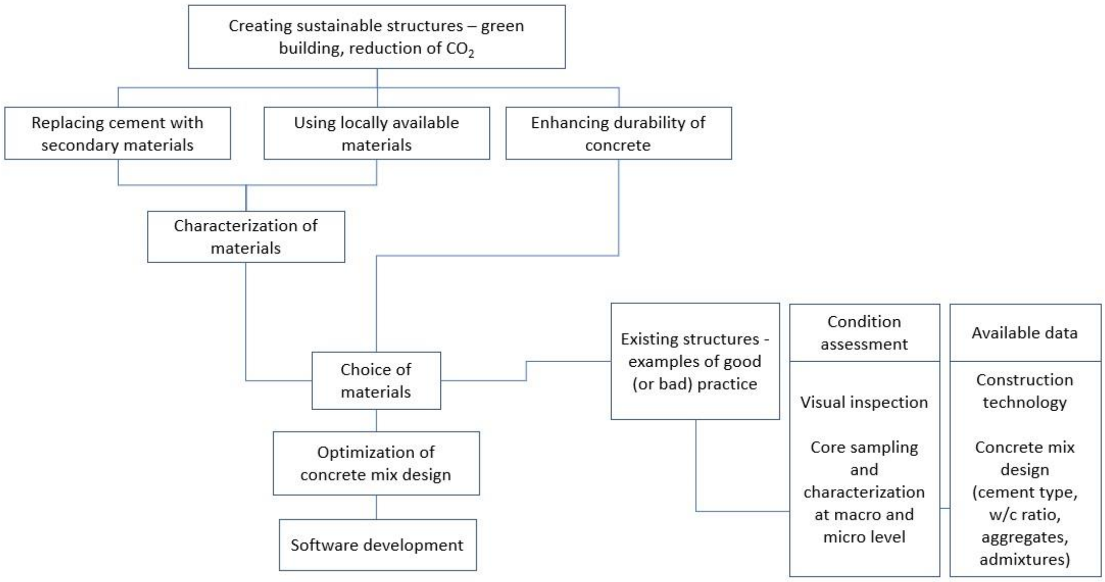

Fig. 1. Schematic representation of project activities.

2.1. Cement and mineral admixtures

There are two cement factories on the Adriatic coast that cover the needs of the local cement market, and in addition, there are two cement factories in neighbouring Bosnia and Herzegovina. All these cement factories produce Portland cements and certain types of metallurgical or pozzolanic cements. Reducing the amount of cement in concrete while achieving appropriate mechanical and durable properties can be achieved by replacing part of the cement with mineral admixtures. Significant amounts of fly ash from coal-fired thermal power plants have been found to be available from mineral supplements in the region. Flying ashes from several wood-fired thermal power plants are also available, and their use in concrete has been intensively investigated in recent times. In addition to fly ash, the possibility of using red sludge from a factory in Bosnia and Herzegovina will be analysed. In addition to these admixtures, the research will also include silica dust and metakaolin, which, although not locally available, play an important role in achieving better durability properties. Selected mineral admixtures have a justified application in concrete, especially those exposed to aggressive marine environment, as they improve its properties or give it special properties by various mechanisms of interaction between solid particles [3]. The use of selected mineral admixtures improves the workability of concrete by reducing the size and number of gaps between relatively large grains of cement, and releasing trapped water, which contributes to better fluidity [4]. Mineral admixtures reduce the permeability of concrete by improving the pore structure and increasing the pore density. This reduces the possibility of penetration of aggressive substances into concrete (especially chloride with a decrease in the diffusion coefficient) and the occurrence of alkaline-aggregate reaction. In addition, mineral admixtures contribute to increasing the compressive strength of concrete and its durability [3, 5, 6, 7, 8, 9]. The potentially negative contribution of mineral admixtures is reflected in the possibility of reducing the workability of concrete, which is often attributed to the increase in solid surface area due to the presence of fine particles that tend to adsorb water, replacement with filler containing large particles (> 45 μm) and open porosity of the particles which increases the specific surfaces [3, 4]. Also, mineral admixtures can have negative effects on concrete properties in the form of reduced early compressive strength which can lead to higher permeability and lowering the pH value of concrete in favor of corrosion, so it is necessary to pay attention to composition, selection and dosage of mineral admixtures [3, 10, 11]. In general, mineral admixtures act on the principle of pozzolanic reactivity, increasing the content of C-S-H gel that binds more cement and aggregate particles to form a cohesive structure, on the principle of filling (fillers) structures reducing permeability, and on the principle of nucleation [12].

2.2. Analysis of existing structures

The project will include tests on reinforced concrete from 5 seaports along the Adriatic coast in the territory of the Republic of Croatia (Fig. 2) to cover different microclimatic conditions (seawater composition, wind intensity and frequency, etc.). The choice of structures covered by the research is limited to those for which there is extensive data on the period, conditions and construction technology, concrete composition, control test results and data on the origin of concrete components, to establish a relationship with condition and properties.

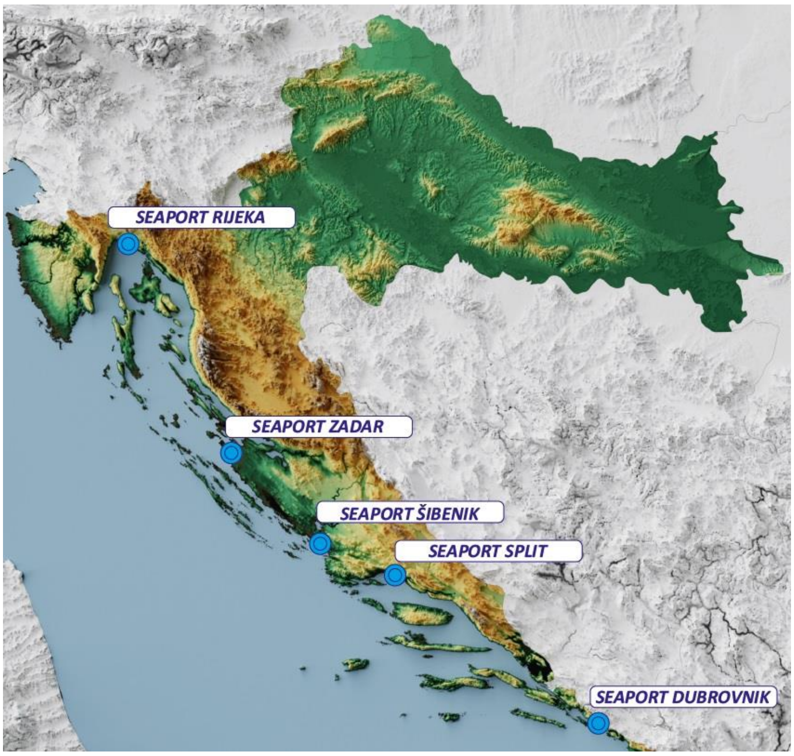

Fig. 2. Map of the Republic of Croatia showing the locations of seaports.

Pure Portland cements and Portland cements with the addition of slag or fly ash were used to produce concrete of selected structures, in quantities from minimum 340 kg (concrete element of seaport in Zadar) to maximum 430 kg (concrete element of seaport in Rijeka). Values of water-cement ratios vary from a minimum of 0.39 to a maximum of 0.45. The aggregates used are natural limestone, added in 3 different fractions: 0-4 mm (most of the total amount of aggregates), 8-16 mm, 16-32 mm. Various superplasticizers have also been added to the concrete mixes. In addition to the visual inspection and assessment of the condition of the structures, drilling of rollers was carried out for the purpose of characterizing the concrete. For each structure, three characteristic zones are analysed:

- 1st zone - part of the structure constantly immersed in sea water
- 2nd zone - part of the structure in the part of the tides
- 3rd zone - part of the structure constantly exposed to the atmosphere (air)

Characterization of concrete samples from selected structures will be conducted to gain insight into the current state. Comparison of compressive strength and measurement of chloride diffusion of concrete installed in the structure with the properties determined by control tests during construction are performed. In addition, to analyse porosity and chemical composition by depth, certain tests will be performed to determine the zone of influence of the marine environment.

a b

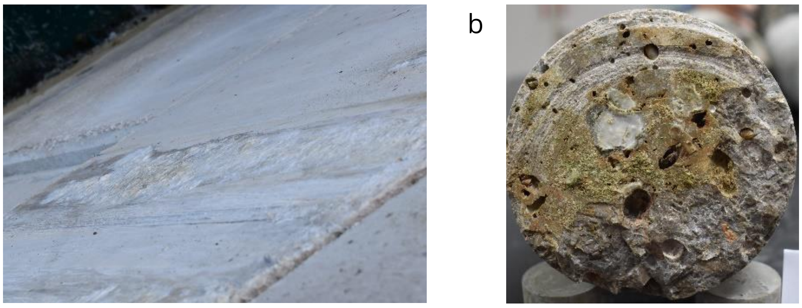

Fig. 3. (a) Degradation of concrete from analyzed marine structures caused by leaching on the surface in the splashing zone; (b) Degradation of concrete from analyzed marine structures caused by growth of shellfish in the area under the sea.

3. Optimization

The optimization process will include the preparation of test mixtures, varying the proportion of individual mineral admixtures. By optimizing the composition of concrete with selected mineral admixtures, efforts will be made to improve its durability and resistance when exposed to aggressive marine environment. During the optimization, different approaches to the design of concrete compositions will be considered, and the possibility of making self-compacting concrete will be explored as well. At the same time, a computer program for designing the composition of concrete exposed to the marine environment will be developed. A database with the properties of locally available concrete components will be integrated into the program.

4. Conclusion

The mechanisms of degradation of concrete exposed to the marine environment are numerous, and the most pronounced is certainly the corrosion of reinforcement caused by the action of chloride. To overcome this problem, efforts will be made to increase the resistance and, consequently, the durability of concrete exposed to the marine environment. Therefore, the main aim of the project entitled *"Concrete development for sustainable construction in the marine environment"* is to optimize the composition of concrete to improve its properties, and at the same time, to promote sustainable, green building. The optimization of concrete will be contributed by using locally available mineral admixtures as a replacement for part of the cement to keep its consumption as low as possible. Thus, the economic and environmental aspects gain in importance. Through the project, the aim is to develop a computer program to simplify the process of designing the composition of concrete and modelling its properties, which will ultimately make a positive contribution to optimizing the composition of concrete.

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Feasibility Study of Using the Technologies of the 4th Industrial Revolution to Manage Surface Water Collection Canals (Case Study of Tehran)

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Abstract

The advancement of technology in the field of IoT and the fourth industrial revolution, along with the development of the Internet, have provided their use to simplify and increase the accuracy of work in better operation and management in the maintenance of buried and open water canals. In this study, first, the use of this type of technology in open canals is investigated, and then suggestions for the management of buried channels are presented. Concerning buried canals, due to the environmental conditions of these types of canals, the available tools are not able to easily scan the canals, and the management of these types of canals could sometimes be tricky. In this study, for buried canals, research has been done on the construction of a mechanical device that can be used by the technologies of the fourth industrial revolution to enable the management and control of buried canals remotely. After fabricating and performing tests on the device made in the prototype and a small sample, studies showed that this device can move and scan all surfaces effortlessly inside this type of canal. This operator is able to detect anomalies and sediments accumulated in the canals in order to adopt the best way to repair and maintain the canal and prevent possible future events.

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Keywords: information and communication technologies, management and maintenance of buried canals, surface water collection canals, technologies of the fourth industrial revolution.

1. Introduction

Lack of a single system for maintenance, control, and management of surface water collection canals, as well as the cost and time of these controls with existing methods for collecting information, and also spending a lot of time and money to prepare three-dimensional construction plans in software (to control it with a modeled mode) for water projects are among the many problems that the Fourth Industrial Revolution seek to solve.

Given the possibilities that have been made available to everyone in the shadow of this industrial revolution, it can be predicted that the use of these new and facilitating technologies will have a significant impact on increasing speed and efficiency, while reducing time and cost for repares plans and creating a unified and centralized system for managing and maintaining water and sewage industry development projects. The use of new technologies and the results of past research can be a basis for creating a checklist to help make decisions about canal management.

2. Review of past research:

Reducing leakage is one of the crucial goals of water network managers in all countries. Only the amount of pipe pressure can be controlled among all the factors that affect the amount of leakage. The increasing complexity of water supply networks makes achieving the minimum standard pressure more complex, and the average overpressure at the nodes increase. There are several ways to reduce the amount of overpressure in the network, such as reducing the pumping head and creating pressure zones.[1]

With proper pressure management and considering the type of pipe used and how prone they are to accidents, coincidences can occur. Consequently, water loss and other damages can be prevented.[2]

Today, water loss in urban water networks in all parts of the world has become a serious and important issue. Water companies that are directly or indirectly involved in this problem are always looking for solutions to reduce the loss of water-valuable material. The main strategies to reduce water loss in water supply networks include four strategies: pressure management, active leakage management, improving the speed and quality of repairs, and asset management such as network reconstruction and modernization. Generally, the most efficient and least costly strategy in managing water loss in the water supply network, which leads to a reduction in actual water losses, is managing pressure or reducing excess pressure in the network, which is usually done by installing tanks or valves.[3]

Among the spectral range used in remote sensing, microwave sensors, due to their ability to pass through the cloud, are the only space-based remote sensing instruments that can provide information about snow and ice, which is an advantage that is not possible with visible and infrared telemetry. However, the complex analysis of microwave data is one of the disadvantages of this telemetry method. Properties of snow that microwaves can measure include equivalent water depth, water content, density, particle size and shape, temperature, snow (dry/wet), and ground cover.[4]

With the increasing shortage of water, some countries in the world have adopted the dynamic control method, in which the operation is based on computer and automatic control. This method enables remote control in which the flow rate and water level are continuously and automatically maintained in an optimal state. In this method, which has been used in Prunes, France, the operation of this system was declared satisfactory. [5,6]

The use of web-based information systems that facilitate spatial, spatial data, descriptive information, and intuitive data sharing through the cloud and standard web browsers, from large amounts of high-resolution remote sensing data and direct integration or indirect geographic information technology (GIS), water management topics, and open-source mathematical models and tools are fine examples of the advances that ICT's can make to the water sector.[7]

Over the past decade, dramatic advances in remote sensing (satellite) techniques have led to a complete overview of the water cycle on a global scale. Satellite Earth observation can provide direct information to Offer processes such as estimating evapotranspiration [8], precipitation [9], and snowfall/snowmelt [10,11]. Indirect methods such as linking remote sensing data to groundwater models can evaluate the infiltration and charge trend of aquifers.

Telemetric monitoring systems have long been used in the water sector to monitor the river flow, water quality remotely, and reservoir levels to help manage water resources or assist with early flood warnings [12]. However, it was only in recent years that the advent of technology in the fields of (a) electronics and microelectronics, such as advances in new sensor technologies and automated controls, (b) energy efficiency and self-regulation, for example, the use of photovoltaic (optical power) panels with electric batteries that have a limited lifespan;(C) GPRS / GSM comprehensive coverage communications technologies; (d) Computer technology with microprocessors and unlimited storage capability And (e) Costs

In terms of reducing the high costs of the above technologies, the ability has been strengthened the continuously monitor the telemetric monitoring system.[7]

Quantitative and qualitative management of urban runoff or urban flooding is complex. Regardless of the economic and social impacts, water engineers always need to know how the urban drainage system responds to different climatic conditions.[13]

In today's world, companies need virtual and physical technologies that enable businesses to collaborate and adapt quickly to businesses and their operations. Implementing industry 4.0 strategies requires much change in companies. [14].

The Internet of Things (IIOT), Big Data, and Cloud Computing are critical to making the industrial sector smarter. According to the Mackenzie Institute, by 2025, the trend of the world's industrial sectors towards smartening and connecting to the Internet and technology development (IIOT) will be accelerating. Mackenzie predicts that the potential market for IoT is $ 4,000 to $ 11,000 billion and that if Iran can capture only 1% of this market, the market will be $ 40 billion to $ 110 billion.[14]

Today, the fourth industrial revolution phenomenon has had a tremendous impact on all organizations, including the performance of universities. The issue of their evaluation among the country's universities has become critical so that quantitative and qualitative indicators are called indicators. Webometric tools have had a significant impact on evaluating the university's performance and its position in the ranking of domestic and foreign universities. It is noteworthy that increasing the number of indicators and their quality will lead to the complexity of the ranking process and spend a lot of time and money to do it. Therefore, for today's management and planning, the old management and decentralized information system methods are not responsible. [15]

The Fourth Industrial Revolution took shape at the beginning of the 21st century and is now in full swing and expansion. This revolution, unlike other industrial revolutions, has various origins. From cyberspace to nanotechnology and genetics to robotics, artificial intelligence and machine learning, mass data, hybrid biology, digital manufacturing, sensors and networks of the Fourth Industrial Revolution, And maybe a new way of thinking and acting. In this new space, technologies such as artificial intelligence, analytics, nanotechnology, and genetics announce the discovery of the fifth dimension; After length, width, height, and time, the discovery of the hidden dimensions of cellular and molecular structures through cyberspace, which as the fifth dimension goes deep into the matter, explores and recognizes molecular and atomic structures to decipher this, the way to achieve intervention at a deeper level of nature and by combining cyber-physics to bring a new way of digital production and programmed through software. [16]

The fourth industrial revolution, called Industry 4.0, is taking place, and it is characterized by production based on cyber-physical systems, heterogeneous data and knowledge integration. The primary role of cyber-physical systems is to provide the dynamic and agility requirements required for production and increase the entire industry's efficiency and effectiveness. Industry 4.0 aims to achieve the highest level of operational efficiency and productivity and a higher level of automation.[17]

Preparedness models determine whether the organization is ready to begin the process, but the maturity model clarifies what level of maturity the organization is in that process.[18,19] defined maturity as being in a perfect state. [20] defined maturity as the development of specific competence and the achievement of desired success. [21] stated that maturity can be used as an evaluation indicator and define maturity as completeness, perfection, and readiness. According to [22], the maturity model is valuable for examining processes and organizing from different perspectives. Today, maturity models have become valuable tools for evaluating organizations. Maturity models guide organizations to evaluate, evaluate, and refine themselves based on the results and follow the appropriate path to reach the desired level and the existing weaknesses, strengths, and opportunities. Identify maturity.) According to [23], the maturity model is a tool to compare the current state of the organization and the processes of the organization with the desired state. Maturity models help organizations decide when and why they should act. It also shows organizations what they need to do to reach high maturity levels.

3. How to do the job:

First, the methods which are currently used for this important thing in the world should be examined. To control and manage any structure and device, including buried and open water canals, it is necessary to have up-to-date information about what is intended to control, then evaluating data, and adopting the best strategies and methods to manage it. There are three methods that has usually been suggested for collecting information from each structure:

Table 1. methods of collecting data from each structure specially buried canals

	Methods	description	problems	result
A.	Visual inspection	an expert, personally enters the site and visits the device or the structure.	Dangers like: lack of oxygen, the presence of flammable gases, the presence of insects and vermin, and the difficulty of carrying the device inside and	lack of suitable conditions to have enough concentration to identify and fix anomalies and also unsuitable situation for human to visit
B.	Field impression	an expert or a representative of this person enters the channel and takes photos and videos from the channel	Same problems as visual inspection	unsuitable situation for human to visit
C.	Automatic system	a series of surveillance cameras are placed inside the canal to monitor the canal	can not be done due to environmental conditions, the number of required cameras, and high maintenance costs	Using other 4^{th} generation of the industrial revolutions

According to table 1, using the technologies of the fourth generation of the Industrial Revolution to create a device that can enter the canal instead of the workforce and can be controlled by an expert or automatically perform the impressions. According to the images taken by the device, the experts are able to plan the strategies to repair and maintain the canal without entering the canal and being in that difficult situation. Moreover, the experts can use the device as many times as they need and whenever they want to update the information in the fastest time, most safely and efficiently.

This research is intended to use the third method specifically for use in buried water canals so that the technologies of the fourth-generation industrial revolution can be used to maintain the canal. Therefore, the existing methods have been evaluated to determine whether these methods are now used to collect information from the channel or not, and it has been found that now only the first two methods have been used to retrieve data in all parts of the world, especially in Iran.

One of the problems of maintenance and management of water canals, especially in buried canals, is monitoring and data collection. In this research, the main intention is to use the technologies of the fourth generation of the industrial revolution in this direction so that information can be collected easier. The procedure is to integrate these technologies, then create a device that informs the operator which parts of the canal need maintenance and takes appropriate action at the proper time by taking the information inside the water canal.

According to studies conducted in open canals, it is easy to use flying robots or drones to collect information. It is necessary to equip the drone with lasers and cameras and monitor the open canal. Nevertheless, the more critical issue intended to be addressed in this study is related to buried canals. Due to the presence of flammable gases in buried canals, it is not possible to use drones inside because the drone engine produces sparks during flight. There is a possibility of an explosion in the presence of gas. Another device must be provided that while it does not produce sparks, It can travel and capture the canal path and transmit the information to the operator to help the operator take appropriate action according to the conditions.

Since the cost of making this device in actual size is high and therefore not possible to test this device in real-sized canals, it has been decided to make a small sample of this device and to perform the test. This test includes the sample device in a canal with a small simulated scale to ensure that the device does not explode in the presence of gas and that the operator can detect after harvest which parts are defective and need to be maintained.

The following are some of the points that are among the requirements of the system in this research:

- Non-explosive in the presence of flammable gases
- Impermeability in the presence of moisture and water
- Ability to move on obstacles and sediments
- Ability to record videos from inside the channel
- Remote control capability
- Ability to rotate in the bendings inside the channel
- Ability to move with standard slopes in the channels, a maximum of 20 degrees.
- Ability to measure the pressure inside the channel
- Ability to measure the height inside the channel
- Ability to measure the temperature inside the device and the duct

4. Findings and discussion:

After conducting research and research background, it can be concluded that a canal harvesting device is required in buried canals.

In the first stage, informations was collected on two issues: the methods used to perform such management, and the researcher's demands on the device, such as what is expected of the device at best. Moreover, the minimum requirements that the device must provide.

The first requirement of the device has been assumed to move in the presence of flammable gases without generating sparks inside the duct and not to explode.

With further investigation of water canals, The most obvious point has been found out as the presence of moisture and water in the canals. Another problem that current devices have is that they are not waterproof, and when they encounter moisture, they malfunction and therefore a device that is waterproof and safe in the presence of flammable gases has not been found so far. The second requirement of this device has been found to be waterproof in the presence of moisture and to be able to move in the water at least to a certain height without disturbing the device's performance.

While the device has been manufactured, moving over obstacles has been considered as the third requirement. after a while, settling sediment particles eventually caused reducing the volume of the water canal and the creation of roughness and anomalies in the canal floor. This device should be constructed in such a way that it can cross these roughnesses. The easier the device crosses the obstacles and sediments, the easier monitoring the channel and meeting the intended remote channel monitoring goals.

The ability to record video has been assumed as the fourth requirement of our device. The device should be able to record video from inside the canal so that the canal's abnormalities can be more easily detected, the best program can be picked to correct the anomalies, and the best plan can be conducted for channel maintenance.

The fifth thing that has been considered at this stage, and the most crucial one, is the remote control. The device should easily be controlled to view the channel from any angle and point.

One of the things that should be considered for the preparation of the device is the ability to rotate smoothly on the bendings. So turning at the bendings is the sixth thing that should be considered in the design.

According to studies, the maximum slope of buried water canals is 20 degrees, so this device should be designed to move on a slope of 20 degrees, either upside or downhill. So the ability to move on a slope of 20 degrees up and down is the seventh thing that should be considered in designing the device.

During the research on system requirements, how to find anomalies within the canal has been addressed. With the surveys done during the filming, sometimes places may be left out of the viewer's view. The pressure has been realized as one of the available methods to detect anomalies in the channel. The device should be able to check the pressure at any point because if there is a fracture in the canal's structure, at that point, the pressure change will occur, and it can be easily found. Therefore, the ability to detect pressure in the channel's body has been found as the eighth requirement for operating the system.

The ninth requirement of the system is measuring altitude at any moment of the device's movement. Due to the presence of sediments in the bottom of the canal, the height of the canal is different from the first day of canal construction, so this height decreases over time, reducing the diameter of the canal and sometimes blocking the canal, and this may not be detectable with the camera. The simplest solution that has been reached in research is to measure the height of the canal at any time because the person who is controlling and managing the canal is aware of the height of the canal according to the maps, therefore, the height of sediments can easily be recogonised and planed to remove them.

The temperature inside and outside the device is essential. Therefore, two sensors inside and outside the device had to be considered to control the temperature. Therefore, controlling the temperature of the device and the canal is the tenth of the device's requirements.

At first, has been intended to send the device into the tunnel and move it on its own, identify all the anomalies, compare it with the modeled model of the canal, and at the same time inform the operator and at the end of the mission, alarm the operator to catch the device at the end of the tunnel. To do this, the point was to use point cloud scanners to measure the entire tunnel in terms of length, height, and width at any given moment and compare it with its 3D model. Furthermore, inform the operator of the inconsistent points. However, studies have shown that finding this type of laser in Iran is not easily possible due to military applications, and secondly, the cost of this laser is very high, so has been decided to find other solutions to achieve the demands mentioned above.

After the investigations and using the tools available in the country according to the sanctions, the equipment needed to build this robot has been prepared and completed. After performing various tests, the robot control programming has been done by Python software and can be controlled and monitored by a mobile phone on the web browser.

After identifying the internal components of the robot and connecting them, the original shape of the device has been designed using Solid software, and then it has been printed by 3D printers, and electronic components and sensors have been carefully placed on the device. In Figure 1, the modeled example can be seen in Solid software and also in figure 2, the final view of the robot can be seen.

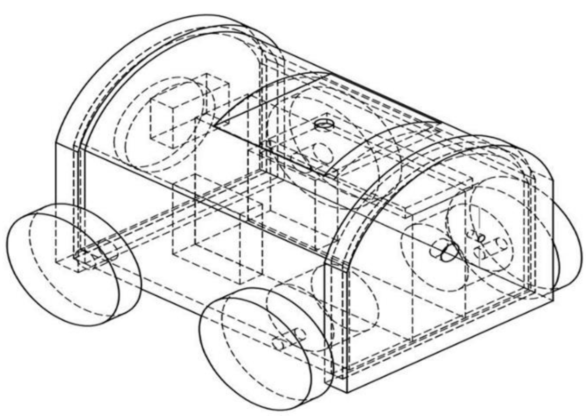

Fig. 1. Perspective view of the device

Fig. 2. View of the real device

A canal should be made in small dimensions to check all the robot's movements in the presence of water and gas. First, a prototype canal has been modeled in Sketch-Up software, See Figure 2. Then a prototype canal has been made by using five 20 cm diameter pulica tubes and four 45-degree and 90-degree elbows. Moreover, by using sand, stone, and wood, some anomalies have been created in the floor and ceiling of the canal to test the performance of the device, in addition to its movement on obstacles, in the diagnosis of anomalies, which acceptable results have been achieved after these tests.

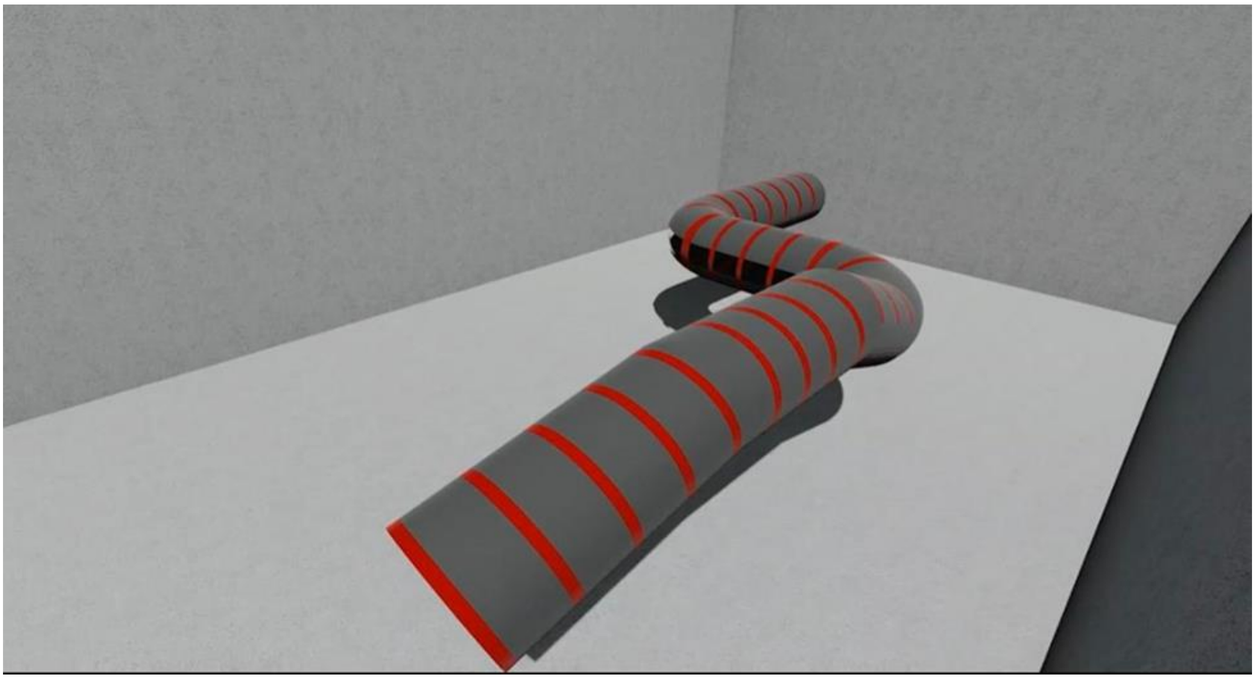

Fig.1. Sample designed channel in sketch up software

5. Conclusion

In this research, technologies of the fourth generation of the Industrial Revolution have been used in the field of continuous canal monitoring and control, which introduces the use of these technologies more comprehensively in the field of repair and maintenance. All conducted tests showed that, the robot has been able to easily cross the obstacles in the presence of gas and moisture. With the help of sensors and cameras used to detect anomalies in the roof and the floor of the canal without occurrence of any disturbances or explosions. According to the results, it can be said that the effects of the fourth-generation technologies of the Industrial Revolution on the maintenance of water canals include continuous canal control to prevent the accumulation of sediments and failures in the canal, which in many cases before the occurrence of canal failure and clogging. It is understood by the person monitoring the canal by a large amount of sediment and other possible obstacles that cause severe damage. By understanding these minor problems in the canal, which sometimes cause floods and create danger in the long run, it is possible to prevent many severe damages before imposing high costs on repairing those parts to the relevant department.

In addition to utilization in existing canals, these robots can also be used to complete as-built maps of canals under construction and easily give the final map of these canals with maximum time savings and earn the cost. According to the results of experiments, it can be said that with the technologies of the fourth industrial revolution, the speed of information retrieval can be increased compared to the traditional method. The fourth generation of the Industrial Revolution technologies allowed us to significantly reduce maintenance costs because it is possible to repair them before more extensive failures occur.

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Implications of Digitization on a Construction Organization: A Case Study

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Abstract

As the construction industry transitions to a post-pandemic world, the use of technology brought forward by Construction 4.0 has accelerated. This increase in technological advancements has placed greater emphasis on the need for digitization and is consequently driving construction organizations to change. Thus, it becomes crucial to understand how digitization is affecting the organizational aspects of construction companies including strategy, structure, people and culture, and processes and technology. This study addresses the gap and presents a case study on a large EPC company (Company X) that has been going through a digitization organizational change of both engineering and construction services since 2017. The company is a legacy company that has been operating for over 100 years and is placed in the Top 400 Contractors List published by the Engineering News Record (ENR). Network analysis was performed on transcriptions from four semi-structured interviews conducted with company representatives to understand: (1) the drivers of digitization (weight of the past, push of the present, and pull of the future); (2) the response of Company X to successfully implement this organizational change (implications on strategy, structure, people and culture, and processes and technology); and (3) the challenges that digitization imposed on the organization. Findings of this paper offer a preview of the dynamics of the digitization organizational change and enable informed diagolgue around the drivers of, response to, and challenges of digitization in the construction industry. Organizations undergoing or planning a digitization information can reflect on the practices identified through this research to succesfully navigate through this organizational change.

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Keywords: Construction 4.0, digitization, network analysis, organizational change, organizational studies.

1. Introduction

The construction industry stands at a crossroads as it transitions to a post-pandemic world. On one hand, there is a serious need to increase productivity, improve project performance, address the labour shortage, reduce fragmentation, address resistance to change, and increase collaboration. On the other hand, the fourth industrial revolution or Industry 4.0, which is mapped as Construction 4.0 in the construction industry, has been slowly altering the industry by introducing a wave of technological advancement that is altering the way projects are designed, planned, constructed, delivered, and operated [2].

One of the main transformations offered by Construction 4.0 is to exploit the potential of digitization in the construction industry [3]. The industry is no stranger to digitization, starting in the 1970s with structural analysis programs, the 1980s with computer graphics, and the 2000s with the rise of BIM [3,4]. Under the umbrella of Construction 4.0, digitization can be achieved through four main key aspects: (1) digital data through collecting and analysing digital data; (2) connectivity through connecting and synchronizing processes, (3) automation through creating autonomous and self-organizing systems; and (4) digital access [5].

As digitization causes disruption to the way organizations work and conduct their business, the traditional organizational structures and culture would need to change [6]. Key enablers for successful digitization efforts include forming holacracy structures, altering decision-making practices, adopting digital skills and tools, leveraging information communication technology specialists, and ensuring proper investments [5–7]. Colloquially, democratization of data to spawn a renaissance of information within the construction industry through the understanding of *people and culture*, *processes and technologies*, and *data.*

To understand the implications of digitization as an organizational change, this study aims to investigate the drivers, response, and challenges of a large Engineering, Procurement, and Construction (EPC) company that is going through a digitization change effort. Drivers of digitization were investigated using the elements of the "Futures Triangle", an approach developed by Inayatullah [8] which maps the digitization change onto three dimensional contexts: the *weight of the past* which represents the barriers that inhibit the change; the *push of the present* which are the drivers and trends that are currently pushing the organization to change and achieve the future image; and the *pull of the future* which represents the image of the digitization vision that is pulling the organization towards the new stasis [1]. The response and challenges collected were investigated across four organizational aspects: *strategy* which determines the long-term path which organizations will follow and dictates which activities are necessary for the organization; *structure* which determines the placement of power and authority in the organization; *people and culture* which relate to human resource policies and include recruiting, selection, rotation, training, and development*; and processes and technology* which are related to the flow of information across the structure of the organization [9,10].

2. Research Method

The research method employed to address the research objective encompasses three phases as described below.

2.1. Research Setting

The setting for this research was a large EPC company (Company X) that is in the Top 400 Contractors List published by the Engineering News Record (ENR). Company X was going through a digitization organizational change of both engineering and construction services since 2017. The company is a legacy organization that has been operating for over 100 years.

2.2. Data Collection

A qualitative approach was first used to tackle the research objective. Among the different data collection methods employed in qualitative research, semi-structured interviews were selected to gather data on the response to and implications of digitization on Company X. Semi-structured interviews create a balance between structured questions and unstructured dialogue and allow researchers to develop rapport with interviewees and learn about critical aspects that are not readily assessed through a standardized questionnaire [11]. This data collection technique provides flexibility to the researcher especially when similar work has not been done previously [12]. A semi-structured interview protocol was designed to collect data on: (1) the drivers of digitization (weight of the past, push of the present, and pull of the future); (2) the response of Company X to successfully implement this organizational change (implications on strategy, structure, people and culture, and processes and technology); and (3) the challenges that digitization imposed on the organizations (discussion of strategy-, structure-, people and culture-, and processes and technology-related issues). Fig. 1 outlines the framework of the interview protocol. Four one-hour interviews were conducted with four individuals within Company X who have great visibility into the digitization organizational change. All interviews were conducted virtually by the first author and were recorded to facilitate documentation.

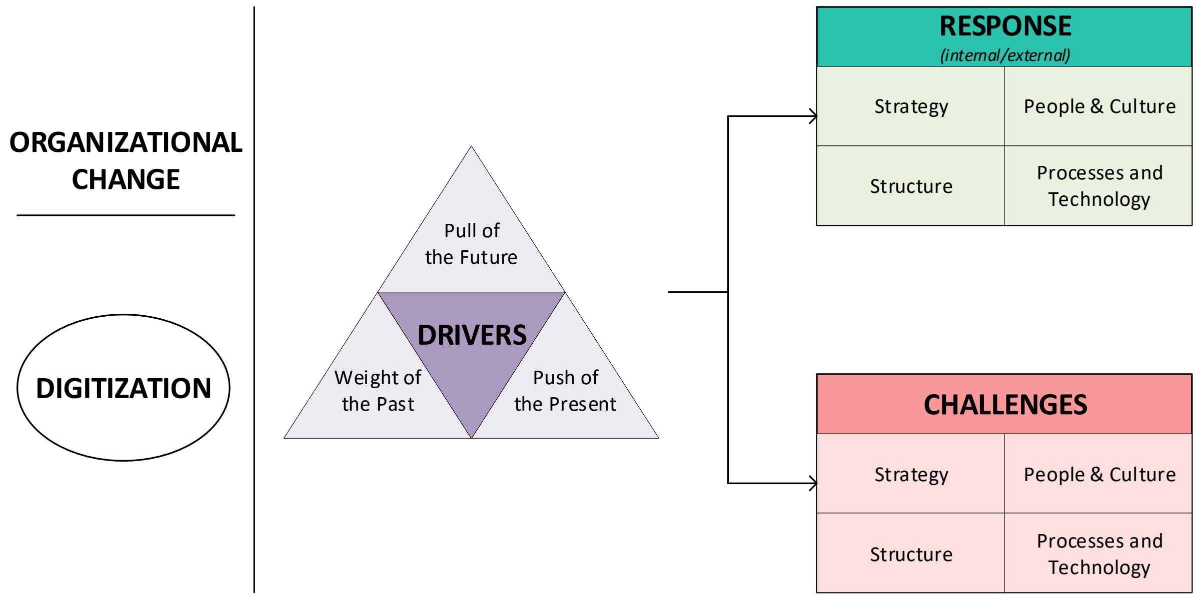

Fig. 1. Framework of the semi-structured interviews.

2.3. Data Analysis

Notes from the semi-structured interviews were transcribed verbatim from the recordings. Next, the content analysis of the interview data proceeded in three phases: initial reading, coding, and creation of themes [13]. The open coding procedure discussed by Strauss and Corbin [14] was followed to inductively identify themes in the data. The coding and generation of themes were carried out using the NVivo software. Once the themes were developed and mapped onto 16 change categories (i.e., drivers, response, and challenges), concept mapping was used to analyze the themes generated from the interview data and draw insights into the dynamics of digitization and understand its drivers, response, and challenges. Concept mapping is a method to graphically represent relationships between concepts, i.e., semantic networks [15]. In this study, concept mapping was applied to identify and visualize the semantic network with the associated implications of digitization on Company X. The semantic network consists of three elements: (1) change nodes which represent the three interview questions, i.e., the categories of analysis; (2) theme(s) nodes which represent the themes identified from the interview data; and (3) edges or ties which represent the relationship between the categories and themes. The semantic network was then quantitatively analyzed using network analysis [16]. Two measures were used to analyze the network: (1) weighted degree centrality (WDC) which identify the nodes (i.e., categories and themes) that are highly impacting the network and (2) closeness centrality (CC) which identifies how close the nodes are to one another [17,18]. The analysis was performed using UCINET 6.0.

3. Case Study Analysis

A total of 33 themes were identified from the four interviews and mapped onto the 16 change categories, namely: *weight of the past*, *push of the present*, *pull of the future* (3 categories representing the drivers of digitization), internal strategy, external strategy, internal structure, external structure, internal people, external people, culture, internal processes and technology, external processes and technology (9 categories representing the organizational response to digitization), strategy, structure, people and culture, and process and technology (4 categories representing the challenges associated with the implications of digitization on the organization).

3.1. High-Level Analysis

Before interrogating the specific themes, Fig. 2. represents a high-level aggregation of the content analysis. When considering the drivers of change, the interviews conducted with Company X show that the organization was mainly driven by the *push of the present* (with 55% of the discussion on the drivers focused on this category) and the *weight of the past* (with 40% of the discussion on the drivers focused on this category). According to the interviewers, the implementation of digitization was not driven by the *pull of the future* as only 15% of the discussion on the drivers focused on this category. However, the disparity of the respondents' macro-observations on digital transformations transpiring universally throughout all organizations and internal awareness may be a direct indication of the ancillary factors associated with competitors/suppliers being driven by the pull of future vs. Company X internal drivers focused on risk obversion (i.e., 'why fix what isn't broken').

Further, when investigating the response of Company X to digitization, the discussion provided by all interviewees was mostly dominated by the focus on the *internal* response rather than external. Particularly, more focus was placed on *strategy* (26%), *people* (23%), and *processes and technology* (21%). Moreover, interviews indicated that most of the challenges associated with the implementation of digitization were faced at the strategy and people and culture aspects of the organization (50% and 39%, respectively). This is an expected resultant when considering the interviewers' response (~85%) predominantly focused on the factors associated with the *Weight of the Past* and *Push of the Present*. Additionally, a majority (79%) of the Response category focused on Strategy, People, Process and Culture. Thus, from the data, one could infer that Company X focused the entirety of the organizations energy on the activity of implementing the organizational change versus the appropriateness of the change.

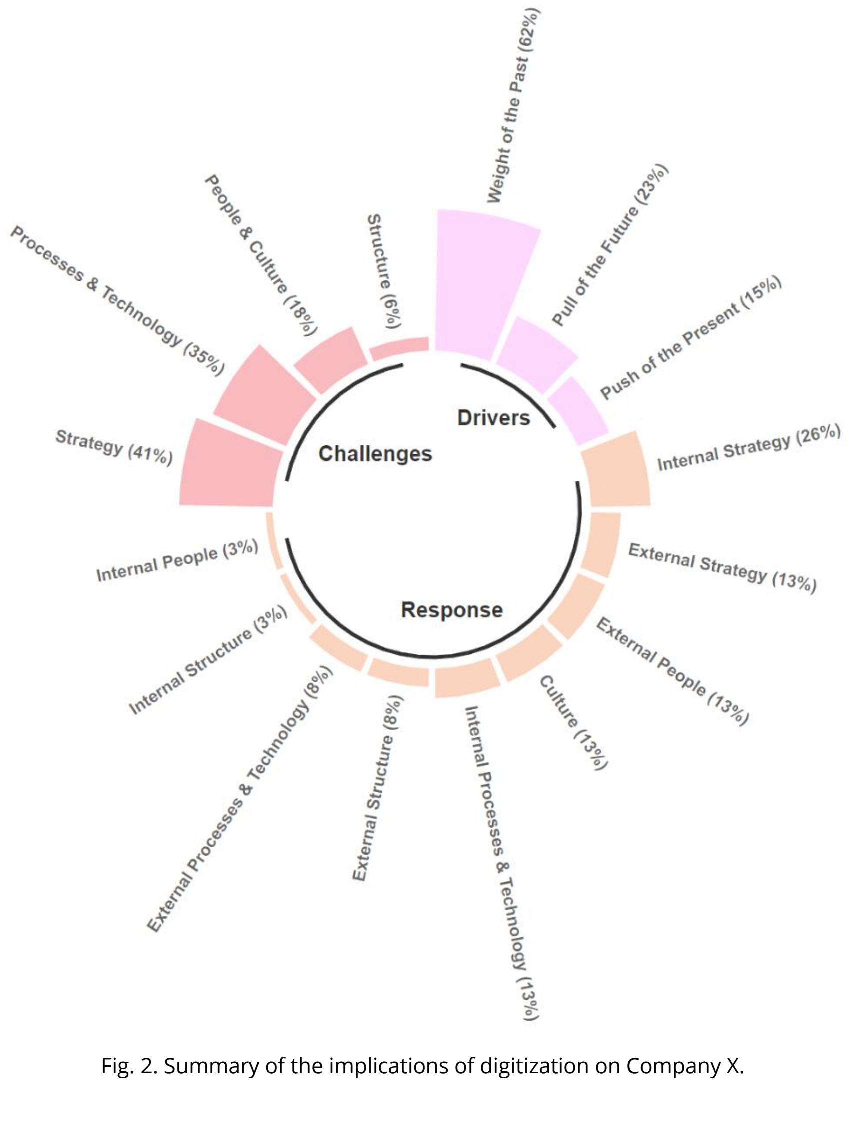

Fig. 2. Summary of the implications of digitization on Company X.

3.2. Network Analysis

The concept map (i.e., semantic network) of digitization as discussed by the interviewees from Company X is illustrated in Fig. 3. Network analysis was then employed to provide a qualitative assessment of the implications of digitization on the organization.

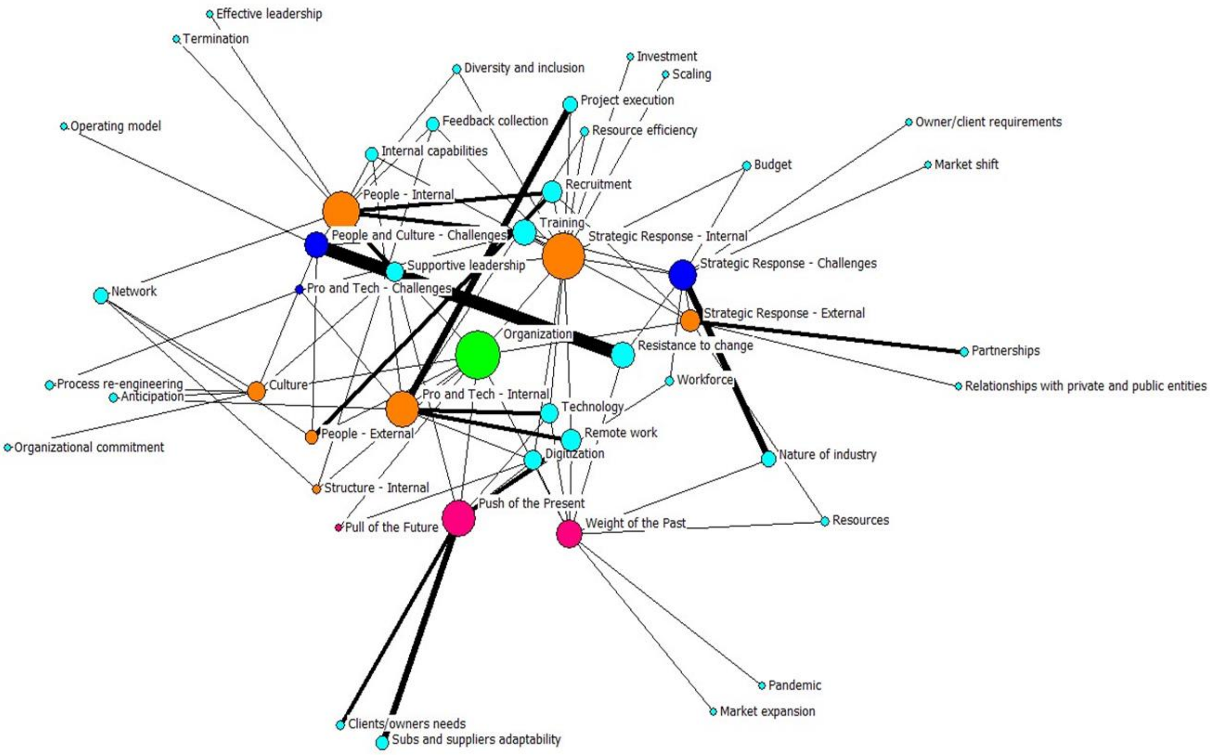

Fig. 3. Digitization Concept Map. The *pink* nodes represent the three categories of *drivers*; the *orange* nodes represent the nine categories of *response*; the *navy-blue* nodes present the *challenges*; and the *cyan* nodes represent the 33 *themes*. *The thicker the edges, the stronger the connection is between the nodes.*

3.2.1. Weighted Degree Centrality

The analysis of the weighted degree centrality (WDC) measure shows that *Internal strategy* (with WDC equals to 0.35), *internal people* (with WDC equals to 0.30), and *internal processes and technology* (with WDC equals to 0.28) are the nodes that dominate the network, meaning that the interviewer of company X were mostly focused on these three internal aspects of the organization while discussing the response of their company to digitization, reflecting how Company X planned this organizational change. The themes outlined in Table 1 were found to be influential and critical for the successful response of Company X to digitization.

Table 1. List of important themes

Theme	Response Catgeory
Training	Internal Strategy
	Internal People
Remote work	Internal Processes and technology
Recruitment	Internal People
Supportive leadership	Internal People
	Internal Strategy
Digitization	Internal Processes and technology
Technology	Internal Processes and technology

To support the implementation of digitization, Company X provided internal training (virtual and physical) on tools and new processes, introduced digital environment to union by providing training to unionized workforce. The company also leveraged remote work to facilitate digitization where virtual machines to access the design tools located in one of the international offices were used to ensure project operations were not interrupted. The company also leveraged the use of remote work tools that are easy to use and allows better integration with different corporate software. To build internal capacity, Company x hired specialized employees with expertise in robotics, data science, advanced materials, and recruited younger project professionals that have a higher propensity towards digital capacity as a digital native. The organization leadership was also supportive of the change initiative and had the mentality of "growing motivational field leaders rather than hunters and gatherers". Further, Company X focused on intentionally making a gradual shift to "working within data" versus "working on paper" with a focus on testing physical innovations such as; robotic welding machines, benchmarking Key Performance Indicators (KPIs) for offsite and onsite work, using mobile apps connected to work packaging management system to facilitate two-way data transfer for construction crews, and enhance decision making data transfer for construction crews. As noted by the interviewers, these practices were instrumental for the success of the organizational change.

Following the focus on the above three aspects, the *push of the present* (with WDC equals to 0.26) is the next dominant node. Particularly, and as shown in the concept map, Company X began its implementation of digitization as a response to the following main trends (having bigger nodes and thicker edges with the push of the present): the shift in customer demand towards digitization where established owners have started developing their digital landscape and are pushing the need to consistently produce and use data (*clients/owners' needs* node), the need for remote work to collaborate across the organization locally and internationally while keeping operations going during the COVID-19 pandemic (*remote work* node), the need to keep up with subcontractors and suppliers that have already embraced the digital environment (*subs/suppliers' adaptability* node).

The main challenges faced by Company X, while implementing digitization, were *strategy*- and *people and culture*-related (with WDC equals to 0.24 and 0.22, respectively). The strategy-related challenges are mainly attributed to the *nature of the industry* where construction is fragmented, more heavily reliant on skilled labour, and fast paced delivery which poses various challenges in the face of new technologies being implemented or embracing dynamic change initiatives, whereas engineering and procurement are faster to embrace the digital transformation than construction. The people-related challenges mostly stemmed from the *resistance to change* where digitization was internally resisted by senior project managers, unionized leadership, and middle management. These challenges created another concern for Company X on whether the money is best spent to further socialize the change and obtain buy-in or to move past them. It should also be noted that *resistance to change* was the most discussed theme throughout the case study and in-line with expectations for a more traditional organizational change implementation.

Following the *push of the present*, the discussion with the interviews indicated that the organization was driven by the *weight of the past* (with WDC equals to 0.20). This category adequately represents the legacy system and practices that has been anchoring Company X and challenging its shift towards the future. Additionally, weight of the past drivers discussed by the interviewees include internal resistance to change, the fragmented and competitive nature of the construction industry, the limited availability of resources and skilled workforce, cyberthreats and security concerns, budget pressure caused by the pandemic, and software packages available in the market do not always fulfil the organization's specific requirements. All of which could be significant barriers to the implementation of digitization.

Further, the focus on internal *strategy*, *people and culture*, *processes and technology*, and *external strategic response* was a focus for Company X while going through digitization (with WDC equals to 0.17). Particularly, the organization was strategic about its *partnerships* with its network; working closely with subcontractors and suppliers to adopt digital workflows.

3.2.2. Closeness Centrality

The analysis of the closeness centrality (CC) measure showed that *training* had a higher score of closeness (with CC equal to 0.46) compared to other themes. This higher score was obtained because *training* was mentioned under different categories (internal strategy, external strategy, internal people, strategy challenges, people and culture challenges, and processes and technology challenges). This finding indicates that *training* was an important action that the organization focused on while going through its digitization change effort, which could be justified by the fact digitization requires a lot of training to be achieved successfully.

Moreover, the concept map shows that *remote work*, *digitization*, and *technology* are plotted next to each other showcasing how these themes are related to each other: digitization requires technology, and remote work supports digitization. Moreover, *recruitment* and *training* are located next to each other, which indicates how these two actions are related to one another and were implemented simultaneously by the organization during the change initiative.

4. Reflection/Discussion

The Futures Triangle combined with the four organizational aspects allows for an in-depth understanding of how the journey for Company X digitization organizational change management implementation occurred. This transformative change highlights many of the anticipated hurdles that an organization may encounter (Fig. 4). However, the key difference between a typical organizational change implementation and the digitization is the significance and breadth of impact the digitization change is having on the construction industry.

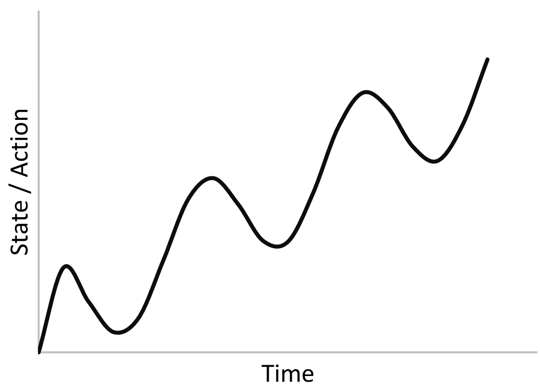

Fig. 4. Representation of the Digitization Organizational Change Management Journey

One key outcome that this case study has shown is the propensity for the weight of the past to heavily influence how quickly an organization within the construction industry is able to progress towards Construction 4.0. Specifically, the need for an increased focus on *strategy*, *people and culture*, and *processes and technology*, see Fig. 2. Further, the gap is not just limited to whether the individuals being impacted are digital natives.

The resultants highlight that a concerted effort must be made to focus on socializing 'why' the change is needed, the benefits of the change, and training to support the transition. Moreover, even with these actions, the organization will still follow the Digitization Journey as represented in Fig 4 to truly accomplish Construction 4.0. Without intentional care and nurturing of the change with a clear vision the organization will never experience the series of successes, followed by learnings will occur along the way.

Further, the uniqueness of this specific case study is one can easily compare previous studies [19] to the impact and speed at which the industry has had to change due to the COVID-19 pandemic and has acted as a catalyst to force the need and conversation on how to make Construction 4.0 a reality.

Digital Natives and Non-Digital Natives are struggling, and will continue to struggle, with the implementation of Construction 4.0 until all of the major EPC contractors and Owners define a clear roadmap/standard in a similar manner to the Internet Service Provider (ISP)/global phone number network.

5. Conclusions

This study presented a case study on a large EPC company (Company X) that has been going through a digitization organizational change of both engineering and construction services since 2017. The company is a legacy company that has been operating for over 100 years and is placed in the Top 400 Contractors List published by the Engineering News Record (ENR). Four semi-structured interviews were conducted with company representatives to understand the drivers of digitalization, the response of the company to successfully implement this organizational change, and the challenges that digitization imposed on the organization. Network analysis was employed to analyze the interview data. Results of the analysis showed that drivers of the push of the present, i.e, current trends, are the major drivers in Company X's decision to undergo the digitization organization change including, the shift in customer demand towards digitization and developing a data-driven digital landscape, the need for uninterrupted remote work to collaborate across the organization locally and internationally, and the need to keep up with subcontractors and suppliers that have already embraced the digital environment.The analysis also showed that while Compnay X was undergoing this organizational change, most of its focus was on the internal strategy, people, and processes and technology. Additionally, the major challenges faced by Company X are mainly attributed to the complex and fragmented nature of the industry from a strategy perpective, and resistance to change from a people perspective. Moreover, findings of the case study show that in the case of digitization, collocation is not required for successful delivery of a construction project, while the strategic training and over communication to socialize the intended outcome is paramount to have any hope of success for Construction 4.0. Furthermore, concerted effort must be made in developing the framework for all organizations to work from in the Construction 4.0 paradigm instead of smaller microcosm of success after significant investments. The results outline in this paper are based on the analysis of one EPC company and will be expanded on in a survey to the broader construction industry to investigate how different companies are responding to digitization and provide guidance to help construction organizations effectively plan this type of organizational change.

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Cold Storage Frost Heave Prevention

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Abstract

Selecting a frost heave prevention method for cold storage facilities focuses on the issue of frost heave, the prevention methods available, and the builders' preferences when it comes to applying those methods, dependent on the region and size of the freezer. To achieve these objectives, qualitative data was collected through literature review and individual telephone interviews. Builders from across the continental United States were selected, vetted, and interviewed. The structured interviews were conducted to secure professional opinions on which frost heave prevention method would be best utilized within a given square foot size range. The interview responses were analyzed, along with region data on average winter temperatures and frost depth, to discern the best prevention option. The data analysis revealed a conceptual decision matrix for selecting the industry preferred prevention method within a given set of variables. Recommendations were provided based on additional thematic data points for further research to support or augment the decision matrix created in this research study.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2022.

Keywords: cold storage, frost, heave, ice, temperature

1. Introduction

Cold Storage facilities face a range of conditions that can affect their optimal performance. There are many factors to consider when building a cold storage facility, but possibly none more critical than frost heave prevention. In its basic definition, frost heave is the upwards swelling of the soil as the cold storage facility temperature causes the moisture in subsurface soil to freeze. Determining the level of frost heave susceptibility is a vital step when designing a facility. Failure to protect a facility from frost heave can have devastating effects on the concrete slab and other building structural elements. As the ice buildup applies pressure from underneath, the slab can crack, and other structural members may shift, causing significant damage to the overall building. The primary method of preventing frost heave is to add heat below the slab to keep the moisture in the soil below from freezing. There are several methods of applying heat to the slab substrate, and a properly designed system can ensure the structural stability of the slab for the life of the facility.

Cold storage facilities consistently operating below 0 degrees Celsius (32°F) can freeze the moisture in the soil below the slab unless a prevention method is applied. According to the International Association for the Properties of Water and Steam, when liquid water is cooled, it contracts like one would expect until a temperature of approximately 4 degrees Celsius (39°F) is reached. After that, it expands slightly until it reaches the freezing point, 0 degrees Celsius (32F), and when it freezes, it expands approximately 9% [1]. A 9% expansion alone is not enough to cause substantial soil heave, but with specific soil characteristics, additional moisture can be drawn to the freeze causing more and more expansion. The expansion will cause the soil beneath the structural slab to heave, thus applying increasing pressure and eventually cracking and failure.

In the case of cold storage facilities, where the temperature is maintained below freezing, without a source of under slab heating, the cold will penetrate downward through the substrate, freeze available moisture, and continue to draw surrounding moisture, thus growing the ice lens, and subsequently heaving the frozen substrate upward, damaging the slab and building structure. The drawing of moisture to the freeze zone creates ice lenses, which is the accumulation of ice along the freezing plane. The ice lens will continue to grow, causing soil displacement known as frost heave. Frost heave is a common condition where either natural or artificial conditions freeze the soil.

To prevent the freezing of the building substrate, prevention methods have been developed. Currently, there are four prevention methods used by builders; natural ventilation, forced ventilation, electric heat systems, and forced glycol heat systems. These prevention methods vary in the ability to prevent the formation of ice based on soil conditions and the amount of moisture present in the soil. Additionally, they differ in installation and operating cost, creating a decision point for builders as it pertains to available funds for installation and year-over-year operating expenses, all valued against the expected life of the facility.

2. Literature Review

Frost heaving is an interaction between soil and an architectural structure in which the freezing process results in internal expansion of the soil. Frost heaving-induced pressure (FHIP) is generated by structures resisting soil expansion. Freezing of moist soil is essentially a process of coupling heat and mass transfer. When saturated fine-grained soil is subjected to a subfreezing temperature, part of the water in the soil pores can solidify into ice, i.e., pore ice particles, close to soil particles and more tightly bound to them, a film of unfrozen water remains. According to thermodynamics, this adsorbed water film has lower free energy at a lower negative temperature. Therefore, a potential gradient can develop along the temperature gradient. Water can be sucked from the warm portion to replace the amount of water lost due to freezing and to feed the accumulation of pore ice. As the pore ice particles grow, they can finally contact each other and form an ice lens, Figure 1, oriented perpendicular to the direction of heat and water flow. In fact, significant frost heave observed in the field or laboratory is attributed to ice segregation and ice lens formation associated with water migration [2].

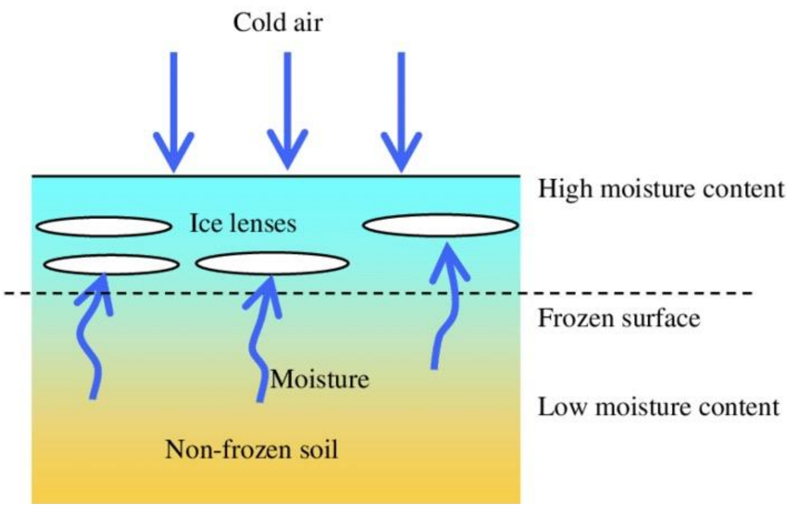

Figure 2: Ice Lens [3]

It is observed that there exists a frozen zone between the growing ice lens and the frost front where the warmest pore ice exists. Within this frozen fringe, the temperature drops from the freezing point at the frost front to the segregational temperature at the warm side of the ice lens. In response to this temperature drop, the pore water pressure, unfrozen water content, and permeability decrease through the fringe. The water pressure at the warm side of the lens, which appears in suction, is affected by the segregational temperature and the overburden pressure. Unfrozen water content and the permeability decay more or less exponentially with decreasing temperature, Anderson et al. (1973); Burt and Williams (1976) [4].

2.1 *Cold Storage Facilities Create Frost Heave Conditions*

One of the most critical design considerations for a facility is the relationship between vapor pressure and temperature and their effects on cold storage facilities. Cold air has a lower vapor pressure than warm air. Warm air, therefore, moves toward cooler air. The ground/subsoil must be warmed above the freezing point to keep the vapor from freezing beneath the slab. Warm air will force its way through the subgrade until the vapor balances or adheres to the underside of an insulating layer. The freezer slab must also be insulated to help maintain the freezer temperature, slow temperature loss, and stabilize the pressure with the ground below the freezer floor. Cold storage Facilities create unintentional permafrost when the ground beneath the facility drops below freezing and the moisture in the subgrade forms ice. As the ice expands, it pushes up on the foundation, causing the floor to heave, illustrated in Figure 2. Floor heave can cause significant damage to the building and disrupt operations [5].

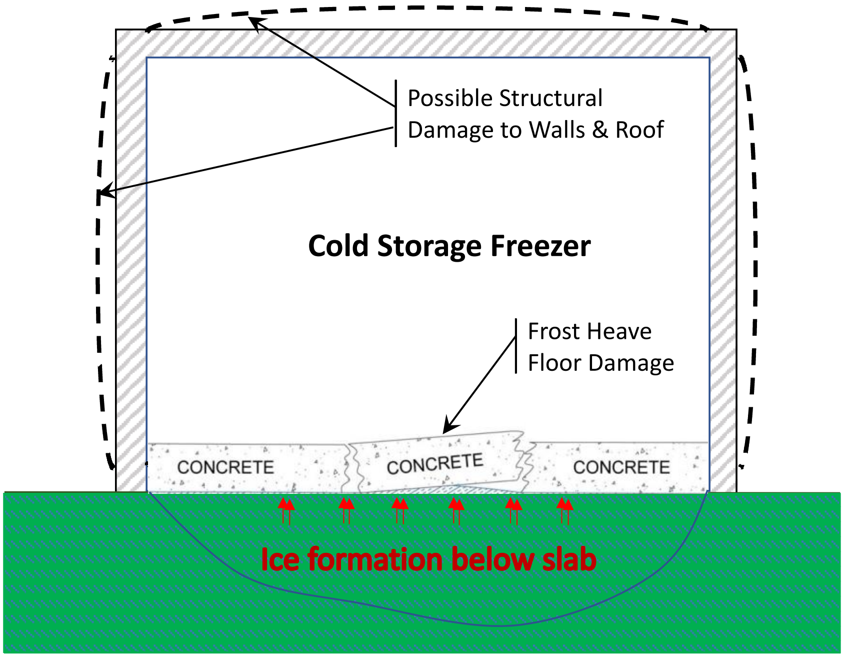

Figure 3. Cold Storage Frost Heave Illustration [5]

As the ice expands, the freezer floor can heave, causing cracks in the floor and distortion of foundation walls. Cracked, damaged floors, as illustrated in Figure 2, can render floor space unusable and potentially dangerous for workers in the facility [5].

2.2 *Cold Storage Building Standards*

Two industry associations provide frost heave prevention guidance when building cold storage facilities. The American Concrete Institute (ACI) is a leading global authority for the development, dissemination, and adoption of its consensus-based standards, technical resources, and educational, training & certification programs [6]. The American Society of Heating, Refrigeration, and Air Conditioning Engineers, Inc (ASHRAE) is a global society advancing human well-being through sustainable technology for the built environment. Through research, standards writing, publishing, and continuing educations [7]. The following sections detail ACI and ASHRAE standards regarding frost heave prevention when building cold storage facilities.

The floor slab is considered a slab-on-ground. When insulation is used, it is generally extruded polystyrene board, rigid polyurethane board, or cellular glass board insulation. The slip sheet is typically a polyethylene film (6 mil [0.15 mm] minimum thickness) used as a bond break between the slab and the insulation. The insulation may be in single or multiple layers, depending on the thermal requirements. Insulation is typically not required for a room at a temperature above 32 °F (0 °C). The vapor retarder/barrier is under the insulation, and a polyethylene film (10 mil [0.25 mm] minimum thickness), 45 mil (1.14 mm) EPDM, or bituminous materials in the form of liquid-applied coatings or composite sheets have been used. For refrigerated buildings, vapor retarders/barriers are always installed on the warm side of the insulation. Under the vapor retarder/barrier, there is either a soil base or a sub-slab. A sub-slab is often installed to ease insulated floor-system construction, or it may encase a grid of heating pipes or conduits. For refrigerated buildings with operating temperatures below freezing, an under-floor heating system is required to prevent the ground from freezing and heaving. The insulated floor system may also be installed over a structural slab supported by deep foundations such as piles [8].

Builders face several critical constraints when deciding which frost heave prevention method to install. Once it is determined that frost heave prevention is required, attention shifts to selecting the appropriate method for the facility and local conditions. As gleaned through the research, the costs, and risk require considerable consideration in determining the frost heave prevention method to apply when building a cold storage facility.

3. Research Methodology

Qualitative analysis using semi-structured interviews with twelve cold storage builders, to understand builder preferences when applying frost heave prevention methods in varying conditions. Personal semi-structured interviews of questions developed from the literature review. Each participate was asked questions in a systematic structure with additional probing quetions where appropriate. Twelve cold storage buidlers were identified to meet the creitieria for participation. Interveiw criteria ensured a solid base of kowledge in the cold stoage freezer industy and frost prevention systems. The interview participants, identified as builders A-M (Figure 3), were selected as builders of Cold Storage facilities within climate regions of North America.

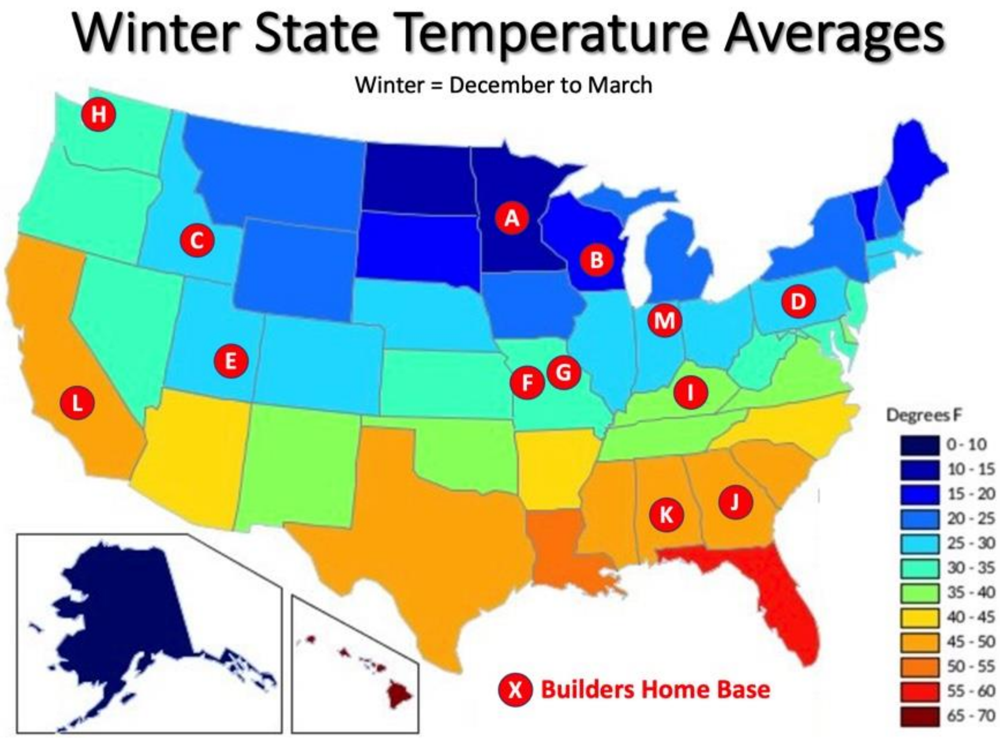

Figure 4. Winter State Temperature Averages [9]

Twenty-one companies were interviewed before selecting the specific twelve. Additionally, during the process, a thirteenth company was identified that could provide two operators, an engineer, and a project manager, to form a focus group. The focus group was reviewed for continuity of responses from other builders through the lens of different positions of the cold storage build spectrum. The vetting process searched for either operations or project managers of cold storage freezer builds to capture a subject matter experts' response to the questions. Participants included 9 Project Managers and 4 Operations Managers. A minimum of 10 years' experience was required to participate. Figure 15 illustrates the experience level in years with an average level of experience of the participants in the research group at 19 years. A total of 251 years' experience is represented.

4. Results and Discussion

All builders use some form of frost heave prevention method when building a cold storage freezer capable of 32°F and below. Small facilities below 10,000 square feet range, it is a mix of opinions regarding natural or forced ventilation systems. Some builders will not even entertain these systems, while others accept them as a reasonable solution, given the right conditions, predominately warmer climates. Ventilation systems need natural or manufactured heat in colder weather. In contrast, electric systems are preferred in colder climates. One can then conclude natural and forced ventilation is primarily used in small facilities in warmer climates and electric heat is primarily used in small to slightly larger facilities in colder climates.

Mid-sized facilities in the 10,000 to 50,000 square feet range, the opinions on prevention methods move away from natural ventilation, with some comfortable using forced ventilation, especially with added heat in colder climate areas. In contrast, electric systems take a more prominent role, and even glycol will be considered. Given the size of the freezer, most likely, the glycol system would require an added heat source, thus increasing the cost of operations. One can conclude forced air and electric heat is preferred for small and slightly larger facilities in warmer regions and electric or glycol heat in colder regions.

Mid-sized facilities in the 50,000 to 100,000 square feet range, builders vacillate between electric and glycol. Several conditions can move the needle on selecting a system, but none potentially more than the facility refrigeration system. In this size range, either a split or centralized refrigeration system is used, allowing builders to choose electric or glycol. If a split system is installed, electric heat and glycol heat can be used; however, a heat source would be applied to the glycol. If a centralized system is installed, electric heat can be used; however, now there is the option to apply a heat exchanger to the refrigeration system to heat the glycol, thus, saving energy costs. One can conclude electric heat is preferred for mid-size and slightly larger facilities in warmer regions and glycol heat in colder regions.

Larger facilities, especially above the 100,000 square feet range, the strategy becomes abundantly clear; glycol is the preferred method. As the data illustrates, larger facilities typically have a centralized refrigeration system, thus providing heat for the glycol. While electric heat can still be used, operations costs are high. One can conclude Glycol heat is the preferred method for larger facilities in colder regions and likely preferred in the warmer regions.

5. Conclusions and Recommendations

Although this research selected some of the top builders across the country, it was a limited sample size with a limited data collection. In retrospect, the methodology did not provide an adequate platform for a deep level of understanding of all the complex issues facing builders when selecting a frost heave prevention method. As noted in the themes uncovered during the semi-structured interviews, many additional factors need to be analyzed to create a usable method selection tool.

Other than ASHRAE or ACI, there is very little definitive instruction for builders to review when selecting a frost heave prevention method. The research and interviews do provide a degree of fact and opinion on which systems are more or less expensive to install, operate, maintain, and the degree of risk they experience. See Table 1.

Table 1: Frost Heave Prevention Method Costs & Risk (Sanford, 2021)

Prevention Method	Installation Cost	Operating Cost	Failure Risk
Natural Ventilation	Medium	Low	**High**
Forced Air Ventilation	High	Medium	**Medium**
Electric Heat System	Low	High	**Low**
Forced Glycol Heat	Medium	Medium	**Low**

Based on the interview data analysis, additional research points are needed to provide a comprehensive frost heave prevention method selection tool. Below is a list of data points necessary to further analyze the factors impacting the decision process.

- Installation, operating, and maintenance costs per method by region and size
- Number of natural, forced, forced with heat, electric, glycol with heat exchangers and other heat sources by region and size
- Number and location of failures by each method. The data can be evaluated to support regional build assumptions

Ideally, future research should be conducted using a comprehensive survey designed to illicit these data points from builders in a substantial and factual way to provide the researcher with enough information to form a solid conclusion. Given the research information, interviews, and theme data, along with future research data, the creation of a robust decision matrix is possible.

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Subsurface Utility Engineering: A Call to Action for Construction Project Owners

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Abstract

Subsurface Utility Engineering (SUE) is an engineering process that can help reduce unforeseen site conditions resulting from the lack of or inaccurate portrayal of underground utilities. It can help prevent construction contract cost and time growth as well as damage to existing utilities, unplanned utility outages, design changes, construction contract claims, property damage, personal injuries, and even deaths. Since 1986 SUE has consistently demonstrated benefits on municipal projects. This study focused on projects and procedures used by the U.S. Army Corps of Engineers (USACE) Savannah District and a case study of one project's challenges with unforeseen site conditions resulting from inaccurate and incomplete utility records. Geophysical techniques for detecting and mapping subsurface utility hardware and software have undergone significant improvements. Primary SUE Benefits include reduced number and scope of utility relocations, minimized contractor delay claims and change orders, and accurate location and knowledge of subsurface utility conditions (Anspach & Scott, 2019). Despite this, project owners and engineers rarely apply these new technologies because 1) SUE is not commonly taught in civil engineering curricula, and 2) SUE specialists are not always commonly available (Anspach & Scott, 2019). This research used a focus group methodology consisting of subject matter experts; three (3) USACE District design branches, Savannah, Kansas City, and Mobile along with three (3) private Architecture / Engineering (AE) firms routinely used by the Savannah District. The objective of this study is to highlight some of the benefits of SUE and compel USACE and project owners to identify and require the appropriate quality level of SUE for their projects on a routine basis.

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Keywords: Subsurface Utility Engineering, SUE, Utility Conflicts, USACE

1. Introduction

Studies from the 1940s through today reveal a consistent leading reason for project delay claims – namely, incorrect or incomplete utility depictions on plans (Anspach & Scott, 2019). Existing utility records are notoriously inaccurate, incomplete, missing, never made, not available, not standardized at a schematic level, are difficult to interpret, and frequently not spatially referenced to a published datum (Anspach & Scott, 2019). This lack of reliable and accurate information of subsurface utilities can lead to construction contract time growth, construction contract cost growth, damage to existing utilities, unplanned utility outages, design changes, construction contract claims, property damage, personal injuries, and even deaths. Subsurface Utility Engineering (SUE) is an engineering process that can help reduce these unforeseen conditions.

While the location of subsurface utilities is generally included on utility maps and drawings, this information alone has proven to be inaccurately recorded, missing information, and often does not reflect abandoned utilities. Even in instances where utilities are owned by private utility companies on military installations, records are often sorely lacking in detail and accuracy. In the past there was no way to reconcile these problems, but SUE is a proven solution.

Successful history of using SUE on municipal projects begins in 1986. Studies show that SUE benefits all project stakeholders, including designers, contractors, project owners, utility companies, and most important, the public. Proper applications of SUE reduce unnecessary utility relocations, damage to existing utilities, change orders and claims, service disruptions, and personnel injuries. The benefits are savings in time and cost for the entire project (Anspach & Scott, 2019).

This paper focuses on projects and procedures utilized by the U.S. Army Corps of Engineers (USACE) and more specifically, the Savannah District. The USACE is the design and construction agent for all U.S. Army and U.S. Air Force real property facilities and infrastructure.

2. Background

Military installations are like small cities with respect to their underground utility systems. Many of the installations supported by the Savannah District suffer from inaccurate, incomplete, or missing utility records. Four common reasons for this problem are:

1. Existing records are not "as-built" drawings. Discrepancies occur if changes from the design are made in the field and not subsequently documented on "as-built" drawings which are then used to update existing utility information. Or existing utility information is not updated with accurate "as-built" drawings.
2. Records are lost or misplaced. Often due to high-turnover rate of personnel on military installations.
3. Obsolete utilities are removed from the ground, but not removed from installation utility maps.
4. Reference points are often removed.
   (Lockhart, 2004)

The Savannah District has experienced this problem on numerous projects.

Subsurface Utility Engineering (SUE) is basically thoroughly investigating and identifying underground utilities to inform and help develop accurate and cost-effective designs. Clearly, understanding what is beneath the ground surface on a future construction site is extremely important for all project stakeholders. Encountering an underground conflict during construction results in significant project cost and time growth (Lew, 2000).

The concept of SUE was introduced in the 1970s by Henry Stutzman to accurately locate subsurface utilities and record the underground information to increase safety and reduce economic loss in the project planning phase (Jung, 2009). SUE became more widely used in the 1980s and since 1991 has been encouraged by the Federal Highway Administration on projects as an integral part of the preliminary engineering process (American Society of Civil Engineers & Construction Institute, 2003). It is recognized as a best practice by the American Association for State Highway and Transportation Officials (AASHTO), Federal Highway Administration (FHWA), Associated General Contractors, Office of Pipeline Safety, National Transportation Safety Board (NTSB), Network Reliability Council, and many state Departments of Transportation (DOTs) (FHWA, n.d.).

In 2002, the American Society of Civil Engineers (ASCE) developed a national engineering standard titled, "ASCE/CI 38-02, Standard Guideline for the Collection and Depiction of Existing Subsurface Utility Data". This document defines SUE as an engineering process that uses new and existing technologies to identify, characterize, and accurately map underground utilities early in the development of a project (ASCE 2002). The 2019 ASCE Manual "Subsurface Utility Engineering for Municipalities: Prequalification Criteria and Scope of Work Guide" recommends the use of ASCE 38-02 and states it is a risk-based process and standardized approach to classifying the confidence of existing utilities where there is a formal deliverable (Anspach & Scott, 2019).

In general, the standard states:

1. The project owner will be responsible for taking appropriate actions to consider and deal with utility risks.
2. The engineer will advise the project owner of utility risks and recommend an appropriate level of utility data for a given project area. Advice should consider the type of project, expected utilities, available rights-of-way, project timetables, and so on.
3. The project owner will specify to the engineer the desired quality level of utility data.
4. The engineer will furnish the desired utility quality level to the owner in accordance with the standard of care.
5. The engineer will be responsible for negligent errors and/or omissions in the utility data for the certified quality level.

To understand the concept of SUE, it is necessary to define the SUE quality levels of underground information that are available to designers, contractors, and owners (Anspach 1994). There are four SUE quality levels. They reflect different combinations of traditional record, site survey, geophysical technology, and vacuum excavation. The accuracy and reliability of underground information increase from quality level D to quality level A. The costs for SUE surveys also increase from quality level D to quality level A, See Figure 1.

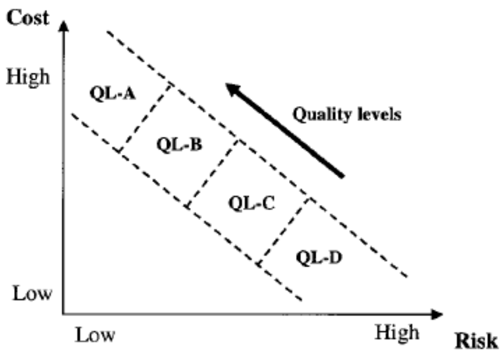

Figure 1. Quality levels in subsurface utility engineering. (Jeong et al., 2004)

Use of these quality levels provides project stakeholders with an understanding of the accuracy and level of confidence they can place on the existing utility information provided in design documents. What quality level is really needed for a specific project is ultimately a question of how much risk the project owner, utility owner(s), construction contractor, and all other project stakeholders are willing to accept. The higher risk tolerance those entities have for a specific project, the lower level of SUE quality that is required. A brief description of each quality level follows.

Quality level "D" (QLD): Review of Existing Records and Verbal Recollection. This is the most basic level of information and comes from existing utility records (Zembillas, 2012). This quality level is assigned when there is no data other than existing records. It is the most uncertain depiction of utilities.

Quality level "C" (QLC): Surveying and Plotting Visible Above-Ground Features. Traditionally the most used level of information. QLC supplements QLD information with a visual ground survey of existing utility features, e.g., manholes and valve boxes (Zembillas, 2012). This quality level exists if only records and visible features can determine the best judged position of a utility because geophysical methods did not work or were not used.

Quality level "B" (QLB) – Designating. Surface Geophysical technology to identify the existence and horizontal position of subsurface utilities. This means geophysical methods were used to search for, detect, and interpret the existence and location of a particular utility segment. This is the first level where the "designating" activity is introduced to the SUE process. This level provides two-dimensional horizontal mapping along the entire length of the utility lines. It is particularly useful early in the design phase of a project as revisions to the design are relatively easy to make and can significantly reduce the amount of utilities requiring relocation (Zembillas, 2012).

Quality level "A" (QLA) – Locating. Nondestructive Excavation Methods to Determine Precise Horizontal and Vertical Positions of Subsurface Utilities. This means the utility was exposed and verified at the exact spot and uncertainty of its location is nearly zero. Provides the highest level of information accuracy available for making final design decisions. This provides a three-dimensional mapping of underground utilities and related structures. QLA conveys the highest level of certainty of attributes and location of underground utilities (Zembillas, 2012).

The terms "designating" and "locating" were developed by James Anspach, a former Penn State geophysicist, and Jeff Oakley, a Penn State physics graduate. By definition, a utility is considered 'located' after it has been exposed and 'designated' when its existence and approximate location have been determined (Lockhart, 2004).

It should be noted here that there are multiple non-invasive methods of designating utilities at QLB including Ground Penetrating Radar (GPR), Electro-Magnetic Induction, Radio Frequency Detection, Magnetometer, and Pulse Induction (Clark Scott, 2010). The various geophysical tools available are not covered here for brevity. However, the various methods allow engineers to 'see' underground utilities and are selected based upon numerous characteristics including soil type, utility material, and the depth of the utility. There is no one best method or piece of equipment for conducting a SUE QLB investigation.

Determining which level of quality is required for a specific project is an important part of the process and should be approached in a uniform manner. If the risk of encountering unknown utility conflicts during construction is low, new construction in a green field for example, the cost-benefit analysis of performing QLA may not be justified. However, this is not the norm for construction on military installations. Selecting the appropriate quality level should be based on cost-benefit analysis (Jung, 2009).

2.1 USACE PROJECT CASE

In 2017, the U.S. Army Corps of Engineers Savannah District awarded a contract to design the future campus of the Cyber Center of Excellence (CCoE) at Ft. Gordon, Georgia. The cornerstones of the campus are four (4) new facilities ranging in size from 235,000 square feet to 139,000 square feet. The entire effort was preceded by the development of a "Campus Master Plan" that outlined the various stages of construction, traffic patterns, road closures, pedestrian walk paths, contractor lay-down areas, existing utility information, and the end-state of utilities for the campus, throughout the 8-year design and construction program. Unfortunately, SUE was not required by the owner, in this case, the Department of Defense and U.S. Army, so the Savannah District did not require it be accomplished to inform the campus plan nor the design of the first building.

The $96,000,000 construction contract to build the first building was awarded in June 2020. After award, project progress was crippled by unforeseen site conditions, namely, the discovery of conflicts with existing and abandoned subsurface utilities. The first encounter was with abandoned steam lines which were directly underneath the future building's footprint. Interestingly, the design team had identified a steam vault within the project limits to be demolished but did not identify the steam lines emanating from the vault. A Ground Penetrating Radar (GPR) investigation after construction contract award confirmed the presence of the steam lines. The steam lines were in direct conflict with the building's geopier foundations. This led to a $872,843.00 contract change and added an additional 63 days to the construction contract duration. Ultimately, these utility conflicts and other issues resulted in work to install the geopiers for the foundation of the building not beginning until nearly one year after the Notice to Proceed was issued.

The second contract change resulting from differing site conditions was the discovery during excavation that the existing hot water piping was not at the elevation the drawings reflected and there was an electrical power duct bank that conflicted with the routing of the new hot water piping. The cost of this modification was $30,708.00. No time was added to the contract duration. The third change for unforeseen site conditions was to redesign and relocate the storm drain and detention pond. This change was required because a concrete encased telecommunications duct bank was incorrectly located on the design drawings. The actual location of the duct bank was confirmed by GPR four (4) months after the construction contract was awarded. It is worthy of note, the electric utility is privately owned on Fort Gordon. There was also roughly $280,000 for the necessary design changes by the Designer of Record. Had an appropriate quality level of SUE been performed during design development this project would have saved more than $1 million and at least three months of construction time.

And there have been numerous other projects significantly impacted by unforeseen utility conflicts in the past five years. An Advanced Individual Training (AIT) complex lost 67 days and the government paid more than $777,000 for unforeseen site conditions associated with underground utilities and features that were not discovered until construction was underway. Obviously, there are costs to other stakeholders as well. Recently, CCoE stakeholders stated they had lost 15 days of training and, when factoring in student population and instructor hours, that equated to nearly 12,000 lost student training hours due to disruptions to utility services during construction. These are just two examples of which I have personal experience with. There are others. It is safe to assume that had subsurface utilities been designated and located during the design process, the contract cost and time growth for these projects would have been reduced significantly.

2.2 Cost Benefits of SUE

"Cost Savings on Highway Projects Utilizing Subsurface Utility Engineering" (FHWA Study, 2000) is widely used to introduce and encourage the use of SUE in evaluating cost savings (Jung, 2009). The study was performed by Purdue University and commissioned by the FHWA in 1996. It evaluated 71 projects from four state Departments of Transportation using 21 categories to quantify savings in time, cost, and risk management. The results of this study showed a total of $4.62 in savings for every dollar spent on SUE. Savings were primarily from elimination of unnecessary utility relocations and a reduction in delay claims. The study went on to state that SUE should produce a minimum of $1 billion annually in savings across the nation (Lockhart, 2004).

Additionally, numerous benefit-cost analyses have shown that the use of SUE provides a significant return on investment. The 2019 ASCE Manual 38-02, "Subsurface Utility Engineering for Municipalities: Prequalification Criteria and Scope of Work Guide" states that "Every academic, state Department of Transportation (DOT), and federal study on SUE since the 1990s shows a significant return on investment to the public." (Anspach & Scott, 2019).

Studies by Pennsylvania State University, the University of Toronto, and others consistently show a positive return on investment (ROI) for projects following the guidelines in ASCE 38-02 (Anspach & Scott, 2019).

Results of a 12-month study by the University of Toronto for the Ontario Sewer and Watermain Contractors Association included 9 successful SUE case studies in Ontario and were published in 2005. (Osman & El-Diraby, 2021) The average ROI was approximately $3.41 for each dollar spent on SUE. Greatest savings were realized from reduced delay claims and secondarily from the avoidance of utility relocations (Anspach & Scott, 2019).

In 2007, the Pennsylvania Transportation Institute of Pennsylvania State University conducted an in-depth analysis of 10 SUE projects executed by the Pennsylvania Department of Transportation. This study calculated that an average of $22.21 is saved for every dollar spent on SUE (Anspach & Scott, 2019). The study reflected a Return-on-Investment of $3.41 for every $1.00 spent on SUE (Osman & El-Diraby, 2021). This study also indicated that the total cost savings may range from 10%-15% on projects utilizing SUE compared with those that did not (Jung, 2009).

3. Data Collection

Surveys and interviews were conducted with three (3) USACE District design branches, Savannah, Kansas City, and Mobile. Surveys were also sent to three private Architecture / Engineering (AE) firms routinely used by the Savannah District. The USACE districts were selected because they all house a military design branch. Among other activities, the branches take on the planning and development of 100% Design-Bid-Build (DBB) or Design-Build (DB) Requests for Proposal (RFPs) for various facility types and stakeholders throughout their Area of Operation. The primary facility types designed include barracks, command and control facilities, dining facilities, vehicle maintenance facilities, aircraft maintenance hangars, and other administrative facilities.

The purpose of the survey was to determine if USACE district's familiarity, use, and general approach to SUE mirrored that of private AE firms. The survey conducted was limited to a very small sample size, i.e., there are twenty-three (23) districts in the USACE with a military mission and only three (3) were surveyed. The number of districts that include a military design branch could not be determined. All the private firms surveyed expressed relatively in-depth experience and knowledge with SUE. Two (2) of the three (3) USACE districts shared the same familiarity.

The survey questions and a summary of the responses received follow:

1. Does your organization perform Subsurface Utility Engineering during design development by routine or by exception?

Responses:
AE Firm A – Geomatic groups deal with several clients with QLB being used on all projects and QLA being used in known critical areas (after the QLB effort).

AE Firm B – We routinely have a subcontractor in the geographic area of the project perform SUE during design development. Under ideal conditions we like to perform two rounds of utility investigations. First is during the initial survey. Usually, GPR is used along with a utility locate service, i.e., call before you dig. The information collected in the field is compared to Base utility maps and GIS information. Sometimes depending on the soil type GPR will not provide good data. The second round occurs when we have a refined design and know the location of the utility alignments. We will pothole each utility crossing.

AE Firm C – We do not perform this work ourselves, however we subcontract this work, and it is routinely completed during design development in conjunction with the survey.

USACE District A (SAS) – Routinely accomplish QLC for the district in-house designs, although given the recent influx of contract changes for unforeseen site conditions we are researching pursuing QLB and QLA in the future.

USACE District B (NWK) – Use SUE classification routinely.

USACE District C (SAM) – Routinely, for all projects SUE is required. The quality level will vary based on the scope and complexity. Typically, QLB is used for in-house designs/surveys.

2. If by exception – what are the primary considerations for when it is and is not performed?

Responses:

AE Firm A – When the site is in an urban environment vs. rural.

AE Firm B – The only projects that have not performed utility location investigation are small projects that do not have a concern of utility crossings.

AE Firm C – It has been our experience that initial design costs are always the determining factor in deciding whether a higher level of SUE is provided. I personally believe that higher quality levels of SUE in design sensitive areas will almost always provide a benefit in lower construction costs, existing utility impacts, etc.

USACE District A (SAS) – By exception. Utility base maps are not well maintained so utilities are not where they say they are, so it is always needed. If projects are in areas without utilities, and or if the project budget is tight.

USACE District B (NWK) – Not applicable.

USACE District C (SAM) – Not applicable.

3. When performed what is considered 'standard' Quality Level (QLA, QLB, QLC, or QLD?)

Responses:

AE Firm A – Standard is QLB. QLA is completed when deemed necessary by the engineer.

AE Firm B – QLB for all alignments and QLA for all crossings.

AE Firm C – Standard is QLB.

USACE District A (SAS) – Standard is QLC.

USACE District B (NWK) – No standard level of quality. The civil engineer classifies information gathered during design (records searches, survey, etc.) to ensure information obtained is adequate.

USACE District C 3 (SAM) – QLB.

4. Is there a noticeable difference in time/cost growth for projects that did not complete SUE to QLB or higher?

Responses:

AE Firm A – Cost for QLB is not high and effort provides confidence for the designer to know where potential conflicts exist and most likely will eliminate change order to redesign when a conflict is discovered during construction.

AE Firm B – Yes, my perception of QLC and QLD utility information is that it is obtained from old drawings or GIS data. No field work was used to confirm location.

AE Firm C – Yes.

USACE District A (SAS) – No data to support, but there have been large modifications in the past that would have been avoided if QLB SUE had been accomplished.

USACE District B (NWK) – Not aware of a case where we have quantified this. From my perspective, the value is twofold. One, this information is communicated to the contractor, helping them characterize the "lines" accuracy shown on the plans. Second, it helps define the risks during the performance of a Cost and Schedule Risk Analysis (CSRA) and Semi-Qualitative Risk Assessments (SQRA). This can highlight that obtaining additional information can better define risk. This could be done without SUE, but this classification helps communicate the level of confidence of utility location.

USACE District C (SAM) – There is a level of uncertainty when SUE is not performed on a project. From a design perspective this is usually relayed to the customer at the beginning of the project and the designer attempts to illustrate the cost associated with utility impacts during construction.

5. Are you familiar with ASCE Standard 38-02, "Standard Guidelines for the Collection and Depiction of Existing Subsurface Utility Data"?

Responses:

AE Firm A – No. Generally, leave SUE QLB and QLA to firms with specialization.

AE Firm B – No. But after a brief overview of the documents, I think it has a decent description of the overall investigation. There is overlap between the different levels which is to be expected. I think our understanding of what is expected for the different levels is slightly more conservative.

AE Firm C – Yes.

USACE District A (SAS) – Cursory familiarity – aware of its existence.

USACE District B (NWK) – Yes.

USACE District C (SAM) – Yes.

The Architect-Engineer (AE) firms were asked three (3) additional questions:

1. Do you see more private owners performing QLB or QLA SUE than on federal government projects?

Responses:

AE Firm A – Believe the mix is even.

AE Firm B – It is mixed. Based on the projects I have been assigned, private owners tend to perform more utility locates during construction. Federal projects tend to do more during design. I am not sure the reason, but it could be due to how contracts are written.

AE Firm C – No.

Have you faced resistance from owners if you recommend they perform QLB / QLA SUE?

Responses:

AE Firm A – When you explain the benefits to the client they generally agree and use SUE where appropriate.

AE Firm B – It depends on the project and the funds available. For most projects, no resistance is received.

AE Firm C – No.

Do you perform the SUE with in-house resources or via subcontract?

Responses:

AE Firm A – Generally sub-contract SUE QLB and QLA.

AE Firm B – Subcontract with oversight during the investigation. We have found that we get better results if an engineer from the design team is on-site directing, answering questions, and coordinating with the Base Civil Engineer.

AE Firm C – Subcontracts.

Obviously, this is a very small sample size and a more extensive evaluation, of both USACE districts and private AE firms, would result in a significantly higher level of confidence in the data. Despite that, the responses indicate AE firms perform QLB and QLA SUE more routinely. Interestingly, they were not as familiar with ASCE/CI 38-02 as the USACE respondents. All respondents had somewhat varying, although firm levels of familiarity with SUE.

The responses to the question regarding resistance from owners is encouraging. All AE firms said they had not faced resistance when recommending QLB or QLA SUE. The benefits and risk mitigation SUE provides are well documented. And when shared with owners and any other project stakeholder, compelling.

It is interesting to note that all the private firms subcontracted the SUE effort because the USACE districts surveyed do not have any "in-house" capability of performing QLB or QLA investigations. Therefore, they must award a contract to obtain the information for those projects designed "in-house". Also noteworthy, only one AE firm sent an engineer to be on-site during investigations. Considering this to be a best practice.

3.1 SUE Decision Making

So, when do we use SUE? In general, decision making on the selection of appropriate SUE quality levels is highly dependent on the experience of project owners, managers, engineers, designers, and construction experts. Additionally, USACE districts have considerable autonomy over design processes, acquisition strategies, construction oversight, and many other project delivery issues. Thus, the use of SUE is not uniform across the enterprise, and on some projects, including the project highlighted in this paper, SUE is not accomplished effectively. This study proposes that the Savannah District require QLB and QLA on all projects. Interestingly, one of the eleven recommendations included in the Purdue study completed for the FHWA was to do this very thing. The author recommended upgrading all projects to QLB and QLA data. Going on to state, "This study shows that the benefits far exceed the costs on average. Trying to select only those projects that may end up with significant utility problems is risky at best." (Lew, 2000).

In addition, to help answer the question of when SUE should be used, the Pennsylvania Department of Transportation developed a SUE utility impact rating form designed to recommend appropriate SUE quality levels based on utility impact severity. The SUE Utility Impact Form provides an analysis of project criteria to determine 1) if SUE is practicable, 2) when SUE should be considered on a project, 3) and what utility quality levels should be utilized (Sinha et al., 2007). Application of the utility impact form consists of three steps. Steps 1 and 2 are screening processes to determine whether QLB and/or QLA data are required for projects. For projects that pass steps 1 and 2, step 3 is performed, which is an evaluation to identify appropriate quality level objectives for the related SUE investigations of project areas (Anspach & Scott, 2019). The Georgia DOT (GDOT) has also developed an Impact Rating Form. These forms can be an important decision-support tool to determine which projects should include SUE and which quality levels should be used based on the complexity level of buried utilities at the construction site. The use of this tool can help ensure SUE is considered and applied in a more routine and systematic method.

4. Conclusion and Recommendations

The benefits of SUE are well documented. The Savannah District, and USACE as an enterprise, must communicate this to project owners to compel them to require it be accomplished early in the design process to designate and locate underground utilities. When a project owner is unsure of which level of SUE to use it is generally wiser to pursue a higher quality level. The cost of SUE should be viewed as an investment as opposed to a one-time fee to prepare contract design documents. If done correctly, the information will be of value and should never have to be repeated provided the data is recorded and managed appropriately (Lockhart, 2004).

Also recommend USACE provide advice and guidance to supported installations highlighting the recommendations of ASCE Manual "Subsurface Utility Engineering for Municipalities: Prequalification Criteria and Scope of Work Guide" to installation Public Works, Base Civil Engineering officials, and other stakeholders to further their understanding of SUE and its benefits. Additionally, USACE should adopt the standards outlined in ASCE 38-02, "Standard Guideline for the Collection and Depiction of Existing Subsurface Utility Data" for all future projects.

There are many variables that can adversely impact a project's cost and or schedule during construction. SUE can reduce, if not eliminate unforeseen site utility conditions from being one of those variables. As such, the Savannah district and USACE should adopt a more deliberate and uniform approach to the use of SUE and should consider requiring QLB and QLA utility data on all projects. The use of a utility impact rating form could help guide USACE project delivery team members, and project owners, to avoid these problems. And perhaps provide adequate and actionable information to help convince project owners to designate the required quality level of subsurface information.

Continued / Future research - recommend the Savannah District develop a utility impact rating form for use to determine appropriate SUE quality levels on design and construction projects for all projects in its Area of Responsibility (AOR) and implement its use.

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A Cloud-Based System for Supporting Quick Location of Precast Concrete Formwork Using Computer Vision and BIM

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Abstract

In precast concrete production sites for elevated roads, adjustable formwork systems are often used to accommodate the precast components of varying shapes and sizes. Therefore, it is needed to locate and adjust the formwork frequently when the elevated road adopts continuously varying cross-sections. However, the traditional way requires significant labor costs and heavy equipment, and is prone to miscalculation. To solve the problem, this paper proposes a quick location system for formwork adjustment based on a smartphone and the latest technologies including computer vision, BIM, and cloud computing. In this research, firstly, the background and existing research were investigated; then, the engineering requirements for quick location of formwork were analyzed and the system architecture was designed; next, the visual measurement and adjustment calculation modules at the back-end were implemented based on computer vision and BIM technology, and the user interface and lightweight BIM interface modules at the front-end were implemented based on HTML, jQuery, Node.js and BIMFACE; finally, the research was summarized and prospected. With the system, surveyors can compute the adjustment amount of the support at the production site with just a smartphone, which can effectively reduce measurement time and improve efficiency. In conclusion, this research provides an effective approach for supporting the quick location of concrete formwork in the production of precast components.

Keywords: cloud computing, computer vision, lightweight BIM, smartphone, formwork adjustment.

1. Introduction

Elevated roads are an important means of transport and are still being built in countries such as China, for which the main methods of construction include cast-in-place and assembled construction. The cast-in-place method has a long construction period, involves pollution, and can cause inconvenience such as road closures, whereas the precast construction method is more efficient, safe, and environmentally friendly, with components usually produced in plants in a standardized manner, resulting in high-quality performance, rapid production with lower costs [1, 2].

The precast concrete components that are used in elevated roads vary in plan shape and section size due to usage requirements and economic considerations. Therefore, the use of adjustable formwork is required during the production of the components. Since these formworks require multiple point measurements to determine their attitude during the adjustment process, the corresponding workload is quite onerous for the staffs. It is expected that similar workloads will increase significantly with the construction of assembled bridges and the widespread use of precast concrete [3]. The traditional method for the process is that two surveyors holding a total station and a prism, respectively, work together on-site to complete the coordinated measurement of specific points and manually calculate the adjustment amount. This method is costly, cumbersome, error-prone, and inefficient. Therefore, there is a great need for a method that can quickly calculate the adjustment amount of formwork.

Hence, this paper proposes a cloud-based system for supporting the quick location of precast concrete formwork, which allows the surveyor to obtain the adjustment amount using only one smartphone. Firstly, the architecture and functionality of the system were designed according to the actual needs. Then, a computer vision-based measurement method and a BIM-based adjustment calculation method were proposed. Based on this, a collaborative cloud-based system was developed using a cloud server and a lightweight BIM platform, and it allows the surveyor to upload data and select marker points in the lightweight BIM, and invoke the core algorithm in the server to calculate the adjustment amounts and present them on the smartphone. Finally, the system is discussed and summarized.

2. Literature review

Computer vision technology is capable of extracting information from images or videos to understand or quantitatively analyze the corresponding physical world [4] and is currently being increasingly used in the field of engineering measurement. For example, Feng [5] et al. used a visual measurement system instead of a traditional contact displacement sensor to achieve real-time, multi-point measurement of structural displacement response. Tang [6] et al. reconstructed a three-dimensional deformation surface of a concrete column based on multi-vision and realized dynamic real-time measurement of its deformation accordingly. Yang [7] et al. combined computer vision with fully convolutional networks to achieve measurements of crack topology, length, maximum width, and average width metrics. Siebert [8] et al. collected and reconstructed the earthwork site using a camera attached to an unmanned aircraft, whereby the measurement of earthwork geometry information was achieved. Marčiš [9] measured concrete slab deformations at close range and analyzed displacement variations between multiple points on the components through an indoor drone camera mount.

The concept of BIM was first introduced by Eastman in 1975 [10] and has been widely used in the construction industry, effectively enhancing the level of informatization in this industry. However, many BIM models take up a large amount of space, are slow to transfer, and have high equipment requirements [11]. In 2011, the release of WebGL promoted the development of lightweight BIM [12], and in 2015, Autodesk launched its Forge platform to help users achieve lightweight conversion of BIM models. China's Glodon launched the BIMFACE platform two years later. Currently, research and applications related to lightweight BIM are increasing, mainly in the fields of building simulation, operation, and management [11, 13-15].

Cloud computing enables users to perform complex computations from low-provisioned mobile devices by shifting the computational work to remote resource providers [16]. Early on, it was mainly used in e-commerce and social media, but with the popularity of smartphones and the development of mobile internet, its market size has grown and deepened into various industries, including construction. For example, Polter [17] et al. developed the BIM-grid framework to support dynamic collaborative management in civil engineering projects by integrating private web and public cloud resources. Chen [18] et al. implemented collaborative mobile-cloud computing to assess the condition of civil infrastructure.

According to the literature review, many researches have applied latest information technologies including visual measurement, cloud computing, and lightweight BIM to the construction industry, providing valuable references for solving similar problems. However, up to now, no research has been found to integrate these technologies to solve the problem of quick location of formworks.

3. System design and development

3.1 Research objective and system requirements analysis

Based on the analysis of the engineering requirements and the limitations of existing researches, this research aims to propose and implement a system that enables surveyors to quickly measure the 3D coordinates of marked points across formwork, calculate the adjustment amounts, and present them on production sites with just one smartphone.

To achieve this objective, the system comprises three main requirements: firstly, a module capable of accurately measuring the relative 3D coordinates of marker points through computer vision; secondly, a module that calculates the adjustment amount of formwork based on the BIM model and visual measurement module; and thirdly, a user interface system that facilitates quick uploading of information and visualization of adjustment amounts by the user.

3.2 System architecture design

In this research, the B/S architecture was chosen to design the system to ensure better serviceability and cross-platform workability. The system architecture is shown in Fig. 1. In the representation layer, the necessary information including images is uploaded by the surveyor through interaction with the smartphone. In the business layer, the relevant data uploaded by the representation layer through the network is received and processed, based on which the visual measurement module and the adjustment calculation module in the back-end server are invoked to quickly obtain the relative position of the formwork and automatically calculate the adjustment amount accordingly. In the data layer, information is received from the representation and business layers, and the adjustment amount is transmitted back to the representation layer for visualization by the surveyor on the smartphone.

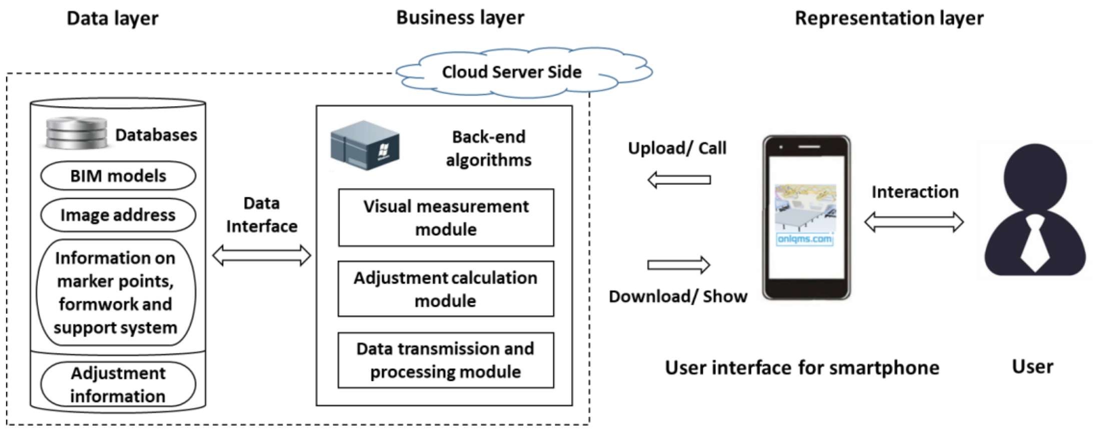


Fig. 1. System Architecture

3.3 Back-end algorithms of the system

3.3.1 Visual measurement module

The process inside the visual measurement module consists of 3 main stages, including preparation, 3D reconstruction, and conversion stages, and its flow is shown in Fig. 2.

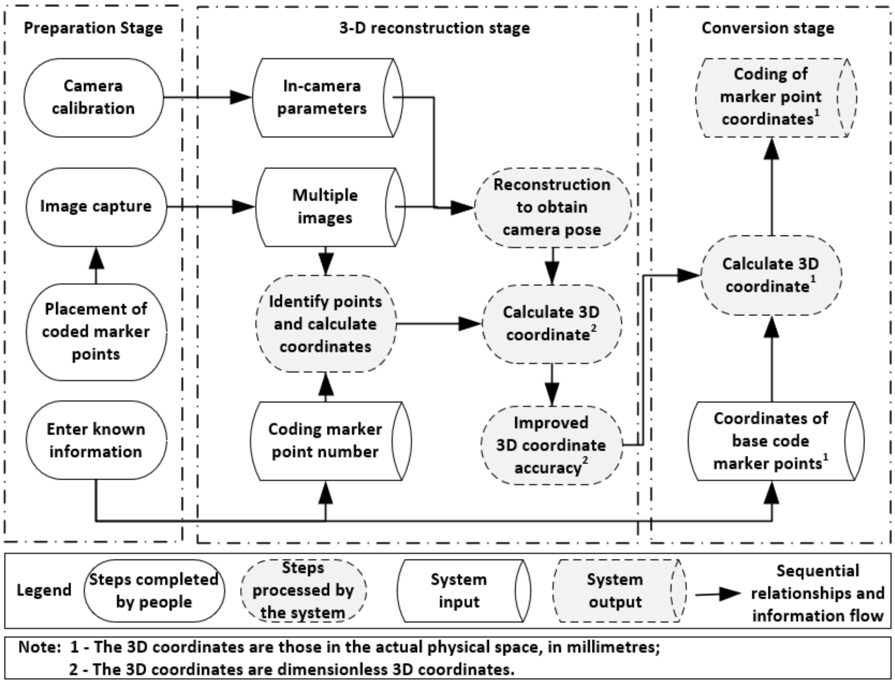


Fig. 2. The flow of the visual measurement module

In the preparation stage, the camera parameters are calibrated in advance and ring-coded marker points (hereinafter referred to as marker points) are arranged in the field, then multiple photographs are taken and uploaded. In the 3D reconstruction stage, the coordinates of the marker points in each image are calculated in pixels by using the modules from the open-source computer vision library OpenCV, and then the modules from Open MVG are used to reconstruct the images in three dimensions and to obtain the position and pose of the camera used for photography. Next, the 3D coordinates of the marker points are calculated based on the image coordinates of the marker points and the camera parameters of each image, based on which the software SBA is invoked to implement the beam method leveling algorithm and output the 3D coordinates of the marker points with smaller errors. In the conversion stage, the conversion matrix is derived from the benchmark plates containing multiple marker points with known actual coordinates, and the actual 3D coordinates between the marker points are derived accordingly. The marker points and benchmark plate used in the construction are shown in Fig. 3.

Fig. 3. Marker points (left) and benchmark plate (right)

3.3.2 Adjustment calculation module

In traditional measurement, the 3D coordinates of the marker points are read manually and the adjustments are calculated manually accordingly. In this research, the process is fully automated through BIM and visual measurement technology. In the previous section, the visual measurement module has calculated the relative 3D coordinates between the marker points, while existing projects usually have accurate BIM models containing a wealth of geometric and attribute information. Therefore, users can interact with the smartphone to identify the measurement points in the lightweight BIM to achieve a digital twin of the marker points, thus determining the relative position of the marker points on the formwork, and in turn, being able to find the relative position between the formwork to be measured and the formwork that has been adjusted into position.

The adjustable precast pedestal for production of concrete components consists of formworks and a support system, the main adjustment process of which is shown in Fig. 4.

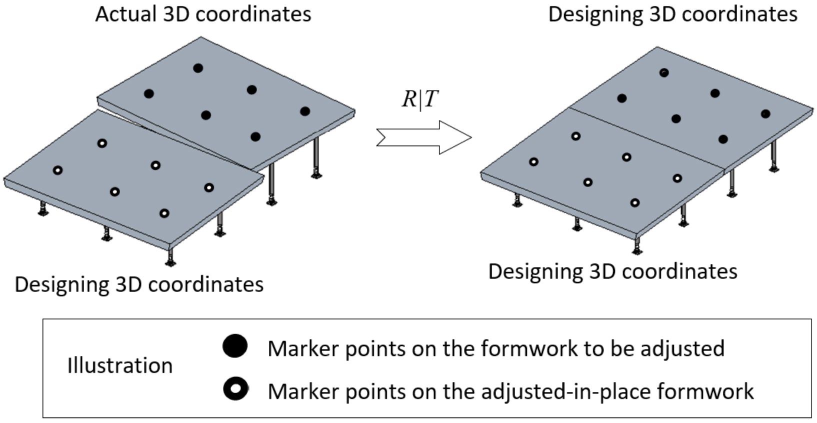


Fig. 4. Formwork adjustment process

When calculating the adjustment of the support system members, it is assumed that the formwork is rigid and free from manufacturing errors, so that the marker points on the formwork to be adjusted can be moved from the actual 3D coordinates to the design 3D coordinates by adjusting the members of the support system, i.e., extending or shortening the cylinder, the screw, and the column, thus adjusting the formwork to be adjusted from the actual position to the design position.

The transformation matrix (rotation matrix R and translation vector T) of the marker points on the formwork to be adjusted from actual 3D coordinates to design 3D coordinates satisfies:

$$X_d = RX_r + T \tag{1}$$

whereX_d is the design 3D coordinate of the marker point on the formwork to be adjusted, and X_r is the actual 3D coordinate of the marker point on the formwork to be adjusted.

In the calculations, since the actual 3D coordinates and the design 3D coordinates of the marker points on the formwork to be adjusted are known, the transformation matrix can be derived from Equation (1), the matrix represents the effect of adjustment of the support system on the actual 3D coordinates of the marker points on the formwork and can be divided into six components, namely translation in the direction of the three axes and rotation in the direction of the three axes:

$$\begin{cases} R = R_z R_y R_x \\ T = T_x + T_y + T_z \end{cases} \tag{2}$$

whereR_z represents the rotation matrix in the direction of$x$, y and$z$, respectively, and T_x, T_y and T_z represent the translation matrix in the direction of x, y and z, respectively.

In fact, since the extension or shortening of each support in the formwork is in the same direction as the axis direction, the relationship between the partial adjustment and the rotation and translation matrix of each axis direction for each cylinder, screw or column is:

$$\begin{cases} R_i = d_i \times a_{ri} \\ T_i = a_{ti} \end{cases} \tag{3}$$

where i indicates the direction of the coordinate axis and can be taken as x, y or z; a_{ri} indicates the partial adjustment amount required for the cylinder, screw, or column to produce R_i in the direction of the $i$coordinate axis; a_{ti} represents the partial adjustment required by the cylinder, screw or column to produce in the direction of the i axis; d_i represents the distance between the axis of the cylinder, screw or column itself and the center of rotation in the direction of the i axis. According to Equation (3), all the partial adjustments of each cylinder, screw, and column can be found, and the sum of them is the adjustment amount.

3.3.3 Experimental equipment and programming

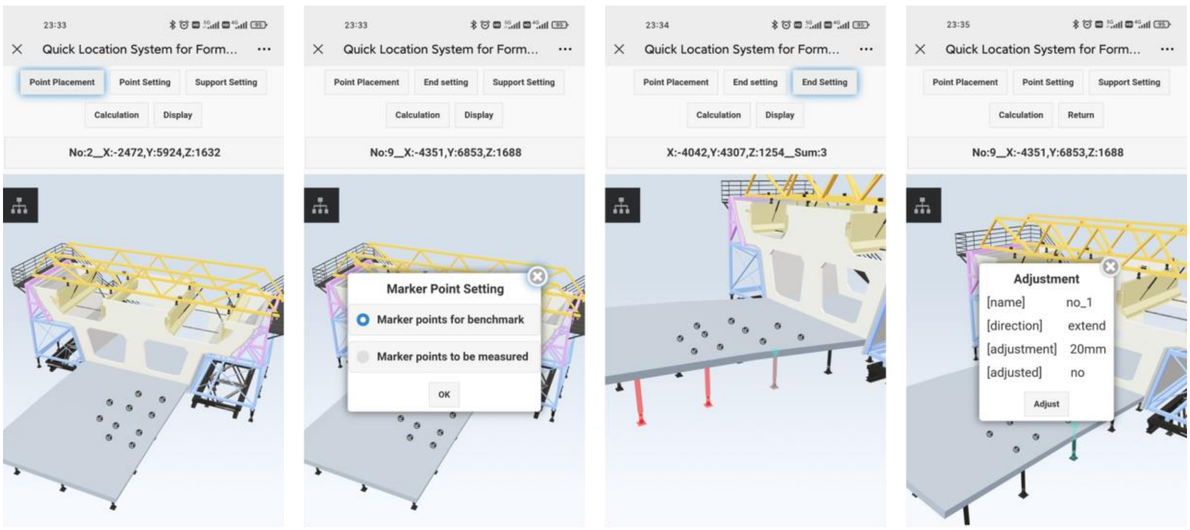
As it is cumbersome and unsafe to bring a laptop to the production site, and the smartphone cannot run measurement programs quickly and independently, a server needs to be set up to run the measurement programs. This research used the Ali-Cloud platform as the cloud server-side, renting an ECS.g5 server with an 8-core 32GB CPU and RAM, Windows Server 2019 operating system and an 80 GB enhanced SSD cloud drive for less than USD 150/ year. The back-end algorithms were established and the modules for visual measurement and adjustment calculation were developed by using C++, where reliable opensource software code, including Open MVG 1.4, Open CV 4.0.0, and SBA 1.6, was used.

3.4 Front-end user interface of the system

To implement the system functionality, it was necessary to select a suitable mobile and develop a front-end user interface for the smartphone. For this research, a Huawei Mate30 smartphone was purchased for USD 750 as a mobile for taking photos, transferring data, and presenting adjustments. It weighs 196 g, has 128 GB of memory, a 40-megapixel main camera, and a maximum photo resolution of 7296 x 5472 pixels. In developing the measurement program, this research developed a user interface system based on HTML5, CSS, and the jQuery Mobile component of the jQuery framework, and wrote a program based on Node.js to transfer data between the mobile and cloud servers, with a Visual Studio Code development environment. The user can create a corresponding project on the smartphone and uploads information such as pictures, camera references, and models required for the measurement procedure to the server by using functions such as Create New Task, Upload Images, Upload BIM Model, and Upload Camera Intrinsic on the smartphone as well.

Then, the user can select the Start Measure function to open the lightweight BIM interface system, which is based on the BIMFACE platform through customization. The main functions include Point Placement, Point Setting, Support Setting, and Display, and its functional interface is shown in the four sub-diagrams a), b), c) and d) in Fig. 5, respectively.

Considering that the screen of the smartphone is too small for the user to directly select the required marker points, JavaScript is used to invoke the API of the BIMFACE platform to highlight the formwork where the marker points are located, while restricting the web page to lock the current view, and at the same time, displaying the 3D coordinates of the marker points at the click in real-time. It makes it easier for the user to accurately place the marker points by moving their fingers. After placing the marker points, the user can click on them one by one and set their properties in the corresponding pop-up window by the Point Setting function. When the user sets support near the formwork through the Support Setting function, the system will automatically read the maximum and minimum coordinates of the enclosing frame of the selected support and calculate the 3D coordinates of the center of the section where the support is connected to the formwork to determine the relative position of the support to the marked points.



a) Point Placement b) Point Setting c) Support Setting d) Display

Fig. 5. Lightweight BIM interface system on the smartphone

The uploaded data are passed to the back-end server in JSON format via the POST method of the HTTP protocol on the web page through the Calculation function, while the data is parsed and stored by Node.js. The algorithm is invoked to conduct the adjustment calculation. Once the calculation is complete, the user can send a request to the back-end via the Display function to obtain the adjustment amounts for each support and present them in the interface, and the supports can be adjusted accordingly.

4. Conclusion

This research proposes a quick location system for formwork adjustment based on the smartphone and the latest technologies including computer vision, BIM, and cloud computing to effectively solve the engineering problems, such as total stations are time-consuming and costly, and cannot adapt to the requirements of measurement tasks. Using the system, multiple points can be measured simultaneously on a production site with just one smartphone, and the amount of adjustment can be viewed visually. The total cost of the system is less than USD 900 and the weight is less than 200 g, which is 10% and 5% of a total station respectively, making the system valuable for engineering applications. With the popularity of cloud computing and the improved performance of smartphone network transmission and photography, this system has the potential to be widely used, and our group will continue to refine the system and validate it in practice in the future.

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A Model-Based Approach to Design A Real-Time Control of Safety Management in Building

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Abstract

Emergency Management (EM) is the organizational function used to avoid, mitigate, and recover from any unexpected events in a specific location and time. It can be considered as a sub-category under Facility Management (FM), which is defined as the organizational function which integrates people, spaces, processes, and technology within the built environment to optimize the overall operation. The performance and management of a building can be integrated into a BIM environment, which the construction industry is approaching to optimize the building performance in its lifecycle.

This contribution will emphasize the findings of the available literature review and embrace the benefits provided by the integration of BIM and technologies in facility management from the perspective of emergency management. This paper starts from the insights provided by the current scientific literature and emphasizes the meaning, benefits, and challenges determined by the use of real-time systems in emergency management. Moreover, a systematic analysis of the specifications and requirements of real-time control systems applied to emergency management will be presented.

Technically, this contribution systematically investigates the requirements related to the design of realtime systems for the control of emergency management in complex buildings. The assessment was carried out within a model-based systems engineering framework, to address interactions among various components of the system as a whole. System Modeling Language (SysML) was selected as the modeling language. A first model was developed, and its potential has been discussed. Eventually, future research opportunities concerning the integration between SysML, BIM, and a simulation environment for requirements verification over the life cycle have been argued.

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Keywords: BIM, Decision-Making System, Emergency Management, Facility Management, Real-Time Control.

1. Introduction

Facility Management is inherently a management discipline that is articulated within the context of a very broad and disparate set of technical-operational domains. The most important areas of knowledge are maintenance, energy efficiency and sustainability, safety and resilience, organization, and usability of spaces. In addition to these purely technical areas, there is the economic-financial management of both current activities and new construction projects. Finally, at the top of this challenging pyramid is perhaps the most important organizational aspect, the management of the quality of the day-to-day service offered by facilities about their intended use and their ability to adapt to the sudden changes in the operational processes that take place there. Today, the holistic and managerial view of facility management, therefore, accompanies every phase of the building life cycle and represents a key competence of construction management engineering.

Although many studies have highlighted the importance of consistency and interoperability in facility management, the processes used in facilities still lack an adequate framework and data management to support informed and data-driven decision-making. The recent development of BIM-based information models is mainly limited within the boundaries of maintenance-oriented management models. Therefore, the development of a profound rethinking of the overall facility management requirements looks necessary, to outline a conceptual framework that allows all the technical, economicfinancial, and operational areas of facility management to be purposefully gathered on the same analysis matrix, to define a management model that enables a systematic and coherent vision of the structures they will be called upon to manage.

In this paper, we will discuss the application to Facility Management of an established System Engineering methodology known as Model-Based System Engineering. It is widely used in product lifecycle management in the manufacturing industry, where it is aimed at managing the complexity of large systems design. We will introduce the concept of the Facility Operating Model as a decision support tool for Facility Management and will give an example of its formulation using the SysML language to produce an abstract Facility Management model that can also be used as a basis for the evolution of the Model View Definition in the BIM environment.

2. A systematic approach to Facility Management

Much research was conducted throughout time for facility management. The target was to discover systematic approaches that the facility can benefit from. Based on prior literature review, BIM-based information models and Model-Based System Engineering (MBSE) showed promising results which will be presented below.

2.1. BIM-based information models in Facility Management

BIM is a detailed 3D geometrical model database with rich semantic information about the physical building that can be considered an ideal source to store data [1]–[3]. It was indicated that contributions of facility management in BIM are not equally researched. Operation and Maintenance is the most advanced section in facility management since the majority of areas are already identified and further modified, such as locating building components, facilitating the real-time performance, data access, visualization, and maintenance to name a few [4]–[7]. Analysis of such methodology approach shows a common pattern of implementation to any specific task within facility management [8].

Emergency management can be considered one of the least intervened within the BIM scope. The lack of sufficient information about the building's indoor environment and its emergency exit ways is a big challenge the facility manager faces in case of an emergency [9]. Promising studies were found regarding emergency facility management systems integration to BIM. For instance, dynamic simulations, emergency evacuation, and post-business operations [10].

2.2. The Model-Based System Engineering (MBSE) approach

Model-Based System Engineering (MBSE) is an interdisciplinary approach, which outlines a methodology and a set of means to enable the successful realization of complex systems. It focuses on defining customer needs and required functionalities early in the development cycle, on documentation requirements, and then proceeding with design synthesis and system validation while considering the complete problem, which is typically made of operations, cost and schedule, performance, training, and support, test, manufacturing, and disposal. Systems engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation. Systems engineering considers both the business and the technical needs of all customers to provide a quality product that meets users' needs [11].

MBSE is dependent on very common concepts: functional and structural analyses, interfaces, and behavior modeling. The outcome of MBSE-based design is a model where the relationships among user needs, system performance, functions, and system structure are clearly and unambiguously stated. From the facility management perspective, an MBSE grounded facility model has the potential of supporting most of the fundamental decisions of its operational framework. The facility management's main aim is to optimize facility operations concerning user needs. Therefore, at the core of the facility management role resides a Facility Operation Model (FOM) able to provide support for operation programming, solving the daily issues, and responding to unforeseen emergencies. The target is to

define how such an operating model works. Hence, two main aspects emerge: it must support Facility Management operation requirements and it must be integrated into the current BIM-based workflows.

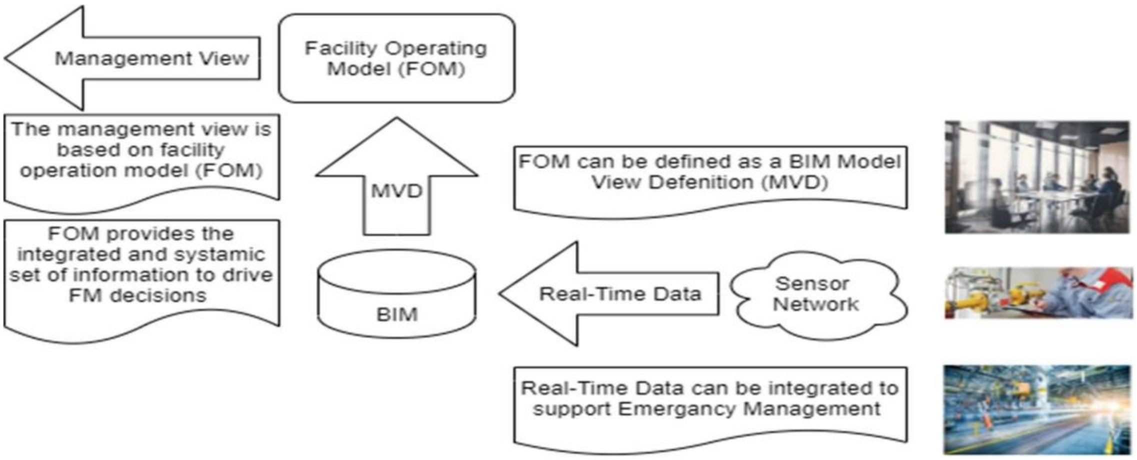

Fig. 1. A Model-Based System Engineering (MBSE) approach to Facility Management (FM)

As shown in figure 1, the MBSE approach could be used to define a Facility Operating Model (FOM) based on the complex FM requirements. The same model is then used as a basis to implement a Model View Definition according to IFC standards. Finally, an extension of the Digital Twin methodology must be considered to include real-time data management.

This is for sure a challenging research statement that requires a sound and widely practiced methodology such as the Model-Based System Engineering (MBSE). MBSE provides three main methodologies for the development of a Facility Operating Model (FOM). First, it introduces the fourpart requirements-Function-Behaviour-Structure conceptualization that allows the complex relationships between functional requirements and the physical structure of the facility to be captured. Secondly, it defines the various components at different levels of abstraction using a very expressive set of conceptualizations including component connections, events, behaviors, and other vital factors. Finally, it provides a visual language called SysML that allows complex models to be represented and their development steps to be automated.

3. SysML

SysML is a graphical modeling language developed in response to the unified modeling language for systems engineering. This language aims at supporting specifications, analysis, design, verification, and validation of systems that include hardware, software, data, personnel, procedures, and facilities. It is a visual modeling language that provides semantics where meaning is connected to a metamodel. As well as a standardized notation for the representation of meaning, graphical or textual [12].

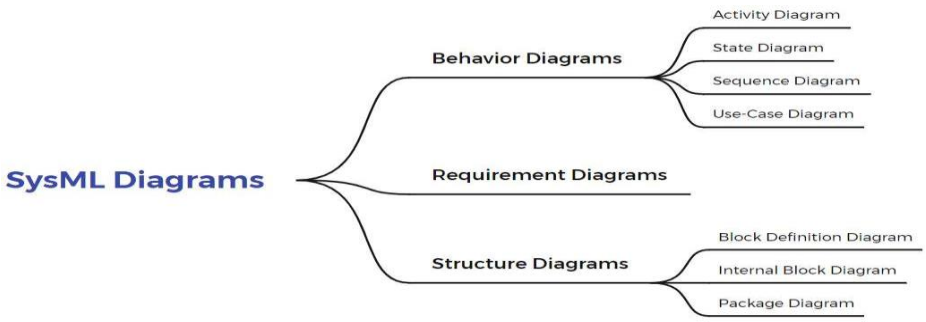

Fig. 2. SysML Diagrams [13]

Diagrams in SysML are mainly categorized into three main categories as shown in figure 2. The categories are based on their purpose, aim, and way of presentation. The main diagram categories are Behavior, Requirement, and Structure. Activity, State, Sequence, and Use case diagrams are grouped under behavior diagrams which reflect their purpose and goal. Block, Internal block, and package are categorized under structure diagrams which are focusing on the structure of the system as a whole. Last but not least, the Requirement diagram is managed as a third category of diagrams since it does not match the behavior or structure diagrams [14].

A package diagram is commonly used to organize the overall system engineering model, this is achieved by generating groups of model elements into namespaces. It is often converted into a tool browser that is typically connected with model configuration management (check-in/out). Three main organizational strategies can be adapted; system hierarchy such as enterprise and components, diagram kind such as requirements and use cases, and use viewpoints to augment model organization. Block definition and internal block diagrams are based on the UML class from the composite structure which supports unique features such as flow ports and value properties. Moreover, it provides a unifying concept to describe the structure of an element or system. Therefore, it can be adapted to any type of system/element, such as software, hardware, data, and procedure [15].

Last but not least, the Requirement diagram represents a text-based requirement that includes the definition of an identification and text properties. This diagram can have user-defined properties such as verification methods, the user can define the classification or hierarchy needed based on the categories assigned. For instance, functions, interface, and performance [16].

4. A SysML application example for fire emergency management

Organizations are exposed to a variety of threats, such as natural disasters, man-made disasters, man disasters, technical failures, data integrity penetration, damage to name or product reputation, unstable markets, or any combination of these factors. Any of these threats could cause a temporary halt in operations or a complete shutdown and collapse of the organization's business. It is vital that facility management (FM) professionals assess these threats, be prepared, and set strategic plans in place to guarantee facility users' safety with limited damages and the continuity of business operations.

From the facility manager's point of perspective, emergency management involves therefore high-level objectives that are articulated and/or qualify in several specific facility management activities, preliminary preparation (communication, asset, and service planning), Emergency response and recovery (control and mitigation), and business operations continuity. The management of complex articulated operations requires an overall view of processes and systems. Considering the inevitability of limited rationality of the predisposed subjects to management, it is therefore required in the system to help manage systemic complexity [17]. The complexity is revealed in the chance of indirect interactions between subsystems that cannot be predicted. Moreover, in the imperfect control of development or operational adjustments of technical systems.

This section will describe a FOM fragment example based on SysML to model the escape paths subsystem, according to the Italian technical fire prevention standards. This subsystem is functionally defined as a set of use cases located in the overall emergency management functional set. The example will be presented in the form of use cases, functional articulation of the fire escape of the facility, and the fire system maintenance management perspective. Basically, according to the Italian technical fire prevention standards, the purpose of the evacuation system is to guarantee that occupants can reach a place of ultimate safety, either autonomously or in an assisted mode [18].

The package diagrams presented in figure 3 (diagrams A and B) describe the organization of the use cases for this model, as indicated by the respective headers. Within the scope range of emergency management areas (figure 3 diagram A), fire safety management is the subject of this example. (figure 3 diagram B) shows the package structure that accommodates the use cases. Two of many were depicted in figure 3 diagrams C and D. Emphasis is set first on the role of the facility manager who is in charge of the building maintenance and implementation in the means of contracting services, which were made on several or different expert crews in charge of operations on assigned sub-systems. The second use case concerns steering evacuation operations, those who are involved in both appointed crews of selected members of expert staff internally to the organization in which reply on the occupant's behavior, therefore interaction with signs and instructions to find the best path towards safety.

Meanwhile, the compound mission statement requirement has been separated into simpler requirements in the form of decomposition, taking into account that this diagram is not included in this paper due to length limitations. The requirement diagram is depicted in figure 4 diagram A, showing a cohesive set of requirements explicitly stated and linked to the technical systems in which their satisfaction can be related to the sub-system design.

The notation allowed for integration tables provided directly by the Italian fire prevention standards. Technically, the diagram's purpose is to depict the derivation of requirements for the provision of adequate escape routes. The table indicates how one requirement can be derived from another, along with the rationale for the relationship, and recommendations from technical standards in this case.

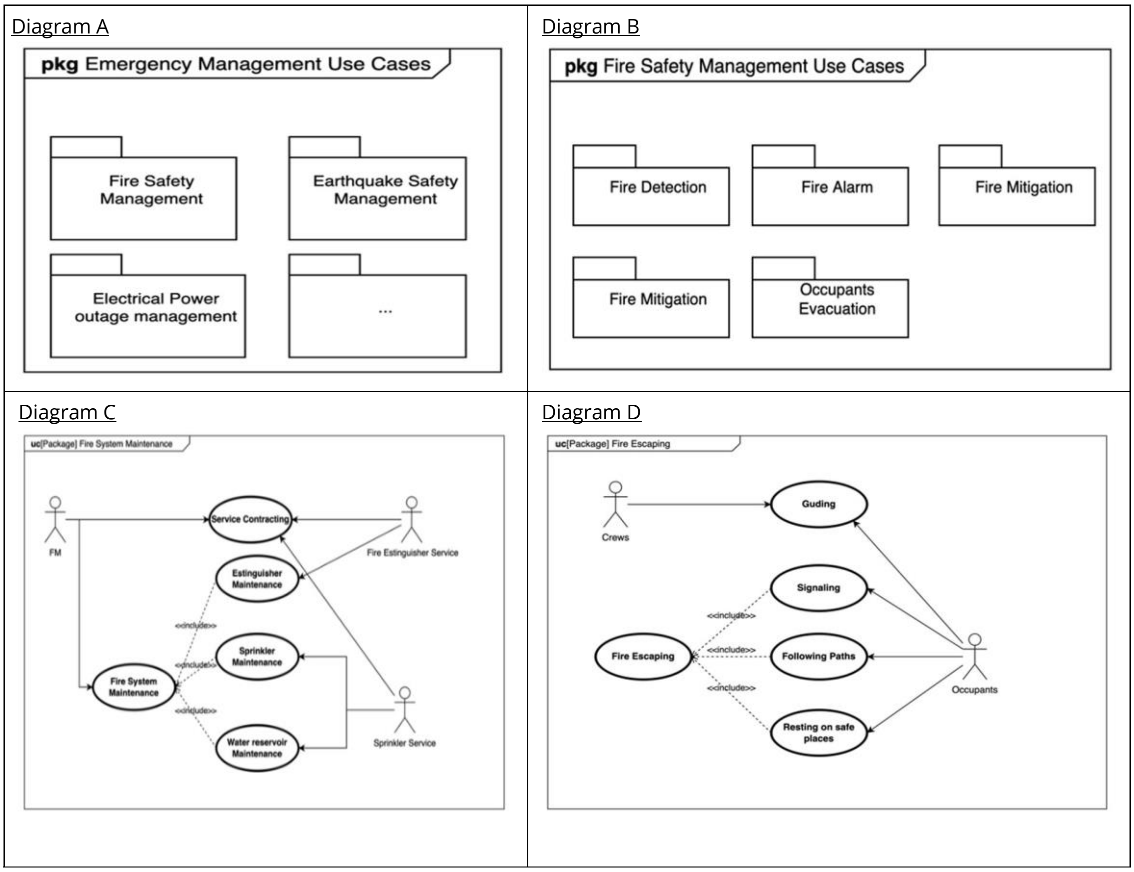

Fig. 3. Use Case packages

The behavior of the escape system (evacuation) can then be characterized based on functional requirements. Initial structural decomposition is provided as a block definition in figure 4 diagram B. The frame encloses a block hierarchy that is consistent with the overall sub-system decomposition of the essential components. The rationale for each component is provided in the diagram as well.

The input and output parameters of every function or block in the diagram can be represented as things flowing throughout the whole system. The space connected with the “escape path” is a changeable parameter that affects the integrity of the interested block. The current value can be monitored with the support of the BIM-based management system of the facility.

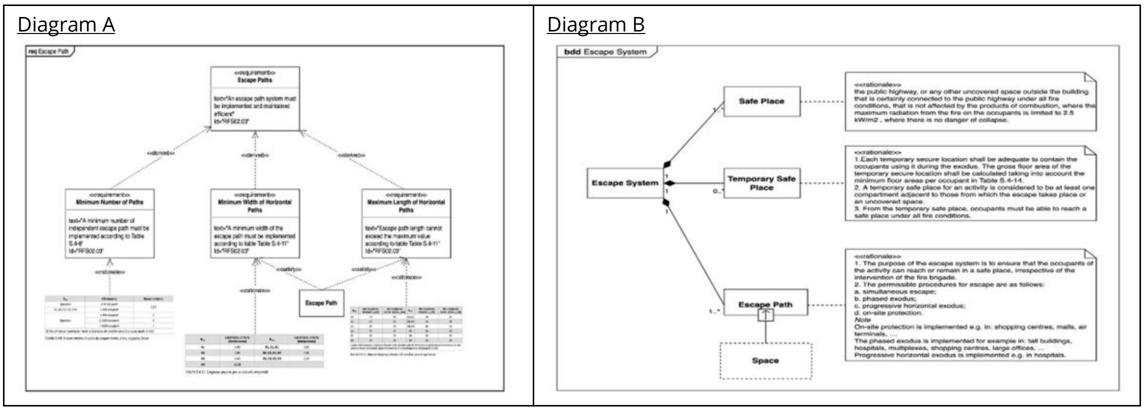

Fig. 4. Requirement Diagram (Diagram A) / Systematic Interface Between Blocks (Diagram B)

Based on the literature ground view of emergency facility management, the implied properties allow users to adapt filters and systems based on search rules applied regionally or internationally to isolate and display components of the system or sub-systems contributing to or being impacted by a maintenance emergency [19]. Taking into account all the obstacles, it was shown by published contributions that BIM-based support for emergency facility management systems is the qualified approach to the interface.

5. Conclusion

Facility managers deal with situations that need a direct response to minimize damages to the building or the occupants, therefore ignoring that most time spent on preparation for disasters. Understanding the dependencies across the different components of the building systems and sub-systems and being able to visualize (aided with 3D models) the expected interaction of the proposed system within the scope of emergency is crucial. The facility management staff be able to determine the impact of the emergency across the facility rapidly and accurately.

This paper has been evolving based on existing literature and theories, developing a multi-level system for the facility that meets the specifications of the local authorities and government bodies. Also implied in this contribution have been the possibilities and benefits of interfacing with a digital model such as BIM/AIM, which would allow the opportunity of the facility management staff to respond to escape emergency events by isolating the necessary elements and systems related to the emergency, and display these elements explicitly while isolating other model elements.

The authors are planning future research to further study the development of emergency system models. Enhancing the system model will also be done and will act as a proof of concept of interfacing BIM with the emergency management to identify the possible issues and detect immediate matters with the current approach and develop solutions to address the issues faced in the process.

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A Review and Comparison of Strategy Diffusion (Top-Down) and Performance (Bottom-Up) in Project-Based Organisations

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Abstract

Many studies have investigated topics related to strategy management, portfolio management, program management, and project management relationships. However, traditional one-way cascading of the strategy is still preferable by many organisations, with few studies investigating the use of top-down and bottom-up techniques to spread an organisation's strategy and getting back the performance, or the possibility of employing one of diffusion theories (e.g., Rogers' Theory of Innovation Diffusion) within strategy or project contexts in project-based organisations. Therefore, the need to understand and apply a strategy diffusion (top-down) and report its performance (bottom-up) was urgent and necessary within project-based organisations, to fulfil the complete drive of the strategy and raise the competitive advantage of businesses.

Thus, this article displays the possibility of matching the Rogers' innovation diffusion theory key terms, elements, characteristics, and decision process stages with the strategy management elements, characteristics, and process stages, which provides theoretical underpinning of the similarity of innovation diffusion and strategy diffusion concepts.

Then, it will show the similarity of the meaning for the four innovation diffusion elements (innovation, communication channels, time and social system) in Rogers' diffusion theory and in David's strategy management model. After that, this study will provide the characteristics' meanings of compatibility, relative advantage, complexity, observability and trialability in Rogers' innovation diffusion theory and the parallel characteristics' meanings (consistency, advantage, clarity, visibility consonance and feasibility) in David's strategic management model. These have different terminologies but the same meanings.

This is to support and confirm the possibility of the study proposed concept of utilising Rogers' diffusion theory for strategy diffusion within project context as top-down method in a project-based organisation.

Finally, the paper explains the detailed bottom-up arrangement from project to program to portfolio and up to the strategy level, which shows the possibility of the bottom-up approach in project-based organisations; this is done in order to fulfil the necessity of improving organisational performance.

All that paves the road for coming up with a conceptual framework proposal. Also, allows solving the research problem, which is the absence of a robust framework for strategy diffusing process that could impact the strategy translation, improvement, and completion the full strategy management cycle in project-based organisations.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2022.

Keywords: Portfolio management, program management, project management, Roger's diffusion theory, strategic management model.

1. Introduction

1.1. Study background to the study problem

Despite the important role of the strategy diffusion process in strategic management, empirical research focusing on project-based organisations in the area of strategy diffusion has been limited. This study seeks to delve deeper to understand the impact of strategy diffusion on organisational performance within project-based organisations. It initiates from the ambition to contribute to what is recognised about the science of strategy management in strategic diffusion practices to improve the ultimate outcomes of project-based organisations in this competitive business world.

Competition in today's world has developed due to various concepts, such as rapid technological changes, changing customer expectancies, new markets and globalization. Therefore, current businesses are enforced to think strategically more often and make faster decisions by applying more strategy management [16]. This is to say that strategic management has become one of the most significant current discussions within businesses [16] especially the strategic distribution part, where the value of the strategic distribution has grabbed more and more attention in society and corporations [18].

The organisational strategy needs to be understood by all staff at all levels of governance within the organisations very well, in order to implement their daily business in a way that contributes to the success of that strategy. In project management literature, an organisational strategy is increasingly delivered through the portfolio to program and project levels, as portfolios focus on the oversight and holistic management of projects, where it also has often been conceptualised as simply being implementation sites on organisational strategy [8,30]. Therefore, despite the importance of strategy for all levels of a project-based organisation, it has been recognised. Yet, strategy remains a theoretical and operationally challenged concept [30].

Strategy management classically uses top-down perception to make sense of the collaborations amongst portfolios, programs, and projects [8]. But several scholars have criticized the common top-down, one-dimensional standpoints of strategy in the project-management literature [30], as the traditional (top-down) approach in project management focuses on rational structural aspects of strategizing, which leads to losing the focus on the fundamental practices and processes that are initiated by the strategy and how these practices and processes frame strategy implementation [8]. Thus, any bad management systems or usage of unworthy exercises can destroy the organisation, for example, through unrelated explanations or reports about what actually is happening with these companies, or because of the absence of a robust platform on which administration or top manager action must be. Moreover, several corporations suffer from a lack of an efficient method to align the business strategy with project management, which leads to misaligned projects. In addition, unfortunately, most studies in diffusion theories have only been carried out in a small number of areas in relation to strategic management, which leads to calling for enhancing the field's understanding about the interface between strategy and diffusion [26]. Some scholars start constructing knowledge about the position of strategic diffusion for the success and survival of organisations [26,18]. In addition, today's economical scholars who are interested in project-based organising have increased the calls for more investigation of strategic management research and its theoretical implications [7]. Several scholars have called for research into the interrelationships between projects and their parent organisation (strategy) rather than a site of 'strategy execution separately [30].

Subsequently, the emergence of using a diffusion strategy (top-down) and (bottom-up) is imperative, so that the diffusion process can be significantly accelerated, and the organisational strategy will be translated, improvised and made sensible. This will also fulfil the complete drive of strategy [8,30], especially as the professional strategy diffusion is the right method to help practitioners to enhance their tasks and activities, contribute more to their organisational strategic objectives, and enhance their organisational outcomes [24]. Similarly, project management levels should know about their corporate aspect of their projects to know how to deal with it, in order to support their top strategy, understand the corporate needs; ultimately, this will lead to customer satisfaction and achieving business success [37]. Thus, a bi-directional link between strategy, projects, and project portfolio management is suggested in the literature on the practicing of strategy over projects, and the ability of project portfolio and project actions and processes to update the strategy [22]. Furthermore, it will build on continuous mixes of bottom-up learning from projects-to-organisation and top-down strategic decision-making from organisation-to-projects [30].

Thus, a strategy concept with diffusion may help in bridging the gap related to the above argument about the utilisation of the strategy diffusion practice as a top-down approach. This can spread the organisational strategy and support reporting performance bottom-up, to learn the lessons and to make decisions accordingly, which will lead confidently to increase all organisational performance indicators. This research seeks to better model the relationships among strategy diffusion top-down, performance reporting bottom-up, and firm performance.

1.2. Study aim

The aim of this study is mainly to show the thorough mapping of the five diffusion decision process that consists of knowledge, persuasion, decision, implementation, and adaptation stages, which are adopted from Rogers' diffusion theory, with the strategic management three phases that consist of formulation, implementation, and evaluation that taken from David's strategic management model at each of the project-based organisation hieratical levels for strategy, portfolio, program and project levels as a top-down perspective.

1.3. Study objectives

This is to confirm validation about the concepts similarity of innovation diffusion and strategy diffusion, which can be utilised in future for developing an appropriate model that can ensure diffusing of the organisational strategy considering the presence of organisational involvement culture dimensions. This is in order to embed, translate and contribute that strategy in the organisation daily activities at all levels, as well as to confirm reporting back all performance and lessons learnt at all levels; for better decision-making and adjustment of the strategy, which ultimately will lead to enhanced and increased organisational performance (including financial, product market, shareholder return and stakeholder satisfaction) in project-based organisations [8,30,24].

2. Study main concepts

2.1. Strategy management

Fred David's model called the strategic management comprehensive models since 1999 is one of the famous models in strategic management. Based on Fred David's strategic management model, the process contains three phases, precisely, strategy formulation, strategy implementation, and strategy evaluation, see Fig. 1.

Strategy formulation, which known also as strategic planning, is the first stage of the strategic management process in David's Model. It participates in the number of sub-phases: development of vision and mission statements of the entity, execute internal and external audit, the creation of long-term objectives, and finally generation, evaluation, and selection of company strategies. The next stage, is commonly known as strategy implementation, comprises activities like launching yearly objectives, allocating resources, and developing policies for every business role, and so on. Actually, in this stage, the company's objectives are being implemented, to achieve the organisational objectives. Strategy evaluation is the last stage of the strategic management process, where it involves company performance measuring and evaluation, accordingly, any changes or corrective actions can be taken for the strategy [10].

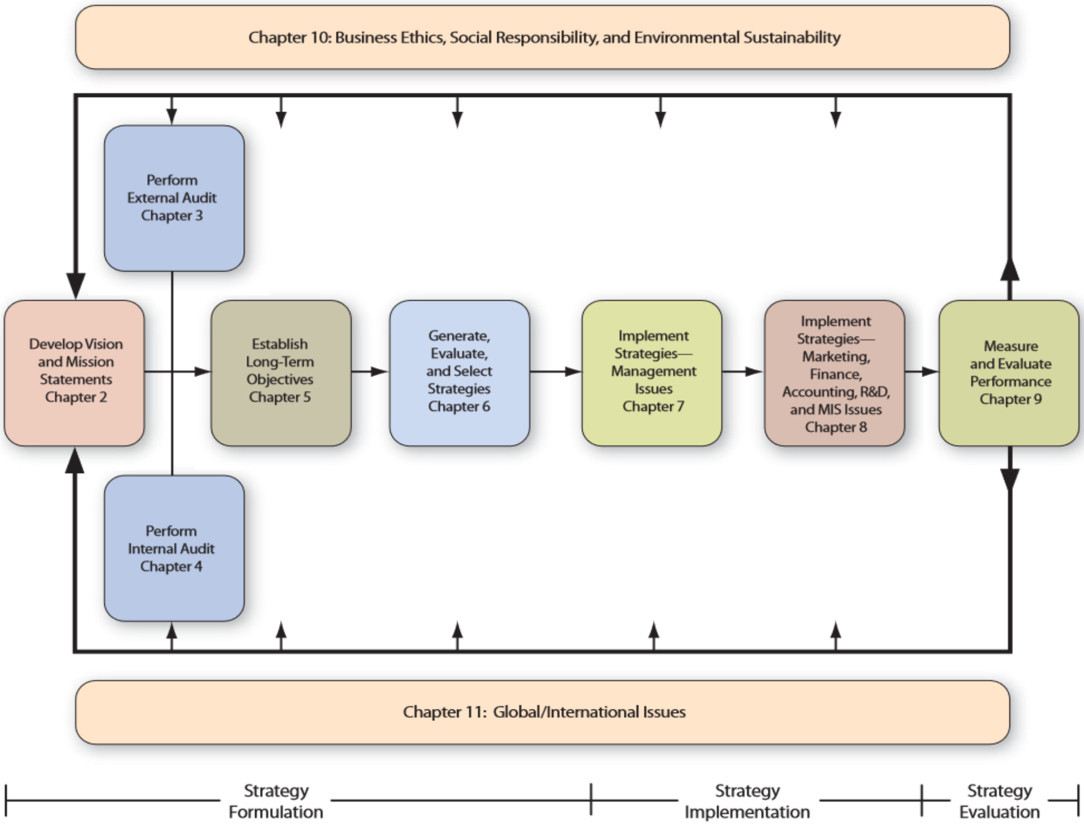

Fig. 1. A comprehensive strategic-management model [10].

Furthermore, [33] utilised David's strategy model to investigate the impact of strategic management on a firm's development and growth and found that there is a significant effect on employee performance and boost in organisational performance and competitiveness. This is because David's model of strategy is one of the more famous strategic models due to its appropriateness with a number of other theories that facilitate project management; such as, contingency theory, resource-based theories, and profit-maximising and competition-based theory, in which, profit-maximising and competition-based theory are referred to the concept that business organisation's key goal is to achieve long-term profit and emerging sustainable competitive advantage in the marketplace.

On the other hand, the resource-based theory refers to the internal resources, their capabilities, and they have the potential to establish competitive advantage and eventually improve organisational performance. Furthermore, the contingency theory refers to how firms should develop managerial strategy based on the situation they are facing; as there is no single idea or way to manage the organisation [33].

2.2. Rogers' diffusion theory process

As indicated by [42,15], the diffusion of innovation process was built up via certain communication channels over time by members of a community structure.

[41,15] identified and described the five stages of diffusion or the communication channels at the individual level occurring as shown in Fig. 2. These include: 1) Knowledge or Awareness Stage, where an individual is open to innovation, but without full information; 2) Persuasion or Interest Stage, where an individual shows more and more interest about the new idea and wants more data about it; 3) Decision or Evaluation Stage, where an individual uses innovation spiritually and expects the upcoming condition, and then selects whether or not to go for it; 4) Implementation or Trial Stage, where an individual fully uses the invention; and 5) Confirmation or Adoption Stage, where an individual chooses to fully use innovation.

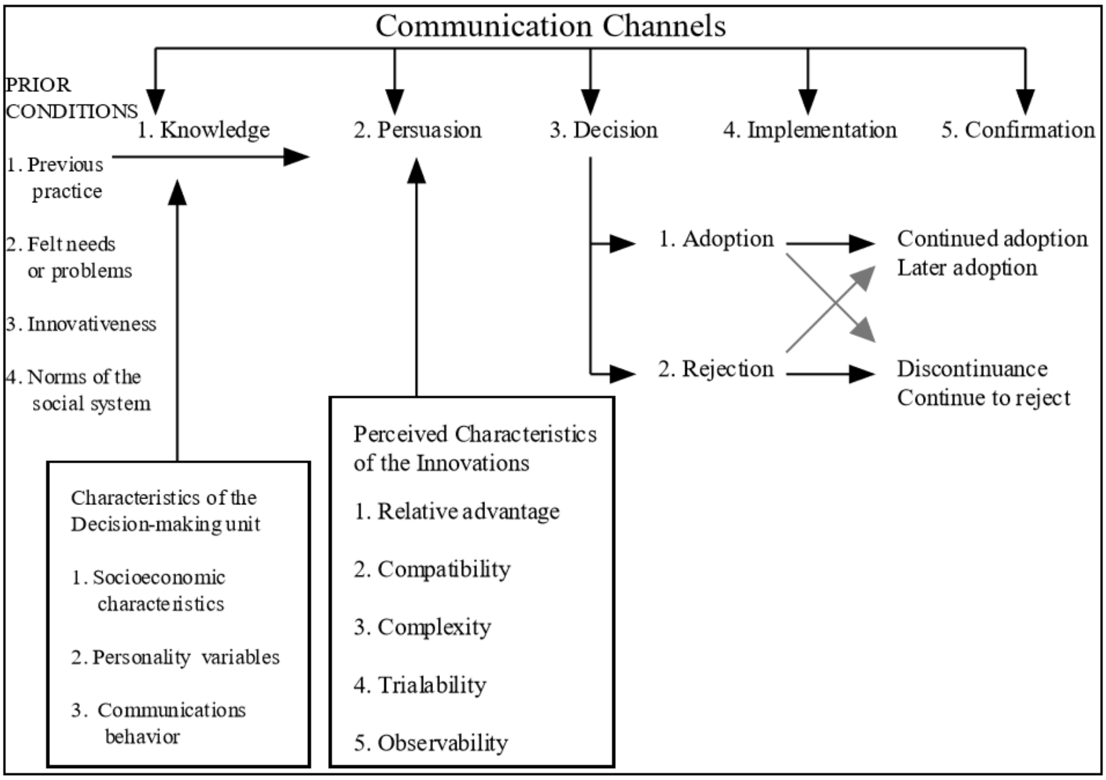

Fig. 2. Decision process stages of diffusion theory [41].

Elements that could influence diffusion amounts contain the features of the adopter, the features of the promoters, the communication process, the social network, and the innovation aspects that influence an individual's decision, when persuading to adopt an innovation. These may include observability, complexity, relative advantage, compatibility, trial ability [15]. Furthermore, [41] identified four elements for the diffusion, as following: innovation, communication system, time, and social system.

2.3. Performance management

Performance management was defined by Armstrong in 1999 as "a systematic approach to improving and developing individuals and teams' performances and capacities in order to increase efficiency throughout the organisation". Several studies mentioned that the performance measures come from top organisation goals and objectives and developed into project business case. These measurements provide a proper guidance to project teams and offer a useful roadmap for results-focused planning. Thus, project performance measurement needs to put attention on the project management method and the project results [9].

Most early studies as well as current works focus on the alignment between project management and strategy of the firm, in order to achieve effective project outcomes and at the same time to gain more business success and a competitive advantage (e.g., [48]). Equally, the oft-promoted wisdom that says, "if you can't measure it, you can't manage it" (Peter Drucker). Consequently, this study addresses the essential need for strategic performance management, portfolio performance management, program performance management, and project performance management, in order to measure the organisational performance in much effective method.

2.4. Organizational culture

Organisational culture is very important aspect of a firm's success as it enhances the support and cooperation culture within the firms. Furthermore, it is an essential instrument for organisational knowledge sharing and learning. In order to accomplish a high-quality performance, organisational culture can offer a countless support to the organisation. Moreover, there are many practices linked to organisational culture like team and individual performance, change management, quality management system, and project management [35].

Studies of Denison and his colleagues are well documented, in which it is also well acknowledged that organisational culture includes mission, adaptability, involvement, and consistency [35,1]. See Fig. 3. for the Denison model of organisational culture, where mission dimension is defined as a clear sense of organisation about its purpose and vision that identify organisational strategic objectives and goals. The adaptability dimension occurs when organisation has ability to adapt changes, organisational learning, and customer focus for organisational improvements purposes. Consistency dimension is about the strong culture of well-integrated, well-coordinated, with high degree of agreement among the organisation people. And, involvement dimension is about people empowerment, capability building and teams [12].

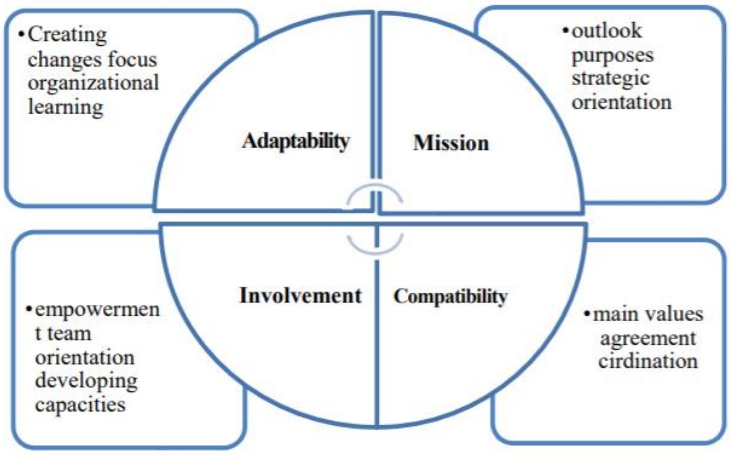

Fig. 3. Organisational culture of Denison [1].

For this study, Denison's model will be used to measure the cultural aspect of the organisation, as the core of the model is the underlying assumptions and beliefs, where the deepest levels of organisational culture are represented.

2.5. Project management concept

A series of recent studies indicated that there are three directions of study in the literature of project management to reformulate project management in such settings. The first direction has highlighted the importance of an exploration phase in projects to allow requirements and specifications to emerge through learning, trial and error [14]; the second direction has highlighted the need to link project management to firm strategizing by, for example, project portfolio selection and decision making methods [20,31,36]; and the third direction has highlighted the critical role of stakeholders and the need to mobilise them to build the political context in which the project will develop [49].

Project-based organisation points to a diversity of organisational forms that contribute to the system related to project activities and performance. Lately, more attention has focused on project-based organisations as a contracture, where project-based organisations need to utilise approaches that enable structures, deliver strategy, and unify the knowledge, in order to develop a common language that fosters the exchange of ideas. Many project-based organisations have moved from managing single projects to multiple project management, and from a "contained" project management prototypical to more strategic perception. Furthermore, now it is well-known that the establishment of project, program, and portfolio management within project-based organisations, see Fig. 4. for the typical project-based organisational structure is explained in recent project management literature. In summary, project-based organisations still need more exploration on the associations between the field of project and general management and more investigation regarding the two-way relationships between them to check the influence of organisational practices [47].

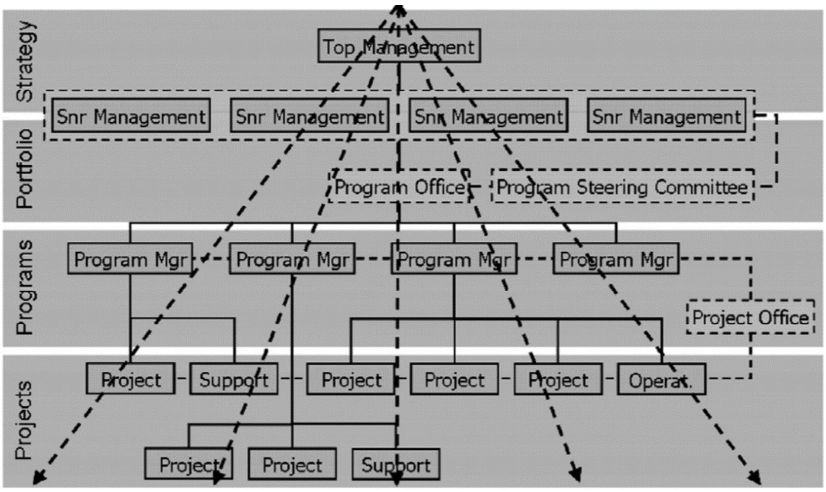

Fig. 4. Project-based organisation model [47].

As the management of multiple projects, such as project management and portfolio management, is now the leading structure in many companies for strategy implementation, business renovation, new product expansion and constant enhancement [51,48].

Although there are many studies, the research in top-down and bottom up approaches remains limited. However, few studies employed the top-down and bottom up approaches in change management, knowledge management and project portfolio management [29]. Based on [29] the relationships between strategy management, portfolio management and project management were explained, as shown in Fig. 5. These types of studies considered how to work on similar ideas for strategy spreading within project-based organisations.

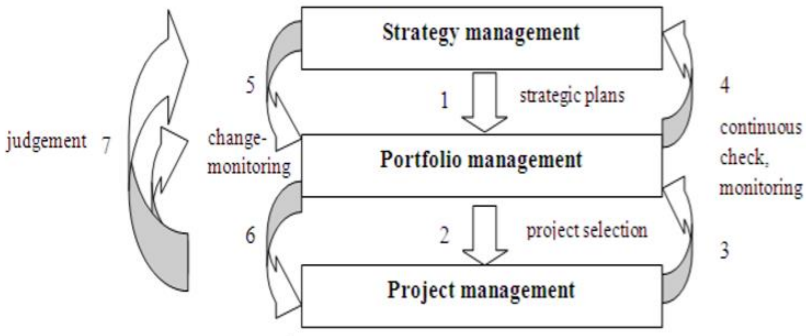

Fig. 5. Relations of strategy, portfolio and project management [29].

3. Research outline

The study objective required a review of strategic management theories and aligning them with business strategy and organisational project management levels. Thus, based on [33], David's strategic management model was a proper framework to utilise for this research as it is a mixture of strategy formulation, implementation and evaluation, which is effective for all types of organisations specially for project management.

Likewise, since Rogers' diffusion theory is the most popular theory in diffusing and spreading practiced and shows its effectiveness within a quite good number of different fields. Furthermore, Rogers' diffusion theory offers a useful theoretical model to support the planning and implementation of any new improvement [15]. It is aligned with the research objective to appraise diffusion theories and assess the suitability of the selected theory for strategy diffusion in project-based organisations. Therefore, Rogers' diffusion model has been used to be imbedded in the suggested system for this study.

Finally, in regard to project management, several literature reviews have been studied in order to define portfolio, program, and project management, to understand more about their main roles, and to explore more about their linkages amongst the portfolio, program, and project terms and the corporate direction. Accordingly, another objective for this study was settled through checking project management models for the appropriate viewpoints of diffusing or spreading the strategy, which is the utilisation of the (top-down and bottom-up) approaches.

In sum, there will be an effort for this research to plan a relative structure of business layers (strategic level, business unit level including portfolio level, then program and project level), and all the intended levels are intersected with the three strategic phases from formulation, implementation, to evaluation. Moreover, for all top-down strategy phases, Rogers' diffusion theory will be utilised to diffuse the strategy from a top-down approach. To be more specific, it is suggested that for the (top-down) approach, the strategic "initiatives" will be spread by adopting Rogers' diffusion theory within each strategy phase, starting from the enterprise level to business unit project portfolio management, reaching to program and project levels. Then, for the bottom-up part, "performance" will be reported to higher levels, as the data will be going upward to the next level above it and so on until it reaches the organisational top level. See Fig. 6. more explanation about the proposed research outline, where the strategy initiatives have been diffused from top levels to down levels, so that each level knows their links to the organisational strategy and to know their precise roles and activities. It is then required to identify the outputs and outcomes (performance) at each level, which are to be reported to the levels above. Finally, and as an ultimate goal for doing so, is to improve the organisational performance for the project-based firms, considering the culture of the organisation and how this influences the overall system.

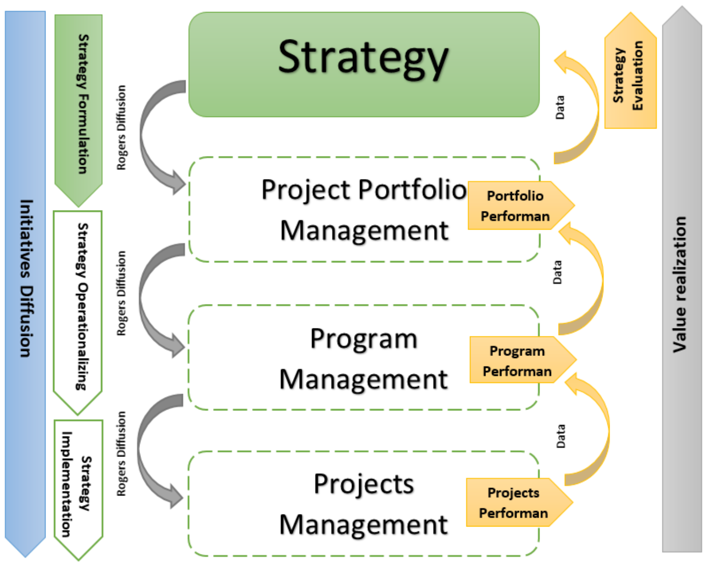

Fig. 6. Research proposed outline.

4. Integrated structure of a project-based organisation

Many researchers argue that to function effectively, a project-based organisation needs enthusiasm and flexibility in the way programs and projects link upwards with business strategy. Hence, there needs to be cooperation among project and organisational top-level management. Again, there should be horizontal and vertical integration processes in order to connect business strategy and project activities. Horizontal integration can be ensured via successfully completion of the project life cycle, however vertical integration will bond project processes and activities to business strategy [47,29], as demonstrated in Fig. 7.

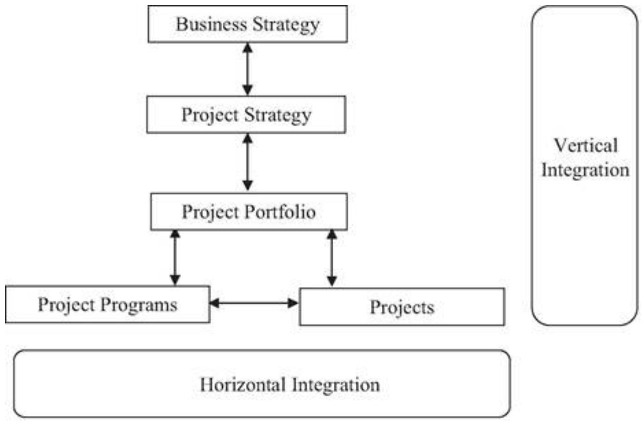

Fig. 7. Integrated structure of a project-based organisation [47].

Likewise, [4] advised that one of the managerial challenges in fitting project management with corporate strategy is to encourage individuals to participate in strategy development practice via creating new ideas and in order to renew current strategies.

Moreover, the literature review shows that firms implement their transformation practices on three levels: portfolio, program and project. Clearly, these levels have dissimilar purposes but must work consistently to deliver transformations successfully [11]. Furthermore, to indicate the importance of utilising the top-down and bottom-up approaches, a risk-intelligent approach was highlighted by [11], where they encouraged organisations to utilise a top-down approach by top level management. This was encouraged to identify risks at a strategic level, whereas risk owners in business units practice a bottom-up approach; to identify and monitor exact risk, escalate fears and create the risk-related statistics to leaderships strategic view.

Strategy diffusion (top-down) and performance (bottom-up) approaches at each project-based organisation level at strategy, portfolio, program and project, practices for both methods will be the main focus of this chapter. Therefore, there will be a detailed description about the strategy diffusion (top-down) method, where the diffusion theory will be integrated with the strategy management stages and then the combined model will be mapped to each level of the organisation's practices. Specifically, there will be a mapping of the five communication channels steps of Rogers' diffusion theory and the three David strategy management phases with each management level of the intended organisational hierarchy from strategic management level, to portfolio management level, then program management level, reaching to the project management level. In the same way, there will a comprehensive detail about the performance (bottom-up) approach, in which the important data and results will feed the level above it according to the project-based organisational hieratical structure till it reaches the top level of the organisation. In this study the focus is on the strategic initiatives which will be the element of the diffusion from the top level of the organisation to the execution level (portfolio), as the strategic initiatives are the core of strategic management. Furthermore, strategic initiatives can be represented by various forms like product development, new processes, major reorganisations, or projects. Therefore, these initiatives in this study have turned into projects for further diffusion purpose at the execution levels, while the performance data will be the feedback element from down level to top level of the organisation [50].

In summary, a top-down diffusion and bottom-up performance link between strategy, projects, and project portfolio management is suggested in the literature for the practicing of strategy over projects and the ability of project portfolio and project actions and processes to update strategy [22].

5. Rogers' diffusion theory and David's strategic management model integration

In this section, there will be further elaborations regarding the possibility of matching Rogers' diffusion theory key terms, elements, characteristics, and decision process stages with the strategy management facets.

There was evidence by [21] for the utilisation of Rogers' diffusion theory in the context of strategy and project management for educational innovation projects, where the strategy implementation often results in the change of identification and innovative projects, and the certainty is also involved in this formula.

5.1. Strategic management and the four main elements of Rogers' diffusion theory

Rogers [42 p. 5] defined diffusion as "the process in which an innovation is communicated thorough certain channels over time among the members of a social system". Therefore, as mentioned in this statement the four key elements of the diffusion are innovation, communication channels, time, and social system.

- ***Innovation****: for Rogers [42], innovation definition is "an idea, practice, or project that is perceived as new by an individual or other unit of adoption" [42 p. 12]. The idea, practice, or project terms in strategic management are synonym to objectives, products, goals, and initiatives terms [10]. Thus, it is clear that strategic decision to "adopt an innovation" happens only when a "shared vision" is approved over a mixture of top-down and bottom-up courses [21].*
- ***Communication channels****: Rogers [42 p. 5] defined communication as "a process in which participants create and share information with one another in order to reach a mutual understanding," with two ways of communication; mass communication and interpersonal communication. Likewise, in the setting of strategic management, in order to support a firm main role as a competitive team, communication and interaction adaptation between managers and employees across hierarchical levels are a must. This is because boosted communication provides deeper understanding of the strategies, which leads to higher commitment as a consequence, offering effective outcomes. Therefore, communication is crucial to successful strategic management. Moreover, top-down flow of communication is important to encourage and develop bottom-up support [10].*
- ***Time****: The innovation-diffusion process, rate of adoptions, and adopter categorization all contain a time aspect. Furthermore, in strategic management there is a long-term objective, where the time frame should be reliable, usually from two to five years. In addition, there are short-term objectives, and the time frame for those objectives are less. Equally, in the strategy implementation stage the time aspect is crucial for deploying the strategic initiatives or projects. Moreover, the time dimension also must be considered for the monitoring, controlling, and measuring performance in the strategy evaluation stage [10].*
- ***Social system****: Rogers [42 p.23] defined the social system as "a set of interrelated units engaged in joint problem solving to accomplish a common goal." Similarly, in the strategic management field, strategy formulation, implementation, and evaluation events happen at three hierarchical levels in a large organisation: enterprise, divisional or strategic business unit, and functional, sharing the same challenges to be solved and same objective to be achieved within targeted time [10].*

5.2. Strategic management and the five characteristics of Rogers' diffusion theory

As per [42 p. 232], the process of innovation-diffusion is "an uncertainty reduction process", and he recommended number of attributes of innovations that could support in reducing the innovation uncertainty. Attributes of innovations consist of five characteristics of innovations: compatibility, relative advantage, complexity, observability, and trialability. Moreover, [42 p. 219] indicated that "individuals' perceptions of these characteristics predict the rate of adoption of innovations".

In [42 p. 229] diffusion theory relative advantage is defined as "the degree to which an innovation is perceived as being better than the idea it supersedes." Compatibility is defined as "the degree to which an innovation is perceived as consistent with the existing values, past experiences, and needs of potential adopters" (p. 15). Complexity is defined as "the degree to which an innovation is perceived as relatively difficult to understand and use" (p. 15). Trialability is defined as "the degree to which an innovation may be experimented with on a limited basis" (p. 16). Moreover, observability is defined as "the degree to which the results of an innovation are visible to others" (p. 16).

On the other hand, the same characteristics can be found in strategic management features as indicated by [43], which are: advantage, consistency, consonance, clarity, feasibility, and visibility. Advantage means that strategy must deliver for the foundation and up keeping of a competitive advantage in the chosen area of activity. Consistency in strategy means to provide consistent goals and policies. In consonance, the strategy must show an adaptive reaction to the exterior environment and to the serious modifications happening inside it. Moreover, strategy mission, vision and objectives should be clear to have the right foundation for all strategic planning, implantation and evaluation undertakings, as well as to have same direction, achieve support, synergy, clarity, and gain higher performance among all levels of company. Additionally, feasibility of the strategy must provide the right resources availability and avoid forming unsolvable sub complications. Therefore, over-all, strategic objectives should be challenging, consistent measurable, clear and realistic [10].

5.3. Strategy formulation phase

Many researchers have argued that the smart strategic planner in strategic-focused companies let their firms' strategies to adapt the changes as per the organisational dynamic environment needs. Clearly, to do so, there is a need for a strong platform that knows about how organisations improve their business value consistently, where leadership makes superior choices about the best shape of their portfolios, and lastly understands more about their firm's distinguished capabilities [19].

The process of founding shared meaning is far from the "cascade of plans". However, it is very much linked with the learning process; thus, the strategic decision about the current or new initiatives requires buy-in from the organisation's individuals [21]. Hence, [42 p. 172] explained the process of innovation-decision as "an information-seeking and information-processing activity, where an individual is motivated to reduce uncertainty about the advantages and disadvantages of an innovation".

The innovation-decision process in Rogers' diffusion theory of five stages, which naturally follow each other in a time-ordered method are involved knowledge, persuasion, decision, implementation, and confirmation. Consequently, in order to attempt to diffuse the strategy in this study, the mapping has been conducted between Rogers' theory adoption decision process stages with David's strategy formulation phase, as per the following:

- ***The Knowledge Stage (Awareness):*** *knowing the business's general direction (vision and mission). Developing a vision (what do we want to become? What is our business?) Additionally, setting a mission is required (what we need? How? Why?) [10].*
- ***The Persuasion Stage (Interest):*** *Future external and internal details assessments; offering the fundamental information, facts, trends, and events for creating objectives and strategies. The main purpose of it is to set a defined number of opportunities that could benefits an organisation with the list of threats that should be avoided. Plus, it provides a list of weaknesses that could be translated into a number of objectives via using the defined strengths in this stage. Furthermore, it can let participants establish a clear idea about their jobs and how they fit into the whole organisation [10].*
- ***The Decision Stage (Evaluation):*** *Generate evaluation and select strategies in this stage via using a three-stage decision making model. Stage 1 (Input Stage) is the fundamental input data required to express strategies. Stage 2 (the Matching Stage) focuses on generating practicable different strategies by aligning important internal and external factors. Stage 3 (Decision Stage) involves tools and techniques, like the Quantitative Strategic Planning Matrix, in order to offer a rational basis for choosing precise strategies [10]. This is followed by deciding to create Long-Term Objectives (Financial or Strategic objectives) via using different strategies approaches that might benefit the firm [10].*
- ***The Implementation Stage (Trail):*** *Strategic planning is typically established on expectations and theories that are repeatedly verified and polished by research, knowledge, learning and experience [10].*
- ***The Adoption Stage (Confirmation):*** *Confirm the Long-Term Objectives (Financial or Strategic objectives) [10].*

Table 1. Comparison between Rogers' theory and strategic formulation stage.

Rogers diffusion theory (The adoption - Decision Process)	Rogers diffusion theory definitions [42]	David's Strategy Formulation Phase [10]

The Knowledge Stage (Awareness)	During this stage, the individual tries to define the innovation and how and why it works.	Knowing business general directions, vision and mission.
The Persuasion Stage (Interest)	Develops interest; gathers more information and facts about it.	External and Internal details Assessments.
The Decision Stage (Evaluation)	Mental trial; after getting all the information from previous stage. Individual selects to accepts or reject it. Or to active rejection or passive rejection.	Generate, evaluate, and select strategies in this stage. Use a three-stage decision making framework. Stage 1 (Input Stage), Stage 2 (the Matching Stage), and Stage 3 (Decision Stage).
The Implementation Stage (Trail)	Innovation put into practice; uncertainty and reinvention can occur in this stage; to change or modify the new idea.	Establish Long-Term Objectives (Financial or Strategic objectives).
The Adoption Stage (Confirmation)	Large-scale, continued use; satisfaction.	Confirm the Long-Term Objectives (Financial or Strategic objectives).

Furthermore, as indicated by [22] that the relationships between strategy management, project management, program management and project portfolio management are well-known and have been discovered in the lots of literature for more than 20 years by many scholars.

Hence, after aligning the diffusion with strategy formulation phase, it is now very much useful to use the same technique in fitting the strategy diffusion at the levels of strategy level, portfolio level, program level, and project level, through diffusing the strategic initiative formed from the strategy planning stage to all organisational levels. The coming sections are the important parts that involve diffusion purposes of the organisational strategic initiatives at each level of the organisation for this research.

6. Strategy diffusion (top-down) alignment

More studies have confirmed that it is very important that the firms know correctly their business management framework and the location of their portfolio, program and projects management within it [32]. A number of scholars [4,32,47,11,17,50] outlined many practices and processes for governing the strategic, portfolio, program, and project connections in multi-project settings.

Traditionally, a pyramidal structure has been seen in project-based organisations, where management debating converted to project discussion. By the time, the practical implementation was renewed in such a way that supported in appearance of the top-down style within project management organisations, where, the style suggested a cascading arrangement from the top management down to a single project, going through the portfolios and programs. In addition, the board of directors in the company can control the portfolio environment, classify programs, and accept projects for improvement. In Fig. 8. there is an individual portfolio, a minor quantity of programs inside the portfolio, and some projects contained by each program, where a synergy is formed amongst the projects [47].

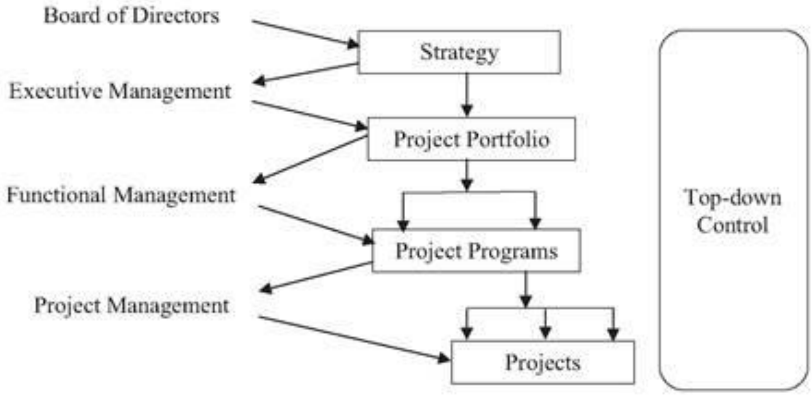

Fig. 8. The pyramid structure of a project-based organisation [47].

Additionally, according to [32] a hierarchy of objectives, strategies and strategic initiatives can usually be created as an output of a planning strategy phase; which can strongly affect the means of configuring, strategy managing and communicating it to the association. As shown in Fig. 9. the cascading process is proposed to show how organisations locate business strategy, portfolios, programs, and projects to accomplish their objectives and goals. As a result of these literatures suggestions, the equivalent top-down model has been adapted in this research.

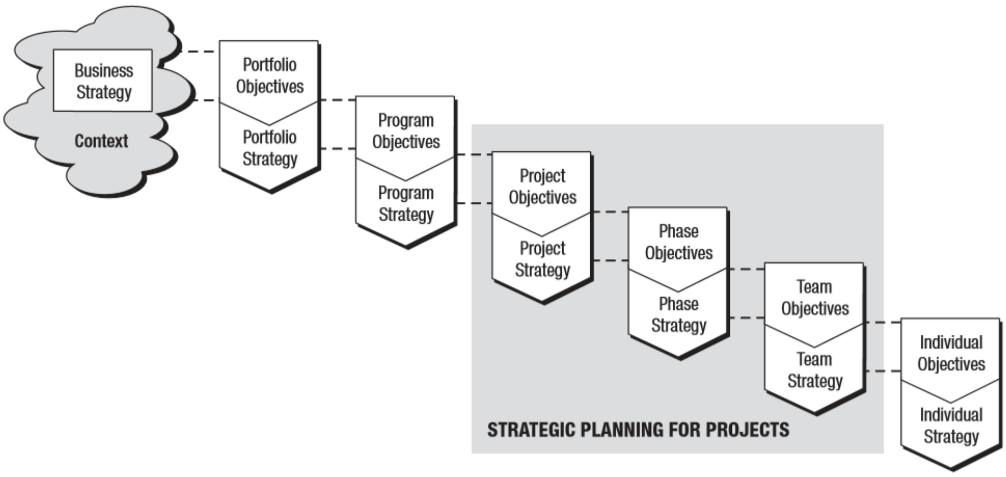

Fig. 9. Linking corporate and project strategy [32].

6.1. Strategy diffusion at strategy level (strategy formulation phase)

[9] stated that strategic effectiveness can be achieved through establishing the correct objectives, goals or initiatives and then implement them in a proper method. Thus, the strategic planning naturally needs to be practiced at all levels of the organisation. To be more specific, strategic planning at the corporate level results in a set of organisational needs and goals, where these needs and goals are transformed into business strategic initiatives, which later on these business strategic initiatives are carried out over projects, whose strategy is the project approach.

Moreover, the strategic fitting concept describes the degree to which all projects jointly reflect the strategies of the business corporate. Based on that, the alignment of project portfolio objectives and resources reflects the overall business strategy. This means that when top management identifies and agrees on its long-term goals, objectives, targets, means, and initiatives, then they put them in action plans and explain the plans in detail to convert them into shared actions [23].

In general, organisational leadership defines and agrees on the organisation mission, goals, and strategies. The key next step will be the identification of precise initiatives or projects or programs that will handle the strategies. These programs and/or projects become parts of an organisation's project portfolio, which should result in achieving the mission and goals of the organisation. Each project in the portfolio is defined in broader part as delivering outcomes, resource requirements, and potential timelines and responsibilities. In other words, the management selects those projects that deliver the most valuable results and ensure the strategy implementation in the greatest efficient and effective mode. The clearer the plan, the higher the chances will be of achieving the goals. This is illustrated in Fig. 10. the link between strategy and project portfolio [28,44].

To facilitate the task of this research, it was decided to change the five steps of Rogers' diffusion into three steps. This will be through joining the first (knowledge) step and the second (persuasion) step together, then the fourth (implementation) step and the fifth (adaptation) step, and finally leave the decision step as is.

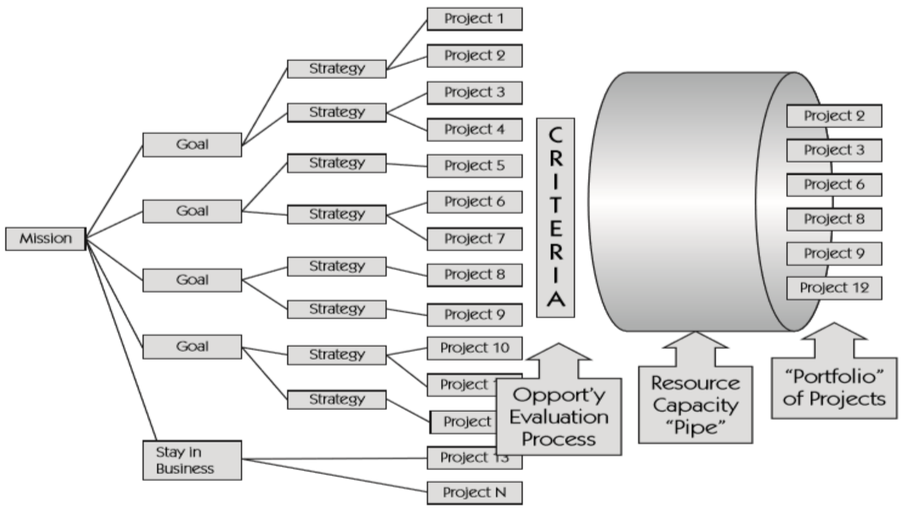

Fig. 10. Strategies competing to enter the portfolio [28]

Thus, this level needs knowledge and persuasion diffusion phase through shared understanding of the business drivers behind the strategic initiatives; the capabilities needed for the strategic initiatives [27,40,19]; the values and benefits of the organisational strategic initiatives [3]; and about the strategic initiatives alignment with the organisational risk management. Then, for the decision and evaluation diffusion phase the organisation needs the strategic initiatives decisions to be based on analysed data [50]; policies, boundaries and guidance; and against organisational values. Finally, for the parts of implementation and adaptation diffusion phase, they can be done through suitable allocation of the capabilities; strategic initiatives risk communications; and key performance indicators, which must be set for the strategic initiatives for better deployment purposes [2]. See Table 2. for further explanation.

Table 2. Comparison between Rogers' theory and strategic formulation stage after forming strategic initiatives within strategy level.

Rogers diffusion theory (The adoption - Decision Process)	Rogers diffusion theory definitions [42]	David's Strategy Formulation Phase / Strategic initiatives formed
The Knowledge Stage (Awareness)	During this stage, the individual tries to define the innovation and how and why it works.	Knowing business general directions, vision and mission. Long-term objectives formed like strategic initiatives.
The Persuasion Stage (Interest)	Develops interest; gathers more information and facts about it.	Share understanding of all details of capabilities, risks, values, benefits of the strategic initiatives.
The Decision Stage (Evaluation)	Mental trial; after getting all the information from previous stage. Individual Selects to accept or reject it. Or to active rejection or passive rejection.	Strategic initiatives decision making is based on data analysing, organisational policies, boundaries, and guidance, and they must be aligned with the organisational values.

The Implementation Stage (Trail)	It put into practice; uncertainty and reinvention can occur in this stage; to change or modify the new idea.	Capabilities are allocated for the strategic initiatives, risks are communicated, and key performance indicators are settled for the strategic initiatives.
The Adoption Stage (Confirmation)	Large-scale, continued use; satisfaction.	Strategic initiatives are translated to portfolio of projects.

6.2. *Strategy diffusion at portfolio level (strategy operationalising phase)*

A study by [32] mentioned that corporate strategy is about thinking and expressing how a utility's higher-level objectives and goals will be accomplished. This strategy later on is normally "operationalized" as a business unit level strategy; where strategic initiatives are then grouped into portfolios of projects, programs, and projects for execution. Likewise, [45] stressed that project portfolios are "powerful strategic weapons" in projects business, because one can consider it as an essential hub in executing the planned strategy. Then, firms utilize project portfolio management methods, for instance non-financial and financial assessment and valuation are practiced to prioritise and select the finest collection of projects [44].

At a top level, portfolio management processes contains a number of elements: 1) classification applicant projects, 2) emerging selection criteria that will facilitate projects ranking, and 3) endorsing or balancing the portfolio via visual assessments that let forming of several choices and modification of the portfolio. In general, organisations recruit portfolio management for the following aims: 1) maximising the value of projects according to the company objective (for example, profitability), 2) achieving a balance of projects (for example, as per risk wise, or time line wise), or 3) ensuring the business strategic objectives alignment with projects [28,36]. Moreover, portfolio management facilitates strategic goals, via offering the benefits of empowering decision making based on strategic objectives and data not as ad hoc judgments determined through the needs of the moment. Additionally, portfolio management does the proper resource allocation to reduce the wastages spending came from inefficient resource allocation or due to duplication of the projects. Furthermore, it can benefit from the source of project information to audit and assess projects' progress and enable organisational learning from earlier strategy choices and decisions [38,28]. Thus, the lifecycle of project portfolio management has five stages, including portfolio inventory, analysis, planning, tracking, and review and re-planning. These stages are iterative, dynamic, and ongoing, see Fig. 11. Therefore, this process must be controlled and managed cleverly, while relying on project lifecycles as well as organisational matters, similarly to financial plan cycles.

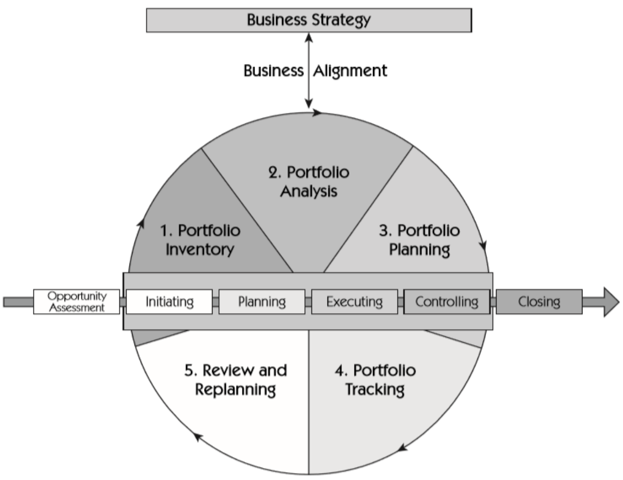

Fig. 11. Project portfolio management and project management lifecycle [28].

Therefore, while comparing project portfolio execution processes to Rogers' diffusion theory in the setting of strategic implementation stage, the linkages will be as follows:

- ***The Knowledge Stage (Awareness):*** *The strategy foundation of objectives and strategies should be clearly understood and openly communicated all the way through an organisation, which means moving a firm to its main direction [10]. To be more detailed, top management provides a broad direction to cascade it in every operational level of the organisational hierarchy. In this context, middle managers can separately accept strategic initiatives to define precise activities that will function their objectives in link with the organisation's comprehensive direction and/or to explore a new opportunity [23]. In this stage project portfolio selection involved in picking a portfolio of projects that in relations to the organisation's goals and objectives, considers resources availability and does not add unsolvable constraints [20]. Agreeing with the current strategic plan and how the projects/programs approved within that strategy contributes to the organisation strategic objectives. According to [39] provides two steps to serve this stage as: 1) Portfolio Mobilization, which translates the strategy into action, where it builds vision and approves strategy and objectives, as well as to found project scope and delivery design. 2) Management design where it sets up success via defining portfolio controller and establishing portfolio office.*
- ***The Persuasion Stage (Interest):*** *as per [10] all bosses and employee's roles in strategy implementation should be created upon prior participation in strategy planning courses and all major external threats and opportunities should be very obvious and clear, and all enquiries of managers and employees to be addressed and answered. In project portfolio there must be a clear understanding of what 'right' project means for organisation; and have the information needed for all the methods to allow proper decisions for projects selection and the efficient and effective use of resources. This can be done via communicating company oversight and assurances with external stakeholders, the organisation's owners, and the wider stakeholder community [48]. [39] defined this stage in project portfolio as data preparation stage, where they get data to know better, by assessing current landscape, personnel interviewing, and collecting relevant portfolio and business information. Therefore, portfolio management roles involve in collecting and confirmation of ability and resource availability figures; using the methods, policies, procedures, and criteria to make and implement effective decisions [48].*
- ***The Decision Stage (Evaluation):*** *for this stage managers and employees from all levels of the organisation should participate directly and early in strategy implementation assessments [10]. The main role of portfolio management is to involve in accepting or rejecting the "right" programs/projects that meet the requirements of the organisation's strategic objectives and plans [48]. Portfolio assessment stage which proposed by [39] is to test and refine the portfolio, vial portfolio optimization, data modelling and analysis, and categorising activities. Ensuring that information needed to allow a proper decision to be made is developed and that the degree of uncertainty (risk) involved in the assessments is understood and is acceptable to the organisation when balanced against the anticipated benefits.*
- ***The Implementation Stage (Trail):*** *the main functions here for the strategic management are creating annual goals and objectives, putting policies, assigning resources, aligning managers with strategy, creating a culture that support the strategy, developing human resources productivity, modifying a present organisational construction, reviewing reward and encouraging plans, reducing resistance to change, reengineering and restructuring, adapting operations processes, and downsizing whenever needed [10]. This is very much matching with the main functions of the project portfolio implementation, as portfolio management is developing process to ensure decisions are aligned with corporate strategy; determining the methods and criteria that could be used for the oversight, selection, or termination of programs/projects; evaluating of the programs/projects; fostering and supporting projects to assist their crews for bringing benefits to the organisation as well as to other stakeholders; and reducing total cost [48]. For this stage [39] proposed portfolio recommendations phase, to make the right decision, where they can draft portfolio blueprint, baseline plans and provide recommendations.*
- ***The Confirmation Stage (Adoption):*** *in the strategic management all main competitors' achievements, plans, actions, processes, products, and performance have to be obvious to entire organisational community as well as when practicing a training for all employees. It will certainly facilitate the strategy implementation and adoption phase [10]. From the project portfolio perspective, there will be confirmation of the right projects/program in order to start and maintain it, and which to cancel or defer, taking in to account the resource availability and the correct prioritising of the programs/projects [48]. This is totally agreed by [39] when proposing portfolio's operational phase for this stage, where it is for the delivering and maintaining stage, through reporting performance and inserting assurance and learning.*

Table 3. Comparison between Rogers' theory and the strategic operationalising stage in the portfolio context.

Rogers diffusion theory process [43]	David's Strategy Implementation Phase [10,23]	Project portfolio management level [20,48]	Project portfolio management level [39]	Portfolio Management Process [29]
The Knowledge Stage (Awareness)	The foundation information for objectives and strategies is available, like strategic initiatives for precise activities.	A portfolio selection of projects that meets an organisation's objectives.	Data preparation For better understanding.	Initial projects arrive the portfolio and knowing that projects has translated from strategic initiatives.
The Persuasion Stage (Interest)	Managers and employee's involvement start from strategy formulation stage and all their questions to be answered for buy-in purposes.	Full and clear understanding of what 'right' projects means for organisation, and full information and methods, procedures needed for the decisions.	Portfolio Deployment is to translate strategy into actions and management design.	Inventory phase: all projects data is gathered (including cost estimates, schedule, budgets, strategic initiatives, dependencies, ranking, relative expected benefits, risk, priority, and value).
The Decision Stage (Evaluation)	Managers and employees should participate from beginning and directly in strategy-implementation decisions.	The function of portfolio management is a decision about the "right" programs/projects the organisation should accept, fund and support.	Portfolio assessment is to assess and polish the 'to-be' portfolio.	Portfolio analysis phase: where projects are checking for their fitting, balancing, and utilizing.
The Implementation Stage (Trail)	The strategic management roles are creating annual goals and objectives, putting policies, assigning resources, aligning managers with strategy, creating a culture that support the strategy, developing human resources productivity, modifying a present organisational construction, reviewing reward and encouraging plans, reducing resistance to change, reengineering and restructuring, adapting operations processes, and, , downsizing whenever needed.	Portfolio management roles are strategy fitting, selecting projects, balancing, resource allocating, and cost reduction.	Portfolio recommendations implementation.	Project is selected and enters to project portfolio planning phase, where the resources are allocated for it.
The Confirmation Stage (Adoption)	confirming the right achievements, plans, actions, processes, products, and performance indicators.	confirming the right projects/program	Operating portfolio to deliver and maintain.	Portfolio tracking phase for assessment to determine whether to continue with the project. And reviewing phase for re-verification of the projects.

For the simplification purpose, the portfolio practice will be for knowledge and persuasion as shared understanding that the portfolio is translated from strategic initiatives [17]; shared understanding about the portfolio procedures; and shared understanding of holistic view of portfolio [39]. Then, for decision and evaluation phase, portfolio analysis helps to confirm new investigation needs [25]; the selection of the projects are based on market needs [31,25]; value benefits analysis used for maintaining the balance between projects [28]; frequent reviewing whether the strategy of the project portfolio is still valid in the light of changed conditions [25]; frequent evaluation of the interdependency between programs and projects; and the selection is based on decision framework [17]. Finally, for the implementation and adaptation stage the strategy initiatives are implemented through portfolio [49] the portfolio charter is approved [28,17]; the resources are allocated to projects [28]; the communication plans are set [39]; and the risk management plan is established [17].

6.3. Strategy diffusion at the program level (strategy operationalising / implementation phase)

Linking business strategy directly with project prioritization and section scheme is usually hard to do specially when managing them for long term. Thus, to facilitate the connection it is better to establish a program management model inserter in between portfolio management and project management [28].

According to [38] from the strategic management point of view, the program management is considered as a key driver for managing various projects after the portfolio, but in a different manner. Programs normally include multiple projects that are supposed to contribute to the achievement of organisational strategic objectives and tactics. Furthermore, various programs take into account elements of existing actions. It also represents organisations that have a robust goal and purpose, predefined expectations related to the benefits and values system, and a plan for effort organising. Moreover, program management is about defining the strategic needs for the program and undertakes obligation for accomplishing the benefits, grouping existing projects or accepting new projects.

A program is a framework that can be practiced to generate specific results and outcomes, which can be identified at a high level of a 'vision'. Therefore, in detail, program management is meant to manage interfaces among the projects, where the objectives of projects under the same project program are interdependent. Therefore, program management can be defied as the synchronised management of a portfolio of projects that can lead organisations to achieve their important strategic benefits [5].

The program management lifecycle requires demonstrating the oratory and perceptions of strategic long-term objectives, instead of the short-term's one. This is to gain top management support and to be able to support strategic decision making [46]. Thus, [46] built a program management lifecycle based on a benchmarking study between three guides including PMI® standard, MSP Transformation Flow standard, and P2M standard, as well as adding the PgPM® certification specification's process, to establish a generic practice-based lifecycle of program management practice as shown in Table 4.

Table 4. Program lifecycle comparison [46].

PgMP Specification	PMI 2008 Life Cycle	MSP 2007	P2M 2005	Benchmark [47]
Defining	Pre-Program Preparation	Identify Programme	Define Program	Formulation
Initiating	Program Initiation	Defining Programme	Acquire Common View (Program Mission and Value)	Organization
Planning				
	Program Setup		Understand common View (Program Community & Architecture)	

Executing	Delivering of Program Benefits (Monitoring and Control)	Managing the Tranches Delivering the Capability	Integration Management	Deployment
Controlling		Realizing the Benefits	Structured Value Assessment	Appraisal
Closing	Program Closure	Closing the Programme	No identified closing phase	Dissolution

By applying Rogers' diffusion theory on the program management lifecycle, we can find it is totally in line with it, as shown in Table 5.

Table 5. Strategy diffusion in programs.

Rogers' diffusion theory process (Rogers 2003)	Program Management [46]
The Knowledge Stage (Awareness)	Formulation stage: Defining the strategic programs expected benefits via stakeholder analysis and agreement on the program objectives and purpose, which consist of functional action plans.
The Persuasion Stage (Interest)	Organisation stage where detailed programs, operational procedure and structures are included, with technical action plans.
The Decision Stage (Evaluation)	Appraisal stage consists of program level benefit realization, assessment, evaluation of the operational achievements.
The Implementation Stage (Trail)	Deployment stage is the delivery of capabilities via program's essential projects and actions that consist of turn into the business.
The Confirmation Stage (Adoption)	Dissolution stage where closing process will be practiced with long-term benefits measurement process.

Again, for the purpose of simplification, the program practices the knowledge and the persuasion stage. This is done through shared understanding of programs' expected benefits [46,38], understanding the resources required by the program, and establishing a common understanding about program stakeholders' roles and responsibilities [46].

Then, for the decision and evaluation part, a program must prioritise projects using evaluation framework, select projects based on organisational strategy [6], and program decision making should be supported by intelligent data analysis [38]. Finally, for the implementation and adaptation part, projects are prioritised within a program. Interdependencies between projects are also managed. Synergy between projects within the program is created, the program's resources are planned [6], and the benefits realisation plan is developed. Change plans are ultimately created and communication plans are established [38].

6.4. Strategy diffusion at the project level (strategy implementation phase)

Integrating project management and project portfolio management allows organisations to choose the top collection of projects that are suitable to the business strategy, track and monitor their outputs, and reprioritise from time to time the portfolio as per business circumstances and financial plan change, see Fig. 11. [28].

Furthermore, [45] recognised two scopes to distribute projects for strategic portfolio management: 1) the strategic goal dimension that consists of strategic and operational projects, and 2) the customer dimension that consists of internal and external customers. For strategic projects, they deal with new long-term business aspects, while operational projects deal with existing business.

As per PMI, the project management process is launched with the initiation of a project, followed by planning, execution and control, and closing processes, see Fig. 11. Each of these stages includes activities and sub-processes that are practiced for the sake of project management effectiveness during the life of a project [28].

Table .6 Strategy diffusion in projects.

Rogers diffusion theory process [42]	Projects Management level [38,37]
The Knowledge Stage (Awareness)	Project Strategy: The project views, positions, and plans for what to do, how to do it, and why to do it. All that is for gaining greater competitive advantage. Initiation stage: It is done via identifying business desires, founding a project strategy with priorities, approving on the project characterisation containing defining project objectives and success criteria.
The Persuasion Stage (Interest)	Planning phase: How to achieve objectives and goals, via setting all the projects plans, methods, processes, and guidelines.
The Decision Stage (Evaluation)	Control and Monitoring phase: Admiring important outputs and making decisions or recommendations at serious points in the project's life whenever needed and when compared to project plans. Ongoing monitoring of the project's business environment.
The Implementation Stage (Trail)	Executions phase: project managers in this phase are responsible to ensure that the project meets its all needs objectives.
The Confirmation Stage (Adoption)	Closing phase: Delivering success or failure for projects, benefit realization. Taking delivery of a project at completion, and project reporting systems that focus on performance against plan or specific objectives.

For the simplification resolutions, the projects practicing knowledge and persuasion stage are done by shared understanding of project management methodology, projects constraints (time, cost, quality, and scope), project risk [13,44,38], realisation of project benefits outputs [44,34], project roles and responsibilities for project governance, and knowing clearly the projects critical milestones [38,34]. Then, for the decision and evaluation part projects' constraints (time, cost, quality and scope) are evaluated based on project information [34], and predefined rules and methods [13].

Project decisions are communicated to the relevant stakeholders [34]. Project execution management plans are checked [38]. The projects' schedule management plan is then set and the cost management plan is confirmed. The scope management plan is approved, the quality management plan is set and the risk management plan is approved. Following this, the resource management plan is approved, the communication management plan is established and the procurement management plan is confirmed; and in addition, the stakeholder management plan is accepted [38]. Finally, for the implementation and adaptation, projects are managed according to project management methodology, where the progress is managed against the project schedule. Cost is monitored-controlled against project the budget plan. The scope of work is done against the scope plan. Quality is monitored-controlled against the quality plan. Risk is responded against the risk plan. Communication is managed against the communication plan. Procurement is conducted against the procurement plan. Stakeholder engagement is managed against the stakeholder plan, and change is monitored-controlled against the change plan [38].

7. Performance (bottom-up) alignment

The strategy top-down and bottom-up mechanisms roles are diverse based on the organisation. This has also been explored in prior studies (e.g., [5,22,23]). For instance, see Fig. 12. representing the model of the process of decision-making divided at three organisational levels, which highlights communication and data sharing amongst those levels. The communication and information flows are very important for the entire decision-oriented procedure for the multiple projects' strategic management. The arrows show communication and information flows, which considered as essential inputs and outputs for particular decision options [5].

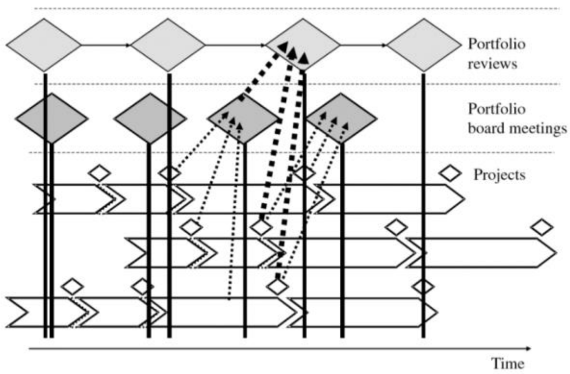

Fig.12. Bottom-up method for information and communication flows within the organisational levels [5].

A bottom-up approach can be developed as an unplanned outline of activities and possibly will realize outcomes not originally proposed by top management. Therefore, bottom-up can shape objectives and action of the operations strategy, at least partially through the knowledge and lessons learnt from its day-to-day activities. According to the initial outcomes, top management strengthens or adjusts its plans as applicable [23].

Furthermore, a study by [44] provided a conceptual example about benefits realisation, launching from projects and ending with the accomplishment of business objectives, as shown in Fig. 13. Theoretically, the process initiates on project results allowing direct delivery of intermediate benefits or business changes. In addition, as a strategic viewpoint, effective projects deliver the predictable benefits, then generate strategic value to the organisation. Hence, a good project management ensures the delivery of outputs, which enables outcomes, and then in turn facilitates the right benefits realisation.

As highlighted by [17] that despite the importance of portfolio, programs and projects should work coherently although they have different objectives, however, in order to deliver the organisational objectives effectively. For example, project management focuses on providing a concrete output, and to do the things right.

On the other hand, program management is the intermediary level that focuses on the provision of business benefits and realising the benefits. Portfolio management focuses on doing the right things via the decision-making process about which projects and/or programs should be implemented, based on their association with the organisational strategic key objectives and goals, see Fig. 14.

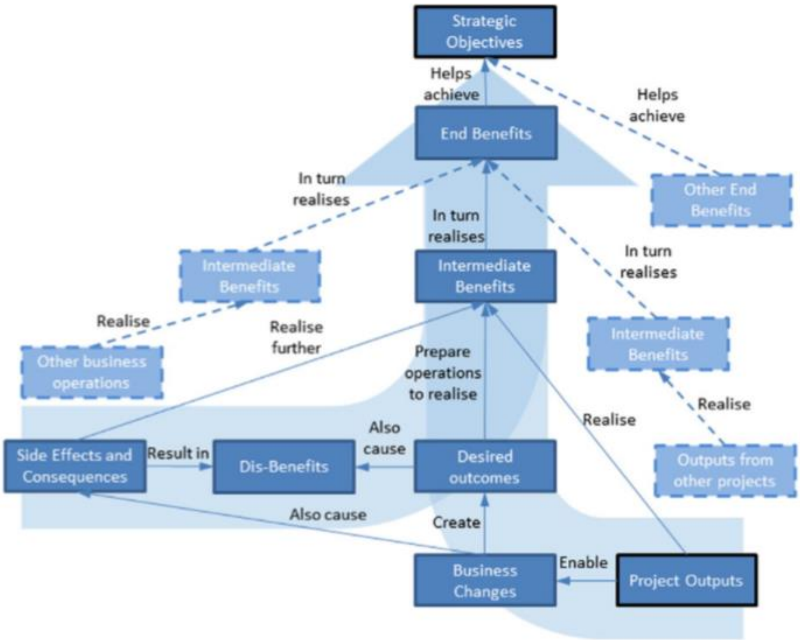

Fig. 13. Benefits realization process [44].

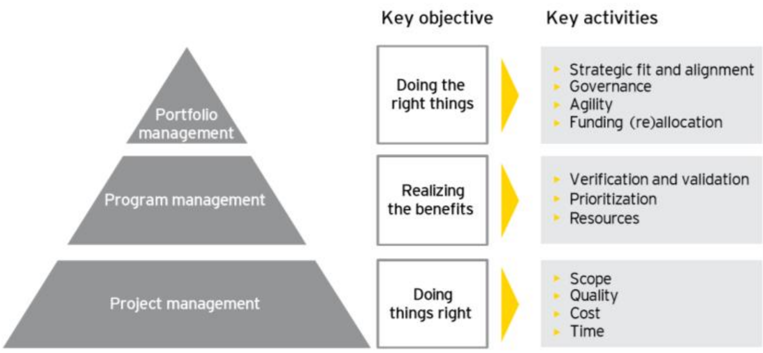

Fig. 14. Portfolio, program and project management objectives and activities [17].

8. Strategy performance evaluation phase

8.1. Performance (data) feedback/reporting from the projects level to the program level (strategy evaluation phase)

Once the selection process of the right projects is done, then there is a need to assess the project success. The project success assessment is proposed to be done in two steps, which are normally called appraisal and evaluation. The appraisal arises before the commencement of respective project, to facilitate the approval of the business case, whereas the evaluation happens at project closing stage. This is in order to identify project accomplishment. Therefore, the success of projects is very important for organisations, because the success of projects reflects the success of implementing the organisational strategy and that their vision has turned into reality [44]. Clearly, project management teams are supposed to identify how to evaluate project success.

Historically, project management has been seen as a functional and operational rather than a strategic advantage and success in operational level measured in terms of time, cost and quality. Just lately, scholars and specialists have started to inspire the measurement of the strategic influence from project results. This is because the project management community has supported its attention on the strategic sides of project management, as well as has put its significant intention on project management and its link with strategy [22]. Moreover, [45] proposed that there are two types of projects; one of them is operational projects while the other is strategic projects. The operational projects are those in which practitioners are dedicated on getting the job done and meeting cost and time objectives. On the other hand, strategic projects are motivated to achieve business results and succeeding in the marketplace. The in-charge teams in strategic projects spend a huge time and attention on decisions and actions that aimed at improving business outcomes in the long-term period. For instance, these teams are concerned with competitive advantage, customer needs, and future market success, and rather than running through the primary plan, they keep doing modifications that will generate improved business outcomes, while an operational projects teams, focus on short run outputs and results. Thus, it has been advised that, in order to measure both project process and business aspects, it is better to utilise a project balanced scorecard method, and the measurements can be used as follows [9]: financial measures, such as economic value-add, business growth, cost saving, and investment; client measures, such as use of product, market share, satisfaction, new clients, and retention; learning and growth measures, such as productivity, empowerment, team satisfaction, motivation, and training; and project process measures, such as time, cost, quality, performance, use of resources.

In the end, various studies [34,38] strongly recommended to use measurements, including meeting business purposes, meeting project's operational performance goals, meeting project's technical performance goals, meeting project's schedule objectives, staying within project's budget limits, meeting project's quality objectives, meeting project's scope objectives, and finally the rate of project's stakeholders satisfaction with project's results. These are intended to act as key indicators to measure the project success at project level within project-based organisations.

8.2. Performance (data) feedback/reporting from the program level to the portfolio level (strategy evaluation phase)

Previous studies have emphasised the programs performance phase, which needs to be reported to the portfolio level. It is important for program management to identify benefits and understand the program context, how it contributes to the broader business strategy, develop a full benefits realisation plans aligned with broader portfolio plans, and then realise the benefits. However, it is also very essential to monitor and report program progress whenever new information is available; in order to assess fairly the performance of benefits against the realization plan and to understand the early warning to whether project outputs are enabling change and delivering benefits. Indeed, in the end, program evaluation stage supports the organisation to take corrective actions if needed and provides lessons learned for future actions [46].

For these reasons, the main program performance measurements suggested by scholars were whether programs reflect the business strategy implementation, the program's shareholders satisfaction rate, and the programs cost-benefit achievements [34].

8.3. Performance (data) feedback/reporting from the portfolio level to the strategy level (strategy evaluation phase)

The project portfolio management is a complicated process that begins at the highest level of the enterprise. It is considered as a key step to generally execute the strategic process. It facilitates the conversion of an enterprise's strategy into results that it desires. It also makes sure that the required results are achieved, new business initiatives are formed. The building blocks of these initiatives are the programs and projects, in which they create products/services that provide ultimate help to achieve the organisational goals by creating value [44]. Thus, project portfolio management is meant to monitor the progress of single projects and intermittently re-prioritising all the projects within the portfolio to have the correct balance, collaboration and success while implementing the organisational strategy [49].

In general, all organisations should control their business and execute their projects wisely through project portfolio management, since project portfolio management allows organisations to put a criteria for picking the correct projects and removing wrong ones, assign right resources to the right projects. This will reduce wasteful cost, make ownership between workforce by contribution at the exact points, support project teams to recognise the value of their influences, and create paths for entities to get support and recognise opportunities [28].

Consequently, monitoring portfolio of project performance must be against the strategic needs. This includes project evaluation, portfolio balancing, and portfolio analysis. In particular, based on the results, projects are selected and prioritised at the right time depending on their contribution to the company's strategy [36]. Moreover, the continuous review and 'learning' is associated with a continuous improvement philosophy in the portfolio domain. In other words, providing feedback to the strategic decision makers and governing body is based on the 'special knowledge' gained through effective portfolio management activities, and that contributes to the organisation strategic objectives modification in response to changing circumstances, as well as it minimises the overall costs of converting 'input' to 'output' through projects [20]. Authors gave a comprehensive review on portfolio performance management linked to the right number of projects against the resources available, containing a high-value projects, excellence balance of projects, whether these projects are aligned with business strategy, budget allocation correctly between projects and based on business strategy, portfolio stakeholders satisfaction rate, portfolio achieves their time, cost and quality goals, portfolio achieves their financial goals, portfolio fulfils stakeholders' requirements, and projects within portfolio achieve their purposes [48].

8.4. Performance (data) feedback/reporting from the strategy level to the organisational level (strategy evaluation / formulation phase)

Strategy performance management according to [10] initiates managerial questioning of expectations and assumptions, must indicate a review of goals and objectives, and should inspire creativity in creating substitutes and framing criteria for the strategy evaluation. Strategy evaluation is essential to ensure that stated objectives are being achieved, where it compares planned to actual progress toward meeting stated objectives. Strategy evaluation can lead to strategy-formulation changes, or to strategy-implementation changes, or to both changes, or even to no changes required at all. The final strategy evaluation task facilitates for taking corrective actions to ensure that performance conforms to plans and requires making changes to competitively relocate a firm for the future. Feedback information must be economical, effective, meaningful, and timely based information. For these reasons, several studies examined the strategic performance measures through strategic initiatives' stakeholders satisfaction rates, meeting strategic initiatives' service expectations, strategic initiatives' benefits realisation expectations, strategic initiatives' revenue expectations, strategic initiatives' profit expectations, strategic initiatives' sales growth expectations, strategic initiatives' market share expectations, and strategic initiatives' environmental conditions adaptations [50,34].

9. Conclusion

This paper provided a theoretical review about the suitability of Rogers' innovation diffusion theory for strategy diffusing within project-based organisations. As well as, confirmed additional validation about the concepts similarity of innovation diffusion and strategy diffusion, thus, this paper was mainly employed to explain the thorough mapping of the five diffusion decision process that consists of knowledge, persuasion, decision, implementation, and adaptation stages, which are adopted from Rogers' diffusion theory, with the strategic management three phases that consist of formulation, implementation, and evaluation that taken from David's strategic management model at each of the project-based organisation hieratical levels for strategy, portfolio, program and project levels as a top-down perspective. Then, it showed the similarity of the meaning for the four innovation diffusion elements (innovation, communication channels, time and social system) in Rogers' diffusion theory and in David's strategy management model. After that, this study provided the characteristics' meanings of compatibility, relative advantage, complexity, observability and trialability in Rogers' innovation diffusion theory and the parallel characteristics' meanings (consistency, advantage, clarity, visibility consonance and feasibility) in David's strategic management model.

In sum, the study supported and confirmed the possibility of the study proposed concept of utilising Rogers' diffusion theory for strategy diffusion within project context as top-down method in a project-based organisation. Where, the detailed bottom-up arrangement from project to program to portfolio and up to the strategy level, which showed also the possibility of the bottom-up approach in project-based organisations; this is done in order to fulfil the necessity of improving organisational performance.

Acknowledgements

Acknowledgements and Reference heading should be left justified, bold, with the first letter capitalized but have no numbers. Text below continues as normal.

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Challenges in Operating SMART Cities: Lessons from the Former Socialist Real Estate Sector of Hungary

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Abstract

The SMART city concept is currently used in various places around the world. The concept itself has been with us for two decades, but only a few real SMART cities are actually in operation. As a political system, socialism has a number of similarities with the SMART concept, such as top-down planning, centralised management, centrally allocated budget and the mandatory participation of members of society. Hungarian socialism of the past can be considered the laboratory of the socialist system with numerous excellent, internationally discussed studies written on the theory and practice of Hungarian socialism.

This article presents the unique characteristics of property management in the former Hungarian socialist system with the goal of making suggestions for the planners and operators of SMART cities. Self-evident elements of the past, such as the all-encompassing legal framework, the expectation of social cooperation, the emergence of the so-called second economy and experiences of failures in planning and implementation can all offer lessons for modern SMART cities.

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Keywords: Facility Management, Real Estate, SMART City, Socialism

1. Introduction

The idea of a SMART city goes back decades, with many elements of the then utopian city concept having been implemented by now, while the concept itself has undergone a lot of refinement over time. Nevertheless, we cannot say that there are real, working SMART cities around us: even the most successful contemporary cases only align with the concept on some points of detail. Urban policy can be used to respond to the challenges of the world today by creating increasingly successful SMART cities. Currently, there are several obstacles to the successful and complete implementation of the concept. These issues include the failure to engage residents, systemic failures in centralised planning and the huge gap between the benefits offered by IT technology and those expected by the public. This article presents and analyses a historical analogy to facilitate the future success of SMART cities.

As an ideology and as a political system, socialism is a rich research field. This system of the past can be used to study group behaviour, processes and hierarchies. The former, so-called “actually existing" socialism in Hungary is an excellent research field, or one might say laboratory, for such an investigation, and countless research projects using the Hungarian case study have revealed the phenomena of socialism to an international audience.

Hungarian socialism exhibited all the characteristics of a centralised, centrally planned economy, and the real estate sector, including property management, was an integral part of the socialist economy. In the following, we want to highlight the kinship between socialist property management and SMART cities. The purpose of this article is to draw lessons from this comparison for the benefit of the cities' policy makers and operators who want to make the SMART cities of the future better.

After this introduction, the article is structured as follows: first is an overview of the literature of observations and critiques on SMART cities. The following chapter deals with the characteristics of the real estate market in the socialist period of Hungary, including property management, and its literature review. The third chapter is a discussion of the links between the two topics, and the final chapter, the conclusion, summarises the lessons learned and makes recommendations.

2. A critique of SMART initiatives

The "SMART city" as a new concept first appeared in the 1990s, but the number of publications on SMART cities has been growing exponentially [1]. Of course, with the incredible pace of development in information technology, what was yesterday called SMART (say, accessing public transport timetables on a mobile app) is now commonplace. Theories and policies on SMART are also rapidly evolving, in parallel with the dramatic evolution of technology. In the early 2000s, Korean experts introduced the idea of the U-city [2] as a great innovation, which meant urban information accessible from everywhere to everyone, thus laying the foundations of today's SMART city. The technology packages providing urban IT services under various names are now all generally called SMART. The critique of U-city cities was that the solutions that mega IT companies offered to cities did not involve citizens and did not meet local needs. The original initiative, now called SMART 1.0, has by now evolved into SMART 2.0 [1].

The current literature has identified 116 different definitions of the "SMART city", including strongly technology-oriented ones and others that emphasise the role of the human community in addition to the ITC elements. The first set of definitions comes from the corporate world, while the second typically originates from academic workshops. However, in reality, SMART-ness is often just a positive label given by city marketing [3]. After a detailed analysis of 10 different cities that have been advertised as SMART, in 2017 Anthopoulos [4] found that the services provided by these cities, internationally acknowledged as SMART, actually differ significantly. The common minimum of the 10 cases includes some kind of a SMART programme (agenda), open access to data and the existence of some community IT services. However, according to the comprehensive study by Zhao et al. in 2021 [1], even though the number of scientific publications on the topic of SMART cities reaches 40,000 (!), the focus of research and the discipline itself are still undefined (fuzzy). The various authors in the literature studied in detail tend to focus on what a SMART city SHOULD be, not on what it really IS.

The case study by Marek et al. from New Zealand [5] demonstrates that the IT-centred, technocratic approach is not viable. The town of Christchurch was completely destroyed by a series of earthquakes in 2010-2011, forcing it to be rebuilt completely. This was an opportunity to develop the city on a SMART basis. Experience has shown that only some of the features of the new smart city, building on sensors and big data (such as bicycle tracking and air pollution measurement), are used by residents. The authors also recommend a bottom-up approach to create true public involvement instead of top-down planning. In this cited article, Marek et al. provide a complex and new definition of a smart city based on the experience of the Christchurch case study: "a smart city is liveable for its citizens, sustainable in environmental aspects and resilient to natural and man-made challenges. It is a city where smart technologies enable effective governance by engaging people, optimise processes in real time, and where smart citizens create innovative environments and business opportunities by sharing knowledge and information." In this article, we also consider the above definition as authoritative when referring to the SMART city concept.

Although most existing definitions consider the human element as an important component of a SMART city, the concept is often criticised for being too technology-oriented. The SMART concept of IBM [6] or Cisco [7] is technology-focused by definition. Actually, CISCO has recently announced that it is exiting this unprofitable business [8]. One of the most important observations about existing SMART cities is that the city services designed and created by IT companies are not what city users actually want or need. Critics often comment on the lack of community involvement in planning [9]. As we have seen, not only the definitions but also the SMART cities differ, and the adoption of a given level of technology depends on the city's location and the local society. This is why the solutions offered by big corporations are not universal: while in one city Wi-Fi coverage is needed, in another e-government solutions are in demand.

The implementation of ambitious SMART concepts is often hampered by a lack of available resources [10] [11]. This not only includes resources required to invest in the project but also to maintain and operate the systems, for which the city has no allocated funds. As such, there are also operational problems that can undermine the commitment of the city's users [12].

The existing fabric and infrastructure of a city (not including completely newly built cities) may not necessarily be suitable for SMART technology. By default, the development of smart city functions requires the digitisation of physical infrastructural data [13]. The city's utility networks, public spaces, buildings and homes form the real hard infrastructure, which can then be intertwined with the information technology's networks and sensors. The hard infrastructure is not designed for SMART goals, especially not to be remotely controlled.

The SMART city concept and the discourse around it is, first and foremost, about an ideology that frames the evolution of technology and needs at the same time. In our opinion, this framework in some respects is similar to the great social experiment of socialism, so it is worth comparing and contrasting the elements of the two movements.

3. Property management in Hungary's socialist era

The period of so-called "actually existing" socialism in Hungary lasted from 1948, the year of the turnaround, until the regime change in 1989 [14]. Within this forty-year period, we can distinguish several historical phases in Hungary, including hard dictatorship and much softer times. The latter was commonly referred to as just "Goulash Communism", referring to the (perceived or real) maverick and relatively permissive nature of the Hungarian regime. The pre-war capitalist economic system was replaced almost overnight by state socialism in the late 1940s, but, in everyday life, the processes of the system took years, even decades, to take shape. And by the 1970s, when the elements of the socialist economic system were fully developed and permeated society, the first signs of loosening and transformation were already evident. The regime change of 1989 found an already hybrid economic system with many capitalist elements. Socialism is, therefore, not a rigid structure but a constantly changing system. In today's terms, we could even say that socialism in Hungary was a failed social experiment, a brief episode in Hungarian economic history. Nevertheless, this forty-year political-social-economic process can be interpreted and analysed as a large-scale attempt to study a new social order. The researchers who worked in this context as living witnesses of state socialism, and often in secret, analysed this great social experiment and its lessons. Internationally influential researchers include János Kornai, Iván Szelényi and Béla Csikós Nagy, an inescapable figure of central planning, as well as György Konrád, who captured the unique characteristics of the socialist system in his literary works. Their labours were not limited to depicting Hungarian socialist society; their impact is much wider. These and other authors partly formulated a critique of socialism for social scientists, economists and politicians, and partly offered a framework for understanding socialist systems in other countries. The scope of this article is not sufficient to present these analyses, not even some details of them, so only the findings relevant to the problem raised are discussed in this study.

The subject of our investigation is the real estate sector. Real estate, like all other businesses, was taken over by the state under the guidance of socialist ideology. At the same time, the introduction of total state control saw the emergence of the real estate sector as a secondary field of action, partly because of its lower ideological importance and partly because of the complex structure of ownership and use [14]. The transition from private to public ownership was made in several steps, but the institution of private ownership (mainly of family houses) continued and the housing cooperative appeared as a new form of ownership [15]. The complicated property ownership relations of "actually existing" socialism led to internal tensions and self-contradictions and, due to the differences in the real estate structure, centralised property management could only be introduced with certain restrictions and only for a limited scope of properties [16]. However, the urban population was significantly affected by this round, with the vast majority of condominiums of more than six flats taken over by the state. Urban infrastructure such as roads, power supply and water treatment were clearly under central control. Thus, it is safe to say that the cities of the socialist era were guided by a “central will”. But what was this central will like?

On the one hand, it varied over time: in different historical periods, cities were treated more strictly or more freely, depending on the priorities of the time. On the other hand, it was contradictory: the bodies and actors in the bureaucracy rivalled each other in their decisions and in the enforcement of their interests [17]. Finally, the target variables of socialist economic governance constituted a complex vector, since the regulating role of money and price was eliminated, or at least softened [18].

The economic policy of socialism relied on state property and the state companies managing it. The goal of the Communist Party was to eliminate private property and to maintain only state or cooperative types of ownership. Despite all its efforts, this objective was never achieved by the system of socialism [14], and was not pushed even further with the introduction of economic reform. At the same time, certain forms of ownership did create some sort of private property, such as the typical Hungarian “rental right” to use real estate, which also triggered the existence of a specific market [19]. As discussed above, the real estate sector was not on the “front line” of socialist ideology, so the economic governance was also lenient in this area. Throughout the period of socialism, the real estate market always had a second, increasingly more dynamic economy, driven in fact by pure capitalism [14]. In addition to the regulated housing market, weekend plots and cottages were traded on the open market and, after the economic reform that began in 1968, apartments were also available on the market for rent. Construction of rural family houses was carried out by the private construction industry, although its workers often did it as a side business, and not infrequently used tools “brought home” from the state company to build in materials that had become “surplus” at the company. This second economy was permeated by an informal network, which also included state bureaucrats. Those who, for whatever reason, were forced out of the regulated socialist real estate market could and did look for a solution in this market, driven by the second economy [19]. This included not only the vulnerable, but also the wealthy and the chosen, who traded the benefits of their extra work or influence for real estate. This is how vacation homes, later condominiums in green belts were built, or prominent business premises changed hands [14]. It can be seen that the real estate sector partly slipped out of the control of centralised economic governance, with players in the secondary market constantly pushing the limits of state socialism, partly in compliance with the rules of the day and partly by slipping into the “grey” zone of the economy.

The process of introducing and adopting the new system was obviously not smooth. After the Second World War, much of the housing stock was damaged and public services were not functioning, so the years of reconstruction chaos “laid the foundations” for the new structure. 1948, the “year of the turnaround”, when the communists grabbed power in Hungary, brought changes in both economic and social matters. The nationalisation and centralisation of real properties was only one of the dramatic socio-economic changes of the time [20]. The first period of the socialist system was characterised by repression, although voices of discontent soon emerged. As Kornai writes, the social economic system softened the role of money as a measure of value; in socialist society, the “voice” unites the combined pressure of society, bureaucracy, and corporations on decision makers [18]. The “voices” about the housing market increasingly expressed the need to find housing solutions and to start building houses. Mass housing construction started in the mid-1960s, doubling the Hungarian housing portfolio in just 10 years [21].

Working against the “voice” of social pressure was the central will to transform people, to “create the socialist ideal of mankind”. The ideal socialist person is able to act in concert on command, accepts the socialist ideology and behaves in the community in accordance with the requirements of generally accepted good morals [22]. According to Kornai, [18] socialist society was guided like a parent guides a small child: control by orders, but still respectful of the loud “childish tantrums”. In addition to the various means of bureaucracy, the repressive organisations (police, state security) took care of the re-education of the people. In Kornai’s view, which was considered anti-systemic at the time, all the economic phenomena of socialism were the result of the structure and mechanism of the governing institutions. However, the re-education of socialism in Hungary was mainly manifested in the Orwellian phenomenon of “doublespeak” or “doublethink”, with the average person displaying the socialist ideal in front of the bureaucracy, while in private (or even in front of the members of the bureaucracy) critical voices were raised quietly and then increasingly louder.

One area of internal criticism was precisely our subject, namely property management. In this case, the “voice” was strong and the bureaucracy was rather permissive. Poor housing maintenance, unequal distribution of housing units and unacceptable building quality were the subject of cabaret stories and so-called letters from readers. State-owned companies themselves operated the real estate they used, and built a significant internal technical infrastructure for this function, so the vast majority of non-residential properties (factories, offices, shops) were under the control of the state corporate bureaucracy [14]. Operation in the housing market was in the hands of facility management companies (IKVs in Hungarian), supervised by local councils. These organisations had to cope with the challenges of maintaining and renovating neglected and war-torn buildings. The IKVs were also the lessors of the apartments and premises so, in today’s sense, they performed not only facility management but also property management tasks [16]. The IKV was one of the emblematic institutional groups of socialism, and the daily confrontation on housing issues for the average person occurred with its administrators. The IKV was also the manager of newly built buildings, so it also had a significant role in the distribution of new apartments.

The socialist economy was characterised by central planning and central distribution. “Economic engineering” was in operation since the turn of 1948 and, in accordance with communist ideology, it sought to eliminate the role of money [23]. The centralised distribution mechanism diverted costs according to social preferences, making basic consumer goods cheap or free and, in the case of some products, distributing them by administrative allocation. Corrective mechanisms made money soft as a regulator and, at the same time, made shortages permanent. Urban planning took place centrally, as part of the centrally planned system, which meant that the state planning companies had to use the guidelines developed by the party in their planning of new cities and city districts [24]. The distribution of housing was based on a centralised allocation system, where shortages and consequently years of queuing was typical among those found worthy of a share [25].

Finally, there is one more topic to cover, and that is the real estate portfolio itself. Many buildings were destroyed or damaged during the Second World War. Furthermore, demand for housing increased significantly after the war: the housing shortage became an issue that pervaded society as a whole. The shortage was partly reduced by ad-hoc repairs of the war-damaged stock and partly by the mass industrialised housing construction projects. The image of the Hungarian countryside has been determined since the 1950s by the so-called “Kádár cubes” (also known as Hungarian cubes), the simple 60-square-metre residential buildings named after the secretary-general of the socialist party [26], while the typical residential building of socialism, the prefabricated panelled residential block, appeared in the cities in the early sixties [27]. Thus, a “needs-driven” portfolio was created by the 1970s that was not optimised for operation and that would have required continuous renovation to maintain capacity.

One of the grave legacies of today’s Hungarian construction industry is the negligent use of technology and the multitude of quality defects in general. The “socialist” approach, valid even today, was created by “socialist morality,” in which the company belonged to the community, so the individual had no accountability. In addition to this approach, another characteristic has been inherited: due to the lack of materials and lack of specialists, home-made solutions were common. The country was and continued to remain the home of backyard handymen. The backlog of renovations also became a burden for old-new private owners in the housing privatisation period of the 1990s [28].

4. Lessons learned from SMART city operations

A comparison of the two ideologies can be based on the fact that, in both cases, the value-measuring, market-building function of money is partially or completely turned off. In fact, in both cases, the theory is centred on a kind of communal well-being; in other words, the intention to establish the common good. And this is where the current question arises, to which Hungarian socialism of the past gave a negative answer: can the common good be imposed on society using centralised means? The examples of the SMART cities cited also suggest that a top-down approach first provokes opposition, and then members of society develop their own workarounds or start to make their voices heard against the measures they find unacceptable. The introductory period, full of struggles, cannot be avoided and the time needed for training and adoption cannot be saved.

The all-encompassing legislation of socialism gave people a new framework into which they were forced. It is equally true of the two systems compared that not everyone wants/needs to be part of the system. Some people are opposed on principle, but others may not be receptive to new techniques, for example because they have not grown up in this environment and are unable to learn its tools. (Socialism was primarily about the adoption of a system of ideas which, with a little exaggeration, can be compared to the technology of the digital world.) The transition period can, therefore, last up to a generation, during which time the ideology, as well as technology and, of course, society change.

An important indication from the socialism of the past is that central planning necessarily creates shortages. It is likely that the toolkit of BIG DATA will make the methodology of planning and back-measuring much more accurate than the socialist planned economy could have done half a century ago, but the institutional system of the mechanism described by Kornai, which suppressed the role of money, means that the needs cannot be fully met. And the missing capacities give rise to a social “voice,” which demands correction.

In this case market logic prevails and a secondary market for services is created, either in the centrally regulated zone or beyond, in the grey economy. To illustrate, the central planning of the energy renovation of properties necessarily defines qualities and quantities and associated limits that some are unwilling or unable to comply with, so market players with new, extended services emerge in connection with these activities.

Another general lesson is that an optimised real estate portfolio is a prerequisite for economic property management. As seen above, the building stock was created by necessity under socialism and, in the building fever, operational aspects were not taken into consideration at all. Cities that set SMART targets also face this problem: the buildings and the infrastructure can only be partially adapted to accommodate new technology and, in particular, to operate in a sustainable manner.

5. Conclusion

Our research suggests that the lessons of socialism’s great social experiment can be applied to other social movements that also strive for the common good. This work includes a comparison of the property management of the SMART city. We have found that centralised planning and the softening of money as a measure of value created a similar situation in both cases, regardless of the value judgements on the underlying ideology. The assertion of a centralised will without taking feedback into account can provoke opposition or even resistance from members of society. Timely detection of the social “voice” and correction to meet demands will bring projects striving for the common good closer to implementation.

On the basis of our analysis, we propose that a deeper analysis of certain aspects of the grand experiment of the socialist social system can be used effectively to plan a sustainable future for the SMART city.

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Characteristics of Project Portfolio Management in the Construction Industry

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Abstract

Researchers have invested a significant amount of time and effort into investigating the process of portfolio management. Topics that have been covered in these studies include the value of the project, the distribution of resources, and decision-making processes regarding the selection of projects. Research on the significance of managing a project portfolio has been going on for many years, and its relevance only seems to be growing as new industries come into being. The fundamental objective of the PPM is to boost company profits via increased financial returns and successful project completion. The issues of this literature review include Project Portfolio Management (PPM) and the significance of its implementation in the building and construction industry.

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Keywords: construction industry, construction management, literature review, PPM, project portfolio management.

1. Introduction

Many businesses are pursuing a way of formalizing project management and using it as an organizational structure in the right direction instead of dealing with a one-time event in their operations. This method can handle all types of assets and operations, increasing the organization's use of PPM to manage their project portfolios strategically. Its growth can be seen through the enterprises' increased capital investment in the project portfolio field [1,2].

For the foundation of the discipline of Portfolio Performance Management (PPM), several researchers have attempted to combine the theory of portfolios with PPM implementation within the NPD and R&D areas [2].

PPM manages investments to finish projects on time by focusing on each project's scope, timing, and budget. Projects are evaluated and valued according to a pre-defined portfolio of projects [3]. Hansen and Svejvig (2022) undertook extensive research and developed an onion-like model to represent how the topic advances. It is noticeable from the organic onion example that each layer has grown unhesitatingly over the previous seven decades [2].

2. Methodology

This paper is a literature review on project portfolio management (PPM) and its use in the construction business. A lot of searching and reading was performed to develop this paper, following the steps of finding the appropriate keywords, filtering the articles mainly related to the subject of study, and evaluating the selected articles.

The first step was to look for reviews of books and articles about project portfolio management (PPM) on academic platforms. After gathering all the relevant material, the main keywords used in this research were established and used to prepare the search string. After setting the main keywords, the second step was to evaluate the articles' titles and abstracts and select the ones with the most relevant content to the research goal. Lastly, the third step evaluated the chosen articles, thoroughly reading and classifying them into fundamental concepts and construction industry applications.

3. Project Portfolio Management

PPM is a technique that takes care of each project individually, focusing on the three limitations of scope, time, and money. It selects and manages projects as investments to execute the best initiatives on time, periodically locating, assessing, and valuing projects based on a predetermined portfolio. Based on the organization's resources, the output is a prioritized list of initiatives to start, re-prioritize, or cancel [1,2].

To ensure that projects are completed on time, PPM evaluates and manages them in the same way as a portfolio of investments. Effective portfolio management adds value by connecting projects with the organization's strategic goals, maximizing scarce resources, and fostering collaboration amongst projects. A poorly managed project portfolio falls short of the plans due to taking the wrong initiatives to prioritize the tasks [4].

All the projects have to compete for limited resources (people, time, and money) because there are not enough resources to undertake every project that fits the organization's minimal standards. Effective project organizations prioritize the best projects with limited resources instead of attempting to accomplish everything by overloading project teams [1].

Research in PPM has shown that this topic is dynamic and has grown through its engagement throughout history. Some of them get more developed and stronger, while others reach a point where they have not been used as much anymore and go in a different direction [2].

3.1. PPM categories

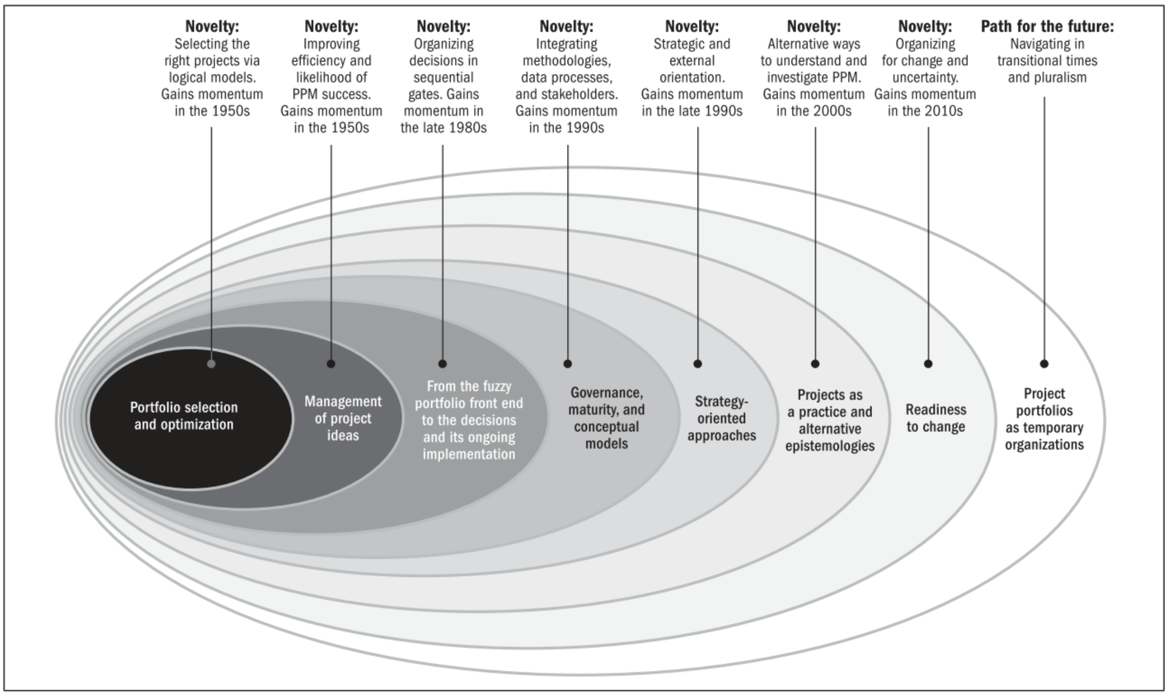

Figure 5. The onion model of seven decades of PPM knowledge by Hansen & Svejvig (2022).

Hansen and Svejvig illustrated the development of the topic by using a model in the form of an onion (see Figure 1). The metaphor of the organic onion has become more complex over the course of the past seven decades [2].

3.1.1. Portfolio selection and optimization

The selection of project portfolios for a company is noteworthy, considering that for many companies, it is not easy to decide which projects to include in their portfolio [1]. This is a common management assignment that takes place within the context of the business planning process, which plays a significant role in determining the long-term success of the entire company [5].

In the post-World War II era, the need for a process that would guide how to choose suitable projects emerged, enhancing studies in this field, and researchers managed to incorporate new management ideas to help with selection. Its main goal is to determine the best combination of projects to minimize investment risks and maximize limited resources and stakeholder needs [2].

The leading portfolio selection techniques in studied literature include ad hoc approaches, comparative approaches, scoring models, portfolio matrices, and optimization models [1,6].

3.1.2. Management of project ideas

It handles the issues to ensure efficiency in bringing a new product to the market, enabling and supporting the PPM selection process. In the postwar optimism, research and development institutes were needed to manage new ideas and get them to market. Discussions on managing PPM issues and preconditions for PPM success have made PPM more effective and efficient [2,7,8].

3.1.3. From the fuzzy portfolio front end to decisions and its ongoing implementation

In order for a project to be successful, several choices need to be selected and implemented. As a result of a decline in market demand, businesses became increasingly interested in developing novel approaches during the 1970s and 1980s [7]. These approaches included minimizing the amount of wasted labor, cutting back on resource consumption, and improving project selection and monitoring. As the researchers understood PPM as an ongoing process, they developed the stage-gate model. According to this model, project teams are responsible for providing information, analyzing the project, and making decisions [2,7]. The stage-gate methodology is used the same way as before, but it is now more scalable, versatile, and beneficial for agile operations [2,9].

3.1.4. Governance, maturity, and conceptual models

It is recognized how techniques and models work together to make PPM successful. As a decision-making system in the 1990s, researchers developed models to illustrate how PPM blends strategy and stakeholder decisions with methodology and projects, and data [1]. People and organizations can now assess their progress considering these “best practices” structures, which have gained traction recently. However, academics are dubious of best practices on the one hand and link them to success on the other. The widespread dispute among scientists regarding the importance of these methodologies has inspired many new researchers to pursue the field [2].

3.1.5. Strategy-oriented approaches

It indicates what is contained in the conceptual view and serves as an integrative term for the whole process. PPM’s strategic impacts were first examined in certain studies after the efficiency of PPM was emphasized, and researchers are currently broadening their scope by incorporating effectiveness into their analyses.

The idea of value and success in PPM has slowly moved away from projects and products and toward value, reinforcing the importance of PPM research focused on managing the creation of value in portfolios. As a result, there is an improvement in setting up a strategic approach to internal and external environments [2,10].

3.1.6. Projects as a practice and alternative epistemologies

Using logical models and focusing on real-world circumstances broadens the scope of research, making it more useful. As a result of these additional contributions, PPM research became more practical and diversified. More than rational motivations influence PPM decisions and practices. Several studies have been conducted on the various roles of stakeholders, project managers, and the PMO in implementing PPM in the real world [1,2,7].

3.1.7. Readiness to change

It describes the strategy's creation process and the effort put into its execution. The organizational environment uncertainty expanded with the rise of businesses participating in the global innovation market, encouraging PPM researchers to focus on an organization's adaptability to unexpected change [2,10].

Although many theories have been developed to help organizations become more adaptable and agile, it is challenging for organizations to implement agile portfolios because of how people and management operate and think [2,4,10].

3.2. Project Portfolio Management and Industries

PPM manages investments to complete projects on time by focusing on the project's scope, timing, and budget. The portfolio is used to locate, appraise, and value initiatives and the resources available to the company to define their priority [3]. Since its beginnings, PPM has been used in many areas, such as IT projects, research and development, oil exploration [5], and the construction industry [6,11–13].

A long-standing observation in the construction business states that most building projects do not succeed in achieving their stated goals. Only forty percent of construction projects are finished according to the goals and aspirations that were initially articulated by management [2]. A predicted profit could turn into a loss in the current highly competitive climate if the strategy, budget, or timetable are implemented incorrectly [11,12].

Kozlov (2017) suggests that construction firms should find new methods to make choices, govern their operations, and improve project management approaches [6]. A construction portfolio composed of many different projects simultaneously has an average risk lower than each project individually [13].

Project portfolio management is an essential concept for managing complex project landscapes. Even though most businesses are more familiar with project management, it is still new in construction. [12].

4. Conclusion

Although Project Portfolio Management has been studied for decades, the issue is still current and growing with the expansion of industries today. The keywords were used to select papers and books on the issue for the study. This article explores the core concepts of Project Portfolio Management (PPM) and the significance of PPM implementation in the construction industry.

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Clash Avoidance in BIM Based Multidisciplinary Coordination: A Literature Overview

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Abstract

In recent years there has been a significant amount of research aiming to increase the efficiency of Building Information Modelling (BIM) based multidisciplinary coordination process. However, unanticipated increases in cost and delays in construction projects are still visible. According to the literature, one of the principal factors affecting the efficiency of BIM-based multidisciplinary coordination and construction process is the conflict between the systems of different design disciplines. Recent years have seen a surge of automatic clash detection tools and strategies. These have provided clear benefits to the construction process by helping to reduce the number of errors discovered on-site, but the significance of this effect is hindered by the inefficiency of the clash resolution process due to the vast number of identified clashes and the resources needed to resolve them. Researchers have started focusing on devising strategies for clash avoidance during the design process to address this phenomenon. Our work is an attempt to present a literature overview of these clash avoidance strategies that range from shared situational awareness to supervised and hybrid machine learning frameworks. This work identified that the most prominent causes of clashes directly occur during the preliminary phases of multidisciplinary coordination which are generating the specialty models and federated models. Additionally, the lack of studies on proper standardized documentation of lessons learned in BIM-based multidisciplinary coordination is also recognized in this study which points toward future research directions for developing such guidelines.

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Keywords: building information modeling, clash avoidance, multidisciplinary coordination.

1. Introduction

There has been a significant amount of research aimed at making the Building Information Modelling (BIM)-based multidisciplinary coordination process more efficient. Nevertheless, unanticipated increases in costs and delays in construction projects still occur. One of the principal factors affecting the efficiency of BIM-based multidisciplinary coordination is the conflict between the systems of different design disciplines. Tommelein and Gholami identify such conflicts or clashes as waste in the production system [1]. Recent years have seen a surge of automatic clash detection tools and clash filtration strategies. These have the potential to benefit the construction process by helping to reduce the number of errors discovered on-site. However, the significance of this effect is hindered by the inefficiency of the clash resolution process due to the vast number of identified clashes and the resources needed to resolve them. Researchers are focusing on devising strategies for clash avoidance during the design process to address this phenomenon. This work presents a consolidated overview of these clash avoidance strategies that range from shared situational awareness to supervised and hybrid machine learning frameworks. This overview is expected to help researchers and BIM professionals to compare the efficacy and applicability of such strategies. It will also help researchers to understand the research gaps in the field of BIM-based multidisciplinary coordination.

1.1. Objectives and Methodology

The objectives of this literature review are: (i) to identify the causes of clashes that affect BIM-based multidisciplinary coordination, (ii) to study the proposed clash avoidance strategies for efficient multidisciplinary coordination, and (iii) to draw connections between the causes of clashes, and the clash avoidance strategies. A 'mixed-methods systematic review' was employed for this work which applies quantitative and qualitative methods to analyze the available literature so any potential biases can be avoided. The mixed-methods systematic review was carried out in 3 stages. Stage 1 consisted of a focused keyword search in the Scopus database which produced 95 pieces of literature. These keywords were selected based on their relevance to the topic of study and include building information modeling, multidisciplinary coordination, real-time collaboration, clash avoidance, clash-free model, clash management, clash optimization, design error, and design rules. In the second stage, Englishlanguage published, open-access journal articles, conference papers, and book chapters were selected. Afterward, VOSviewer was used to conduct the bibliometric analysis of the shortlisted literary works. A co-occurrence network map for the author keywords was created to view the topics of research and their interconnection in the field of BIM-based multidisciplinary coordination as shown in Figure 1.

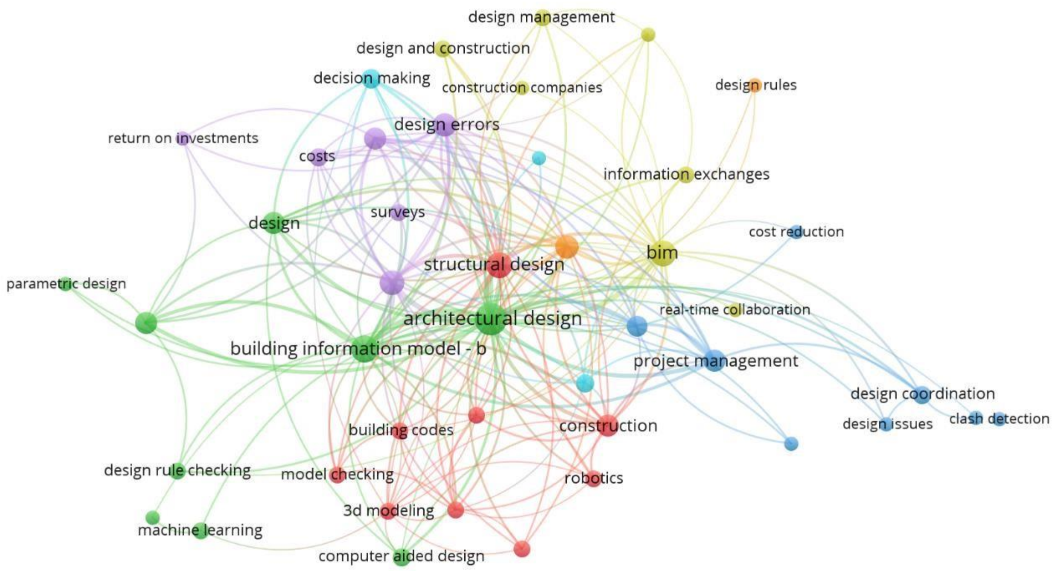

Fig. 1. Most prominent areas of research are shown via the author keyword co-occurrence network map.

The network map highlights the most frequent topics of research related to multidisciplinary coordination and clash management alongside providing insights into the scope of potential research directions. It can be observed from the map that there has been significant research focused on the economic impact of design errors, building code compliance, and automated clash detection. However, there is a lack of comprehensive study pertaining to clash avoidance.

For the final stage of the review, qualitative analysis was adopted where the relevance of the literature is determined by comparing the contents of all shortlisted works. First, the literary works that directly address clash management, causes of clashes, and design errors in BIM-based coordination and collaboration were selected. The documents were then analyzed carefully to identify and extract information for the next step. Subsequently, the documents were coded based on the specific cause of design clash and the clash management technique they discuss to further identify the potential solutions for the said cause of clash. The total number of papers shortlisted in Stage 3 of the mixed-methods systematic review was 25.

1.2. Identifying causes of clashes

The most prominent causes of clashes or conflicts in BIM-based multidisciplinary coordination considering multiple scientific publications are discussed in this part. Previously, Tommelein and Gholami classified clashes based on their existence into (i) hard clashes, (ii) soft clash, and (iii) time clash [1]. Afterward, Akponeware and Adamu reviewed the factors influencing hard and soft geometric clashes [2]. This work identified 12 drivers of clashes and mentioned the scarcity of experts, designers working in isolation, and design errors as the most prominent drivers among them [2]. Other important causes mentioned in this work included failing design rules, the use of different file formats, and discrepancies in 3D modeling. Mehrbod et al. specified design discrepancy, design error, and missing items as the causes of design coordination issues [3], design error being the most frequent cause in the study. Elyano and Yuliastuti corroborated this in their case study where they found design errors causing 52.36% of the detected clashes which were mostly between structural vs MEP components [4]. Design inconsistency caused 39.13% and design discrepancy caused 8.51% of detected clashes, and these clashes were mostly between structural, MEP, and precast components [4].

This work will address the most prominent causes of clashes identified by contemporary literature while discussing potential clash avoidance strategies. These causes of clashes are: (i) lack of experts, (iii) designers working in isolation, (iii) design errors, (iv) failing of design rules, and (v) discrepancy in design and 3D models.

2. Potential clash avoidance strategies

Strategies that can help reduce the clashes in light of studied literature are discussed in this section.

2.1. Lack of experts

Akponeware and Adamu specified that the lack of experts involved in the BIM-based design process received the most mentions as the main cause of clashes [2]. To increase BIM experts in the construction industry, many studies recommend educating students on BIM-based collaboration platforms and coordination process during their training. Tayeh et al. elaborated that the integration of BIM-based collaboration in the construction industry has made it crucial to include BIM-centric education in construction management and engineering training [5]. This will ensure the success of aspiring professionals by increasing their skill level as well as ensuring proper communication and exchange of information across construction projects. The authors studied the integration of collaborative learning platform in BIM education and documented student’s feedback that identified remote real-time collaboration, ease to resolve communication errors, and availability of information in a single repository as some of the most important benefits of such platforms [5]. Students also specified that such platforms could speed up the model coordination significantly. The authors deduce that such exercises during the training period have the potential of improving the learning experience of future experts. Additionally, researchers emphasized the necessity of skill-developing programs, such as intensive training or workshops in the workplace where experienced professionals can share their expertise to increase the level of understanding and knowledge about BIM [6]. Alongside BIM training, addressing the lack of knowledge about coordination issues faced by team members can be another promising approach. Mehrbod et al. attempted to define a taxonomy of design coordination issues was undertaken that would assist team members in gaining a better understanding of such issues as validated by industry professionals [3].

2.2. Designers working in isolation

According to Akponeware and Adamu, workplace silos or designers working in isolation is one of the primary causes of clashes [2]. Complications in the relationship between team members, such as lack of trust and communication gaps between team members can drive them to work on their own in the crucial preliminary stages of design. To solve this the researchers proposed an open-work-in-progress (OWIP) stage in the common data environment instead of the traditional work-in-progress phase where all disciplines participating in the collaboration can have secure access to the design and provide feedback [2]. To improve the communication within the team Adamu, Emmitt & Soetanto proposed a social BIM framework and tested four distinct types of collaboration protocols ranging from low to high levels of shared situational awareness within the team [7]. The protocol offering maximum shared situational awareness enabled members to communicate with each other over the BIM platform and improves efficiency [7].

2.3. Design errors

Several groups of researchers recognized design errors as one of the most prominent causes of clashes [2] [3] [4]. As explained by Lopez and Love, in the case of an error an unforeseeable or chance intervention takes place [8]. Researchers had previously deduced that the mean direct and indirect costs for design errors were revealed to be 6.85% and 7.36% of contract value with errors leading to schedule delay being the most detrimental [8]. This finding makes design errors a significant hindrance for efficient construction process. Johansson et al. studied the impact of BIM in preventing errors and determined that even though the knowledge of a potential issue and solution of the issue is located in the organization, but there is no matchmaking between these two [9]. Wong et al. after studying the linkage of BIM adoption and error reduction, found clash detection and design coordination to be the two most crucial factors in design error reduction [10]. Formerly, Al Hattab and Hamzeh appraised the use of social network theory and simulation to compare traditional versus BIM/lean-based environments for design error management [11]. The researchers reasoned that errors are resolved faster in a BIM/lean network as individuals detect and resolve errors by frequent checking and communication. According to Al Hattab and Hamzeh, addressing the root causes of human-based errors despite the progress of BIMbased automated checking procedures is important for reducing design errors. The team should analyze the root cause, find the solution, and record lessons learned as defects are detected maintaining a continuous learning attitude and instilling a quality-at-bay principle [11].

2.4. Failing of design rules

Tommelein and Gholami defined the lack of specificity on how specialty systems are to be developed relative to others to avoid occupying each other's space as failure of design rules and identified it as one of the root causes of hard clashes [1]. Many researchers in recent years are studying different applications of artificial intelligence to mitigate such failures which in turn can reduce hard clashes in design significantly. For example, Song et al. investigated deep learning based natural language processing (NLP) techniques for translating design rule sentences into a computer-readable data structure [12]. In this work, a deep learning model was trained to extract the predicate-argument structure (PAS) from the building design rule sentences, and the trained models were used in the rule interpretation process. Here, the computer analyzed building design rule sentences using a bidirectional long short-term memory model to extract the logical elements. As stated by Song et al. this approach has the potential to expand the scope of BIM-enabled rule checking where natural language based design requirements exist [12].

2.5. Discrepancy in design and 3D models

Akponeware and Adamu had identified several causes of clashes from existing literature that can be labeled as discrepancies in the 3D modeling stage of BIM-based collaboration. Use of low or wrong level of detail (LOD), design uncertainty, 3D model objects exceeding allowable clearance, and the use of 2D drawing instead of 3D models are notable among such drivers of clashes [2]. To resolve the issue of low or wrong LOD, the construction industry has started incorporating LOD standards. Some renowned LOD matrixes are being introduced by the United States Army Corps of Engineers (USACE), American Institute of Architects (AIA), and BIMForum. These matrixes provide standards to be referenced by the contract and the BIM execution plan.

Regarding design uncertainty, Tommelein and Gholami went on to state that the use of placeholders by designers might end up causing a hard clash with other systems or components when the exact component intended for the space is uncertain [1]. While contemporary literature does not address this issue separately, open, and constant availability of communication channels between members of the team might help to reduce such clashes. Shared situational awareness among team members can empower them with visual access to the early-stage model and improve the quality of information exchange [7]. Furthermore, in their work, Tommelein and Gholami also raised concerns about soft clashes caused by 3D objects exceeding allowable clearance and components not maintaining minimum clearance from each other [1]. Even though BIM-based coordination tools still struggle to identify soft clashes, researchers have discussed several promising approaches in recent years. In their 2021 work, Mangal et al. investigated the usage of BIM and a two-stage genetic algorithm(GA) to automate clashfree optimization of steel reinforcements in reinforced concrete (RC) structures [13]. In this work, the first stage GA focused to generate clash-free steel reinforcement layout designs. Afterward, the second stage GA optimized the size of steel reinforcement by exploring different diameter combinations of steel reinforcement and minimizing the overall steel consumption. Mangal et al. estimated that this same method can be customized and employed for solving similar design optimization problems such as member sizing optimization [13]. Additionally, Li et al. presented an alternative approach to rebar design optimization with a hybrid metaheuristic algorithm and BIM [14]. This approach identifies activities related to the manufacture and assembly of rebar, then proposes a multi-objective cost design formulation that includes the design code requirements. The authors also proposed the use of a hybrid genetic algorithm incorporated with Hooke and Jeeves's method for rebar clash avoidance and optimization [14]. Furthermore, Y Hu and Castro-Lacouture who had previously investigated network theory for filtering out irrelevant clashes and grouping relevant clashes, explained that considering building as an inseparable whole component is important for holistic clash detection and clash resolution [15] [16]. Y Hu and Castro-Lacouture went on to add that this idea can be further explored for soft clash management alongside clash detection and resolution [15] [16].

The final cause of clashes this study will discuss is the use of 2D drawings instead of 3D models. Akponeware and Adamu mentioned that mandating designers to adhere to a 3D standard can have a positive impact on the issue however this does not address the frequent occurrence of design errors [2]. Contemporary researchers propose the use of cloud BIM for real-time collaboration and easy data exchange within the project team which reduces the possibilities of design errors as well [17]. Onungwa et al. conducted a case study of digital modeling to identify seamless communication, real-time progress monitoring, and visualization of files as some of the benefits of cloud BIM technology [17]. Mostafa et al. explored the most significant BIM opportunities and specified Seamless and timely information exchange among key project stakeholders via a BIM system as the most critical success factor [18]. Bhonde et al. went on to add that the use of virtual reality with traditional drawings can be viable for improving the quality of design [19].

3. Conclusions

This review summarizes current literature that discusses the causes of clashes in BIM- based multidisciplinary coordination and the clash avoidance strategies ranging from shared situational awareness to supervised and hybrid machine learning frameworks. It is also summarized via this review that the most prominent causes of clashes directly occur during the preliminary phases of multidisciplinary coordination which are generating the speciality models and federated models. Researchers emphasize on the importance of documenting lessons learned within the organization so team members can access the information in need and clashes can be avoided. However, there is still no guideline for such documentation. Thus, design teams still struggle with unwanted design errors and discrepancies which increase the number of clashes. Our study points towards future research directions for developing guidelines for proper standardized documentation of lessons learned during multidisciplinary coordination to avoid unwanted design errors and clashes.

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Examining the Suitability of Lean Tools to the Construction Industry in UAE

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Abstract

Lean construction has been capturing the attention of construction practitioners seeking to improve performance at company, project and process levels. With a variety of principles, tools and techniques, Lean construction now has a rich record of successful implementations that positively impacted construction companies and projects. In the UAE, the adoption of Lean construction has started but is progressing with a slow pace. Previous research addressing the implementation of Lean construction in the UAE has addressed different aspects such as exploring barriers to implementation and examining potential impacts. This research takes a step further to bring companies closer to the practical adoption of lean construction. This research examines the characteristics of construction projects in the UAE and analyzes the capabilities of common Lean tools. Through matching the analysis of Lean tools capabilities with characteristics of the local construction market, this research concludes with recommending and discussing a shortlist of tools to be implemented by companies seeking to start adopting Lean construction into their companies and projects. The results of this research contribute to bridging the gap between lean awareness and the actual adoption of Lean in daily operations in companies and projects in the UAE.

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Keywords: construction management, lean construction, productivity, waste reduction.

1. Introduction

The construction sector is one of the largest economy drivers in the UAE, directly contributing to nearly 10% of the country's GDP [1]. Although this sector is witnessing a slowdown in 2022, it is still growing. The construction sector is forecasted to witness a 3.0% year on year growth in 2022 which is lower than 2021 year on year growth of 5.95% [2], while longer term forecasting is predicting cumulative annual growth of 4.69% for the period 2022 to 2027 [3]. The country's social and political stability portrays it as a safe investment and relocation destination for many people originating from less stable countries, which reflects positively on the UAE's construction sector.

In terms of UAE's construction industry's indirect impact, the prosperity of this sector is an essential foundation for the growth of other sectors. For example, the leading status of the UAE as a tourism destination is based on the successful construction of high level infrastructure and globally recognized landmarks such as the Louvre Museum Abu Dhabi, Sheikh Zayed Grand Mosque, Burj Khalifa, Expo 2020 event site accommodating more than 24 million visitors and the recently opened iconic Museum of the Future in Dubai.

However successful, the construction industry in the UAE faces the same steep challenges faced by construction markets all over the world. A recent study [4] surveyed professionals in the UAE to identify and quantify the impact of such challenges and presented the main challenges as design variations, change orders from client and consultant, unachievable schedules, delays due to late issuance of governmental permits, poor cost estimation, delays in payments from client side and slow decision making by the client. The study concluded that these findings match findings of similar studies in various countries. Additionally, the UAE construction sector possesses some unique features and faces additional challenges that are not commonly shared by global construction sectors.

Construction companies active in the UAE are facing a lot of competition bidding for public and private projects as the market is open and attractive for locally and globally established companies. This competitiveness encourages companies to explore different ways to enhance their performance and improve their efficiency. Due to global success stories, one of the efforts gaining popularity lately is the adoption of Lean construction. Through hiring external consultants or qualifying their own engineers, several construction companies are adopting Lean construction to improve their process and project performance, reducing waste and maximizing profit. With these initiatives, it was noticed that companies are initially hesitant to make investments in software and training modules and are left unsure about how to select a Lean tool or method out of the rich portfolio of available Lean tools.

To help address this issue, this study aims at reviewing the main distinguishing characteristics of the construction sector in the UAE, reviewing common Lean methods and tools already proven effective, and recommending Lean methods to be adopted by companies desiring to adopt Lean construction. Through the successful implementation of one of the recommended methods, a company is more likely to develop the confidence to invest in a more comprehensive adoption of Lean construction.

2. Relevant Lean Construction Studies

Several research initiatives have been directed towards investigating the application of Lean construction in UAE. A few other initiatives were directed towards similar markets such as other Gulf Cooperation Council (GCC) countries and the middle east and are also considered during the course of this research due to the similarities between these markets. Research published can be grouped into 3 main categories. Research addressing Lean construction application, research assessing the impact and benefits of applying Lean construction and finally research exploring the barriers to applying Lean construction.

Acknowledging the differences in the construction industry between Abu Dhabi and UK and the US, a study was carried out in Abu Dhabi which aimed at assessing the need for and the degree of applications of Lean construction tools [5]. Using a survey tool, the author asked construction experts in Abu Dhabi to identify types of waste they experience. Out of 27 identified types of waste, the top 5 most common answers were late work delivery, long approval process, activity start delay, repair work and equipment breakdown. The second part of the survey asked construction experts about the frequency they use Lean tools in their projects. The answers were 48% “Always”, 27% “Frequently” 12.5% “Rarely” and 12.5% “No”. These results were interpreted to demonstrate that once a company starts implementing Lean tools, they don’t abandon those tools. Another research conducted was focused on the implementation of Lean construction in Dubai [6]. The research didn’t gather or analyze new data but rather reviewed results of previous research by Kanafani [7]. Since Kanafani had previously identified the possible barriers to Lean implementation in Dubai, Small et al. [6] reviewed those barriers and inferred the likelihood of those barriers to actually impede the application of Lean tools in the Dubai construction market. This paper concluded by recommending the presence of a motivating force such as a Lean change champion, a crisis affecting the construction market or a government directive to motivate the application of Lean among construction companies. Another study explored the implementation of Lean construction in Morocco [8]. Through a questionnaire survey, the authors gathered information on awareness of Lean construction among experts in the Moroccan construction industry. The experts were asked about 18 Lean tools extracted from literature, and the results indicated that 17 tools were being used. 39% of the experts were not familiar with any Lean tools, 35% were familiar with some Lean tools but never implemented them, and 26% are implementing Lean tools in their projects. A different angle was explored by Watfe and Sawalha [9] as they researched the critical success factors for the application of Lean Construction in the UAE. After an extensive literature review the authors extracted 22 success factors, and due to similarities between some of the factors, this list was reduced to only 15 factors. Through a survey tool, the authors asked construction professional in UAE if each one of these 15 factors is considered critical to the successful implementation of Lean construction. The results indicated that 13 out of the 15 factors were identified as critical to success, with the top three being management commitment and involvement, organizational culture and employees' participation and motivation. A secondary finding of this study is that Lean construction is not widely used in the UAE, as 62% of the surveyed companies were not familiar with or using lean tools.

In terms of assessing the impact of applying Lean, Shurrab and Hussain [10] conducted an empirical study to assess the impact of applying Lean to the construction industry in Dubai. Instead of assessing the impact of each one of the many Lean tools, the authors classified Lean tools into categories according to what each tool addresses. The categories are waste reduction, process focus, end customer focus, continuous improvement, business performance indicators, economics and competitiveness. Without quantifying the impact, the authors surveyed construction experts and asked them which of these categories have more impact on construction performance. It was concluded that continuous improvement, process focus and waste reduction were the top three categories, while economic performance was the least impactful. Another study to assess the benefits of applying Lean construction was conducted in Egypt [11]. This research identified 31 potential benefits of applying Lean and asked construction experts from Egypt to rank those benefits in terms of their importance. The results indicated that in terms of importance, experts identified the top three desirable potential benefits to be improving process control, improving planning and improving material storage control. It is worth noting that this study didn't attempt to quantify the benefits of applying Lean construction and didn't ask how likely is applying Lean construction going to result in achieving such benefits. The questionnaire was only asking practitioners to rank the benefits based on their importance, this was seen as a motivation for experts to further adopt Lean construction.

Lastly in terms of exploring barriers of applying Lean construction, two publications were located. The first was conducted by Sarhan et al. [12], where the authors investigated the barriers to the implementation of Lean construction in Kingdom of Saudi Arabia (KSA). The authors extracted 22 barriers from literature and asked construction professionals to rank these barriers. The top ranked three variables were the influence of traditional management practices, unfavorable organizational culture and lack of technical lean techniques skills. The authors re-produced the ranking again based on replies only from contractors and another time based on replies only from consultants and very few differences in rankings were noticed, which enforces the meaningfulness of these results. Secondly, a similar research was conducted but targeting UAE [7]. The author asked construction experts to rank barriers to implementing Lean construction extracted from literature. Experts were asked to identify if each factor is very unlikely, unlikely, undecided, likely or very likely to influence the implementation of Lean construction. Out of the 35 listed factors the most likely to be influential factors were incomplete and complicated design, cyclic nature of the construction industry and no or limited involvement of contractors in the design process. By the cyclic nature of the industry the author meant that the industry is easily affected by economic status as it grows and slows down with the economy as experienced during the crisis in 2007.

After reviewing the relevant literature, it can be seen that the awareness of Lean construction in UAE and similar regional construction markets exists but is still limited. The publications located addressed the application of Lean construction, attempted to assess the impacts of applying Lean construction and also identified barriers to applying Lean construction. Most of the research conducted relied on extracting initial information from literature and then surveyed professionals to augment this information relying on their experience to qualitatively assess different factors.

3. Characteristics of Local and Regional Construction Markets

In order to be able to nominate Lean construction tools for the initial adoption by companies desiring to try Lean construction in UAE, an insightful look at the characteristics of Construction projects in UAE is needed. The localization of this research is essential as different cultures and geographies lead to necessarily different construction and production plans [13].

The boom in the construction industry in UAE has been mainly linked to money from oil and gas sales. This guarantees availability of liquidity in the country; this liquidity is being continuously directed to big numbers of construction and infrastructure projects. To procure enough labor to suffice the needs of the construction market, UAE relies mainly on overseas workforce. This workforce, typically from south east Asia, is characterized by being under-compensated, poorly trained, and of limited experience. Managing affordable workforce invites managers to add more workers rather than train workers in response to drops in productivity or delays in progress. Accordingly, this workforce is managed with a strong authoritarian management style. This leads to a decrease in workforce motivation and lack of focus on assigning clear responsibilities and measuring performance [6].

The local and regional construction markets tend to put more pressure on time rather than on cost. Being an oil-rich country levitates some of the financial pressures that would be the most important constraint in other markets, especially developing countries [6]. The increased pressure for shorter schedules results in starting projects with incomplete designs where items in tender are priced as “provisional items” until design is later completed. This increases the numbers of change orders and disputes arising during the project, and limits a contractor’s ability to optimize construction plans before start of works.

Another relevant characteristic of the construction industry in the region is the amount of solid waste produced. Studies addressing waste in GCC region found that the weight of waste is 120 million tons in total and average waste per capita is 1.8 kg putting GCC among the top 10% global waste producers per capita. The portion of waste generated through construction related works mounts up to 55% in GCC and 75% in Abu Dhabi, UAE [14, 15, 16].

Other characteristics include lack of proper risk management practices [7]. This results in diminished or absent contingencies in budget at the bidding stage, followed by poor management of such contingency amounts during the project. Also, the increased number of project participants (government entities, client, consultants, contractors and sub-contractors and providers of professional services) results in delays in obtaining different permits and project approvals unlike other countries [4].

Finally, this region is known for its hot weather and very high humidity levels. This weather has a direct impact on productivity over extended months, starting around May and lasting till around October. The peak impact on construction works is between the 15th of June till the 15th of September, were companies are prohibited by law to carry out work in open spaces for a daily period starting at 12.30 pm and lasting until 3 pm.

4. Examining Suitability of Common Lean Tools

A number of tools that are commonly used for Lean construction are identified to be investigated in this research. The aim of this investigation is to examine the suitability of these methods to be applied by a company seeking to try Lean construction in UAE. For this aim, several aspects are considered when analyzing Lean methods. Each method is analyzed in terms of its expected benefits, required investment in terms of time, technology and training required, its applicability within a construction company’s teams (as opposed to being applied between different project participants), and its resonance with UAE’s construction market characteristics discussed earlier. A brief description of each of these methods is provided along with an analysis of its suitability to the construction market in UAE, and a summary is shown in Table 1.

Just in time (JIT): JIT is one of the most known tools for Lean construction. It is a method that aims at providing supplies only when needed. This applies to supplying materials, information and any resources, and also to releasing work from upstream stations to downstream stations. The main benefit is to reduce waste through reducing inventory, and help achieve *Pull* which is one of the goals of Lean. Although JIT is proven to be beneficial in construction, it is not easy to apply as the - typically long - supply chains are run by vendors not the main construction company. Accordingly applying JIT requires motivating and qualifying vendors to apply JIT and depends on forming long term relations with qualified vendors. It may also necessitate using specialized software to communicate work progress and organize the release of work and supplies.

Kanban: this tool is used to organize the use of inventory items during a project. It organizes the amounts and times materials and supplies are pulled from inventory and tracks their usage along a process. Kanban does this tracking typically using marking cards, and recently through a computer or mobile application. As construction sites witness waste in the form of increased inventory, items lost or damaged in inventory and poor tracking of use of supplies, Kanban can be very beneficial. It doesn't require purchase of technology or extensive training and can be easily run by supervisors and store keepers.

5s Process: this method aims at clearing, organizing and cleaning work areas and sites. This structured housekeeping activity reduces time spent looking for tools, prevents accidents and increases productivity. This method doesn't require investment to adopt and is easy to turn into a habit through repetition. In UAE construction sites are typically periodically cleaned and waste is hauled away, which leaves less beneficial impact for 5s process to add.

Increased Visualization: This method refers to the efforts simplifying construction processes through improving communication between involved parties and facilitating information flow. This can be achieved with limited impact through bill boards and visual performance dashboards, and with higher impact in case of the adoption of modern technologies such as virtual reality models of projects and 4D BIM models. Increased visualization improves constructability, reduces mistakes and miscommunications, increases productivity and enhances safety. However, shifting to use modern technologies requires investing in software and training.

Standardization: This process aims at developing standard methods to be followed by workers in repetitive tasks. Those methods are developed to optimize workers performance. Developing standardized operating procedures helps workers avoid waste, increase productivity and enhance safety. This method is easy to adopt in construction as workers are expected to receive training and frequent instructions. Taking the time for supervisors and engineers to optimize workers processes and teaching workers doesn't require significant investment and can be particularly useful in UAE as it directly addresses the issue of workers with poor training and limited experience.

Prefabrication: this method aims at increasing the amount of work performed off-site in comparison to work done on site. Work performed off-site, such as when using precast concrete or modular construction, is of better quality and produced at better efficiency. Reducing the amount of on-site work reduces site area, site indirect expenses, and site waste and enhances safety. Applying prefabrication necessitates establishing off-site workshops and factories, and producing designs that are fit for prefabrications. Although beneficial, adopting this method is contingent upon a significant upfront investment.

Last Planner System (LPS): LPS is a planning system especially designed to facilitate Lean delivery of projects. Through multiple layers of schedules, LPS focuses on involving participants closer to the work (called last planners), scheduling only activities that are free of constraints and making reliable commitments rather than promises to complete tasks. By doing so, using LPS helps improve workflow, reduce variability and reduce wastes. Adopting last planner does not require investing in software, however, to achieve full benefits it ideally involves all project participants (consultants, different contractors and suppliers), which requires significant preparations and training before project starts.

Value Stream Mapping (VSM): VSM works by graphically representing the current state of a process while including flow of material and information between different process steps and taking different efficiency related measurements. After classifying steps into value-adding and non-value-adding, VSM helps produce a future state of the process which is ideally more efficient and more focused on value-adding activities. By doing so, VSM helps reduce wastes such as waiting and inventory between steps and work flow interruptions. VSM doesn't require investing, but requires trained personnel to analyze processes, and identify and eliminate wastes, and has to be followed by training workers to follow new process map. Due to poor workers management in UAE, VSM has the potential to significantly improve labor intensive processes. As construction sites are highly dynamic, VSM can be continuously repeated as the same process takes different shapes as a project evolves.

Total Quality Management (TQM): TQM is a management approach that seeks to involve project participants from different companies, departments, teams and managerial levels to manage the project. These participants are integrated in a quality steering committee and tasked with optimizing project delivery decisions to achieve project's required quality and other objectives. The cooperation of committee members with different backgrounds and with unified objectives helps avoid miscommunication, reduce waste and better achieve project objectives. This management approach specifically resists the prevalent authoritarian approach in construction companies in UAE. TQM requires training and orienting a group of people and helps improve works quality and reduce works through reducing mistakes, rework and constructability issues.

Five Whys: this is a problem-solving technique, that provides a structured approach to reach enough depth to find root causes of detected problems. It works by asking "Why" for five times, to find five layers of reasons behind a surface problem. Answering the questions means the causes for the problem have been identified which leads to solving the problem from its roots. This method's efficiency depends on properly identifying the problem and finding the right answers to the questions. Using Five Whys correctly can lead to different kinds of process improvements on construction sites.

Table 1. Summary of Lean Methods Review.

Lean Method	Anticipated benefits	Required investment	Applicability
Just in time	Beneficial if applied in full scale for releasing work and tracking supplies	May require specialized software	Requires qualifying users from project participants outside contractors' company
Kanban	Beneficial in tracking inventory usage addressing a common construction source of waste	May require specialized software	Applied by a small team within contractor's team
5S	Not significant compared to current practices	Training workers for simple tasks	Applied within contractor's team
Increased Visualization	Beneficial in producing designs better suiting workers capabilities, reducing mistakes and enhancing safety	Considerable investment in technology	Requires involvement of multiple parties beyond contractor's company
Standardization	Beneficial in terms of improving workers performance. Contributes to improving productivity, reducing waste and enhancing safety.	Doesn't require investment or involvement of external training	Can be applied within contractor's team
Prefabrications	Beneficial as it reduces work on site, which is a source of many issues	Requires considerable upfront investment in off-site facilities	Requires designs to suit prefabrication and might require client's involvement
Last Planner System	Generally beneficial, but doesn't address UAE market specific problems	Requires training project participants at different levels (managers, engineers and supervisors)	It cannot be applied within contractor's team only, and requires a culture change to empower supervisors to make scheduling decisions
VSM	Beneficial in optimizing processes	Requires qualifying a limited number of engineers to optimizes value stream, followed by training workers to apply new map	Applied by a small team within contractor's team
TQM	Beneficial, as specifically changes UAE authoritarian management style	Requires qualifying a limited number of participants	Requires culture change as supervisors and workers participate in making decisions
Five Whys	Benefit contingent upon identifying important solvable problems	Requires qualifying a limited number of participants	Applied by a small team within contractor's team.

5. Discussion and Conclusions

This research aimed at bridging the gap between research and application of Lean construction in UAE. The objective was to nominate several Lean construction tools to be applied by construction companies keen to explore Lean construction without making big investments or hard to justify commitments. This research discussed several characteristics of the construction market in UAE. Due to limited number of publications, this research took into considerations publications exploring characteristics of similar regional construction markets. Key characteristics identified include high dependency on less qualified and poorly compensated overseas workforce, more pressure on schedule in comparison to cost and high volumes of solid waste. Ten of the most common construction tools were reviewed to investigate their suitability for the companies new to Lean construction in UAE. This suitability was detailed in terms of each tools anticipated benefit, its required investment mainly in terms of technology and training, and its ease of applicability within a company instead of in-between different project participants. The verdict on the ten reviewed Lean tool is delivered through classifying the tools into two groups based on being recommended or not recommended for application.

The tools that are considered not recommended for early adoption of Lean construction include JIT as it requires participation from vendors and suppliers, who will take time to convince and qualify for applying JIT. Increased Visualization and LPS are also not recommended for similar reasons. For both of these methods to be properly applied they require participation from different project participants beyond contractor’s team. Given that the lack of contractors participation in the design process has been previously identified as one of the barriers to applying Lean construction, these two methods are not recommended. Although 5S method is easy to adopt, but it is not recommended, as the anticipated benefits are not significant in comparison to current practices in construction sites in UAE. Relying on Prefabrication is also not recommended due to the significant upfront off-site investment. The last reviewed tool that is not recommended is TQM, as the proper application of TQM forming a quality steering committee involving field supervisors and workers in decision making. This requires enforcing a degree of culture change which takes time to be accepted, given that the prevailing influence of traditional management practices has been previously identified as a barrier to applying Lean construction.

The recommended methods are more focused on solving problems and enhancing process efficiency more closely related to workers performance. The first is Kanban, which is recommended for two reasons. Firstly, due to its relative ease of adoption as it can be adopted by a few people on site, and secondly due to its direct contribution to solving the problem of excessive solid waste produced on construction sites in UAE. Five Whys method is also recommended for adoption. Five Whys is not problem specific and can be directed towards different problems related to waste reduction or to workers performance. With repeated application of Five Whys the gained experience will help better identify problems and their root causes paving the way to solving these problems. A final recommendation is to adopt VSM and Standardization jointly. VSM is extremely useful identifying problems and inefficiencies through mapping, and an improved future state of the process can be used to standardize workers performance. Jointly both methods do not require investment in equipment or technology, and can in a reasonable time frame improve workers and processes performance.

As as these methods are initially recommended for adoption by companies starting to adopt Lean construction, it is concluded that further research is needed for two purposes. The first purpose is to validate the recommendations provided above through feedback from construction experts and Lean construction practitioners in UAE. The validation is needed as this research relied on theoretical exploration of the topic, accordingly, a more practical input on the suitability of the recommended methods to the UAE construction market is needed. The second purpose is to provide a more specific set of recommendations. The specific recommendations could be nominating one particular Lean tool to be applied for a particularly inefficient construction operation, or focusing on a specific project type (residential, commercial or infrastructure), a specific sector (public or private) or a specific project delivery system.

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Factors Constraining Work Motivation in Construction Projects: A Case Study in Vietnam

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Abstract

Motivation plays an important role in improving construction labor productivity (CLP). Although previous studies have identified various motivational factors affecting CLP, exploring factors constraining work motivation in construction projects has been rarely discussed. This study attempts to bridge the research gap by identifying and assessing the key barriers to the work motivation of the construction workforce. This study differs from past studies in CLP research by investigating the severity level and occurrence frequency of barriers to work motivation in construction projects, and a more realistic ranking of these factors by adopting a risk mapping approach. Based on a comprehensive literature review, this study managed 35 factors constraining work motivation in construction projects. These factors were presented in a questionnaire to investigate the severity and frequency of occurrence. The risk mapping approach was adopted to evaluate the 215 completed responses. The results indicated that the following barriers as the most significant factors constraining work motivation in construction projects: (1) payment delay, (2) lack of financial incentive schemes, (3) lack of professional training and advanced learning opportunities, (4) poor work conditions, (5) unskilled workforce, and (6) work dissatisfaction.

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Keywords: Construction Industry, Factors; Labor Productivity, Motivation; Risk mapping.

1. Introduction

Despite the significant technological advancements, construction remains an intensive labor industry [1]. Improving construction labor productivity (CLP), therefore, is very important for implementing construction project performance successful. This domain has been frequently discussed within the research community and construction practitioners; consequently, various factors affecting the productive capacity of the labor force have been identified and assessed to reveal reasonable strategies for effectiveness and efficiency of construction workforce management, enhancing CLP particularly [1-3]. Previos studies emphasized the importance of human-related factors affecting their productivity in construction projects. These factors, for example, experience [4, 5]; attitude [6-8]; self-confidence [8, 9]; behavior [6, 10]; motivation [5, 11-13]; aptitude [8, 14]; solving problem ability [8, 15]; and desirable [8]. Among them, motivation was demonstrated as a significant element affecting labor productivity, which is one of the most driving factors for the overall productivity of a construction organization [11, 13].

Although previous studies have identified and assessed various motivational affecting CLP, exploring factors constraining work motivation in construction projects has been ignored. This knowledge gap hampers further efforts to explore new determinants that promote work motivation and increase CLP. In the Vietnamese construction industry, the literature on work motivation or CLP issues is still very limited. This leads to ambiguity in both the academics and the Vietnamese construction industry regarding the practical importance of exploring factors constraining work motivation in construction projects.

To assess motivational or demotivational factors affecting CLP, previous studies have adopted several approaches such as mean, Relative Importance Index by only using the level of influence without considering the frequency of occurrence of each factor. This could not provide a comprehensive picture to reflect the fact role of these factors in construction projects.

This study was designed to fill these gaps by investigating factors constraining work motivation in construction projects. These factors were assessed by adopting a risk mapping approach based on considering severity level and their occurrence frequency in the Vietnamese construction industry context. The results of the study have evidential uniqueness, methodological novelty, and contribute to the knowledge of construction workforce motivation barriers, thus making a visible contribution to the science of human resources management.

2. Research method

This study managed 35 factors constraining work motivation in construction projects by referencing previous studies and considering the specific context on construction industry in Vietnam. These factors were then tabulated in a questionnaire.

A total of 215 workers involved multi-storey residential buildings in Vietnam were chosen for the interview to fill out the questionnaire. The majority of the respondents were male (87%), which reflects the male-dominated characteristic of the Vietnamese construction industry; whereas, only 13% were female. They worked in two main trades, including 122 rebar workers (56.7%) and 93 masonry workers (43.3%). In terms of educational levels, 65 (30.2%) completed primary education or no schooling, 94 (43.7%) acquired secondary education and 26% (n = 56) had credentials covering high school or above. Out of the 215 workers, 23 (10.7%) aged less than 23 years old, 139 (64.7%) aged from 23 to 35 years old, and workers have more than 35 years old were 53 (24.6%). In terms of work experience, 94 (43.7%) workers have less than 5 years of experience, 84 (39.1%) workers with experience of 5 to 10 years, and 37 (17.2%) workers have more than 10 years of experience.

This study adopted the risk mapping to measure severity level of each barrier to work motivation and its probability of occurrence in construction projects. We decided the limits of each zone by looking at past studies applying the risk mapping [16, 17]. Accordingly, the low-risk zone would have a severity times frequency (SF) value from 1 to less than 10, the moderate-risk zone would have a value from 10 to less than 14, and the high-risk zone would have a value from 14 to 25. To calculate SF, the severity index (SI) and the frequency index (FI) are estimated by using mean value of each barrier. The SF will be calculated according to equation (1) as follows:

$$SF = \text{Severity index (SI)} \times \text{Frequency index (FI)} \qquad (1)$$

3. Results and discussions

Table 1 indicates the analysis of 35 factors constraining work motivation in construction projects. Each barrier's average severity level and its frequency of occurrence, the multiplication, and the risk zone is based on all completed responses.

Table 1. The results of barriers to work motivation in construction projects

Barrier	SI	FI	SF	Risk Zone
Bad treatment by supervisors	3.79	3.35	12.68	Moderate-risk
Changing on workmates	3.42	2.47	8.44	Low-risk
Delay in responding to Requests for Information	3.60	2.43	8.76	Low-risk
Delay in payment	3.92	3.67	14.37	High-risk
Health personal problems	3.81	3.64	13.87	Moderate-risk
Inadequate managerial competence	3.88	3.50	13.60	Moderate-risk
Inappropriate evaluation and feedback	3.76	3.47	13.04	Moderate-risk
Inclement weather	3.44	3.48	11.97	Moderate-risk
Incompetent teammates	3.77	3.07	11.56	Moderate-risk
Laborers' disloyalty	3.72	2.30	8.57	Low-risk
Lack of cooperation	3.39	3.44	11.67	Moderate-risk
Lack of discipline on site	3.75	3.45	12.92	Moderate-risk
Lack of financial incentive schemes	3.91	3.91	15.26	High-risk
Lack of participation in decision making	3.76	2.24	8.43	Low-risk
Lack of periodical increment	3.98	3.34	13.28	Moderate-risk
Lack of professional training and advanced learning opportunities	4.30	3.64	15.63	High-risk
Lack of recognition of efforts	3.76	3.24	12.17	Moderate-risk
Material unavailability	3.60	3.71	13.36	Moderate-risk
Not enough challenging task	3.56	2.67	9.48	Low-risk
Not enough responsibility	3.77	3.41	12.86	Moderate-risk
Overcrowded work areas	3.42	2.40	8.22	Low-risk
Overloads and working long hours	3.40	3.50	11.89	Moderate-risk
Personal life interference	3.73	2.46	9.15	Low-risk
Poor communication	3.40	3.22	10.94	Moderate-risk
Poor inspection and supervision	3.70	3.47	12.85	Moderate-risk
Poor relationship	3.41	3.55	12.11	Moderate-risk
Poor work conditions	3.93	3.76	14.79	High-risk
Quarrels and hassles	3.38	3.42	11.56	Moderate-risk
Rework	3.60	3.52	12.66	Moderate-risk
Strict company policy	3.83	2.33	8.92	Low-risk
Tool unavailability	3.00	3.80	11.39	Moderate-risk
Underpayment for the work done	3.90	3.55	13.85	Moderate-risk
Unrealistic contract duration	3.78	2.31	8.73	Low-risk
Unskilled labor force	3.83	3.76	14.40	High-risk
Work dissatisfaction	3.83	3.74	14.33	High-risk

As provided in Table 1, among 35 identified barriers, 9 barriers were classified in the low-risk zone which revealed these constraints have a low impact on work motivation of workers participating in construction projects; 20 barriers were located in the moderate-risk zone, representing medium risk factors; whereas, 6 constraint factors were located in the high-risk zone of the risk mapping. This means these six barriers have the highest negative impact on work motivation in construction projects. These six barriers assessed in the present study were of great severity, and their negative impacts should be taken into consideration. Accordingly, the surveyed respondents ranked the following barriers as the most significant constraints were (1) payment delay, (2) lack of financial incentive schemes, (3) lack of professional training and advanced learning opportunities, (4) poor work condition, (5) unskilled workforce, and (6) work dissatisfaction.

Based on the findings, several recommendations were proposed to enhance work motivation in construction projects as follows:

Payment on time should be ensured by construction companies because delaying salary payment may lead to a decrease in their motivation because they tend to be unwilling to perform designated tasks in an efficient manner, resulting in a low productivity level.

It is necessary to promote and reward construction laborers as a way of enhancing motivation and work satisfaction to improve labor productivity in the work environment [18]. Being rewarded, while not being financially exclusive is key motivational factor that improved the construction workforce's productivity [19].

Lack of professional education for the construction workforce is now a reality in Vietnam where workers have mostly improved their skills only through the apprentice-craftsman relationship on sites. Due to the insufficient professional construction workforce, recruiting skilled laborers is challenging for many Vietnamese contractors. To meet the demands and fill the skill gap, it is essential for construction companies to invest in human resource development programs that increase the availability of a skilled pool of professional workers through short training programs, on-the-job training, or seminars in occupational establishments.

In the construction site, a better work conditions enable workers to do their harder and more efficiently and effectively in their tasks. Ambient temperature, lighting condition, ventilation, air quality, and facilities on site such as restrooms, food, and rest areas should be carefully considered by construction managers in order to motivate them willing to participate in tasks; which leads to reaching higher productivity.

Unskilled and poorly trained laborers are commonly characterized by low and faulty outputs coupled with unjustifiably high inputs. Construction managers should pay more attention to well-arranged tasks onsite to mix unskilled and skilled workers among a construction crew in order to reduce rework and optimal work performance.

Lack of development opportunities, poor relationships with teammates or supervisors, and unchallenging work were the most influential elements causing worker's dissatisfaction [20]. Construction managers should tackle these issues early on in order to enhance worker's satisfaction which may result in higher productivity, enhance work motivation, and promote collaboration which contributes to construction project implementation successful.

4. Conclusion

This study aimed to identify and assess the most influential work motivation barriers in construction projects. A literature review was carried out to reveal a list of 35 barriers. The data was collected from 215 workers in Vietnam by using the questionnaire survey to investigate the severity level and occurrence frequency of barriers. A Cronbach's test was adopted to validate the reliability of internal consistency. The risk mapping approach was used to measure the severity level and occurrence frequency of each barrier. The results showed that the most significant constraints on work motivation in construction projects were: (1) payment delay, (2) lack of financial incentive schemes, (3) lack of professional training and advanced learning opportunities, (4) poor work conditions, (5) unskilled workforce, and (6) work dissatisfaction. This provided a better understanding for construction managers to minimize and eliminate the adverse effects of the most barriers to enhance work motivation and labour productivity and, consequently, increase the chance of implementing construction projects successful.

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SMARTbook for Foreign Construction Focus Japan

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Abstract
Execution of successful construction projects involve knowledge and experience in means, methods, codes, regulations and business practices. These elements vary in international settings. Foreign United States (US) Government construction increases complexity as it encompasses both local nation and US facets. The requirement for employees to return to the US from foreign assignments after five years compounds the challenges as the pool of experience is continually drained. The importance and effectiveness of developing a usable training guide to capture institutional knowledge for incoming personnel was studied for content, format and if current employees would be receptive to using such a tool. The SMARTbook platform was analyzed to see if it would be an executable format for US foreign construction subjects. This study focused on The US Army Corps of Engineers (USACE) Japan Engineering District (JED), employees were surveyed on their opinions on content and interest. The feedback provided the overall contact structure for a JED based SMARTbook. Employees' responsiveness to a guidebook was a resounding yes with caveats of apprehension that another large doctrinal type document would be circulated.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2022.

Keywords: construction, guide, japan, smartbook, training.

1. Introduction

Building in a foreign country on American (US) bases poses very unique challenges on standards and methods spanning all facets of project development and execution. A majority of materials and labor are from the local market. There is considerable rotation of government staff in overseas positions due to the 5-year rule. Even an experienced engineer has a considerable learning curve when working with foreign partners. That curve may be significantly shortened if there was an engineering focused smartbook for USACE employees.

The US government uses a range of "SMARTbooks" to familiarize personnel when they are going to be working in a foreign country or in a specific field. Foreign country specific books cover geography, cultural norms, wildlife, weather and other key elements that define a country's identity. Some of the specialty field literature are disaster response, foreign training, advise & assist, and country culture guides of US government operations. The format and logistics for SMARTbook use are already within the government system. That SMARTbook format should be transposed into usable country specific construction guidance for US forces in international environments.

The United States Army Corps of Engineers (USACE) conducts a significant amount of construction in foreign countries. Specifically in Japan, they are responsible for all construction on the 23 military bases in Japan [1]. Because a majority of the work is on US bases, there are US codes to follow – most of the time. Dependent on the type of construction, Japanese codes are sometimes followed. Additionally, because of logistical and maintenance challenges "equivalent" means methods and materials may be used. There are instances when the specification would normally call for US standards, but there are often Japanese standards that can be substituted. For example, a typical US contract may require a material to meet an American Society for Testing and Materials (ASTM) standard. If working with Japanese materials, meeting that certification is not reasonable. Therefore, contracts generally allow materials that meet Japanese Industrial Standards (JIS). Knowing how to employ these alternative practices is often unknown to the heavily rotated staff. There are also "host nation" projects which are funded by the Government of Japan, wherein US codes are not followed at all. This is just a small sample of the unknown challenges a US Government employee faces when executing construction projects abroad.

Currently, there is no centralized location whether in onboarding packets, unit website or office reference materials for employees to understand the specific construction challenges inherent to the nation they are working in, in this case Japan. It appears, the way people learn what items they need to focus on are when modifications are necessary and this occurs too late. There is an onboarding process for new hires but that is mainly setting up desks, email accounts and generic cultural and geographic factoids. There is little guidance a new employee to Japan Engineering District (JED) would even know to ask questions about with regards to construction in Japan.

The Department of Defense has already identified the need for "SMARTbooks" – basic travel guides to new environments and operational standards.

> "SMARTbooks: Reference Essentials for the Instruments of National Power (D-I-M-E: Diplomatic, Informational, Military, Economic)! Recognized as a "whole of government" doctrinal reference standard by military, national security and government professionals around the world, SMARTbooks comprise a comprehensive professional library designed with all levels of Soldiers, Sailors, Airmen, Marines and Civilians in mind. SMARTbooks can be used as quick reference guides during actual operations, as study guides at education and professional development courses, and as lesson plans and checklists in support of training [2]."

This platform already integrated into the Department of Defense. The government purchases SMARTbooks developed in the private sector and create their own. Army branches create "smartbooks" for initial training for that specific field [3]. There is even a smartbook on how to properly employ military doctrine [4]. The idea to create smartbooks to assist Department of Defense assets abroad would not be out of scope for the military's mission.

2. Literature Review

Individual governmental entities have created their own smartbooks. These can range from government agency publications down to the tactical military unit. The smartbooks surveyed exist to serve one of two purposes: to familiarize new personnel to the mission or to provide a single source collection for multiple references. The CIA has developed a "WORLD FACTBOOK" [5] that encompasses global regions, countries and comparisons. US Army Headquarters used the smartbook format to explain the relevance and hierarchy of its multitude of Joint Publications (JP), Army Doctrine Publications (ADP) and Field Manuals (FM) [4]. The Combined Arms Center created a smartbook to "exploit lessons and best practices from numerous warfighter exercises, experiments, and named operations in order to empower division commanders and their staffs to learn from others [6]." The Army's Chaplains Corps produced a smartbook to assist incoming officers [3].

There is a wide range of individually published "smartbooks." When the need arises for a centralized reference for mission familiarization, a smartbook is developed. In order to develop a consistent series that would be adaptable to the different sovereignties the US government operates in, a tested format should be employed for ease of transition and familiarity to the end users. For this reason, the official "SMARTbooks" publications will be used as the model for development.

The breadth and depth of these tools are as varied as the subject matters. Using the SMARTbook format, they are anywhere between 100-300 pages. They begin with NOTES TO READER; which is a basic introduction of the scope of the SMARTbook. Definition of key terms follow and documents the references used in the development of the SMARTbook. This is where all the regulations, codes and doctrinal publications are credited. After this publication orientation is the table of contents which enumerate 5-10 chapters. Each chapter is broken up into anywhere from 5-25 subheadings. It is common to have three or four subheadings on the same page. This detailed table of contents allows for quicker reference use.

The JED Fact Sheet is the only Japan construction-oriented document distributed to new employees. It is a two-page PDF that discusses the history of the organization, the area of operation and the basic mission. The only guidance that indicates a difference of mission from US based missions is as follows:

> “The Japan District differs from most stateside districts in two respects. First, it does not have a “civil works” mission, i.e., congressionally-funded projects and programs such as flood control, dredging, hydroelectric power, and wetlands regulation. Second, the district has a Host Nation Construction program, mostly funded by the Government of Japan, which provides the majority of work for the district. Host Nation projects are designed and constructed in collaboration with the Japanese government. The district provides coordination, facilitation, and oversight to ensure that the facilities meet U.S. life safety and operational criteria. [7]”

Although it does mention “Host Nation” projects, it does not explain what those are, what effects they have on construction norms compared to the US, nor the differences in US funded military construction (MILCON) projects within Japan.

The US Army Japan (USARJ) website is used to orient new staff to being stationed in Japan [8]. It includes information on Japanese customs, geography, US forces presence, driving tips, disaster preparedness and links to local US media publications. There is no USACE specific information nor assistance in addressing challenges in construction overseas. As most international private sector work does not need to encompass US standards in construction, no trade documentation would address the specific challenges the DoD faces with construction on foreign soil.

3. Research Methodology

The current employees of JED were surveyed to find if they believed there was a gap in their ability to perform because of unknown differences in construction in a foreign environment. The disciplines and subject areas were quarried. The creator of the SMARTbook publication series was interviewed and the focus of the JED commander were used in conducting research.

A 12-question survey was distributed via email link. It was divided into two branches: one for the American and one for the Japanese employees. This was to differentiate those that rotate regularly and would be the target audience of the SMARTbook from those that have longevity with the organization and bear witness to the assimilation patterns of incoming staff.

The intent of the survey was to answer the key question of interest of the target audience. Questions were also included to help develop the scope of the SMARTbook subjects. Of the 412 employees of JED, 127 responded to the survey. This size of response achieves a 99% confidence level with an interval of 10, producing reliable response assessments.

The developer of SMARTbooks, Mr. Norman Wade was interviewed to understand the reasoning behind SMARTbook development and if it would be a transferable tool for the subject of foreign construction [9]. Interview questions were formed to answer key questions on SMARTbook format and depth. The Commander of JED, COL Thomas Verell, recently addressed challenges facing US construction in Japan at the Bilateral Senior Engineer Conference. His talking points such as current local construction market challenges and insights on Japanese contractors’ avoidance triggers for US contracted work were encompassed in the SMARTbook formulation [10].

4. Results and Discussion

The key element in developing a useful tool is to understand the demand and needs. In the survey of JED personnel, identifying the background of potential users as well as data gaps they identify are critical for product development. Firstly, understanding the framework of survey responders is essential for proper evaluation. As overseas government assignments have high turnover rates and restrictions on extended assignments, it was important to evaluate the experience with Japanese construction. Most responders have over five years of experience. However, only about a third of US personnel have that level of expertise. The bulk of experience working with JED is with the Master Labor Contract (MLC) personnel. The bulk of US responders only worked 2-5 years in Japan.

The US personnel surveyed had significant experience working in other foreign environments. Almost all respondents (including the MLCs) state their daily duties are impact by differences in foreign effects, whether US personnel acclimatizing to Japanese requirements or Japanese personnel working within the US government system. When asked on how current standards of training and onboarding, the most common response was "moderately well", but more personnel believed did not prepare them properly than those who had confidence is a well-developed training program. Most personnel are not even aware of what a SMARTbook are let alone its benefits. When a simple description of what a SMARTbook encompasses, a resounding majority believe it would facilitate mission success. The responders that disagreed with SMARTbook deployment stated concerns of "long winded" doctrinal government encyclopedia – which is what the SMARTbook format attempts to sift through to make a usable quick reference guide. The disciplines identified by responders' echoes the general staffing levels for the makeup of JED staff. The areas personnel believe would be most helpful to be included in a guide are subjects that reference scattered information or 1000+ pages of doctrine and regulations (Figure 1).

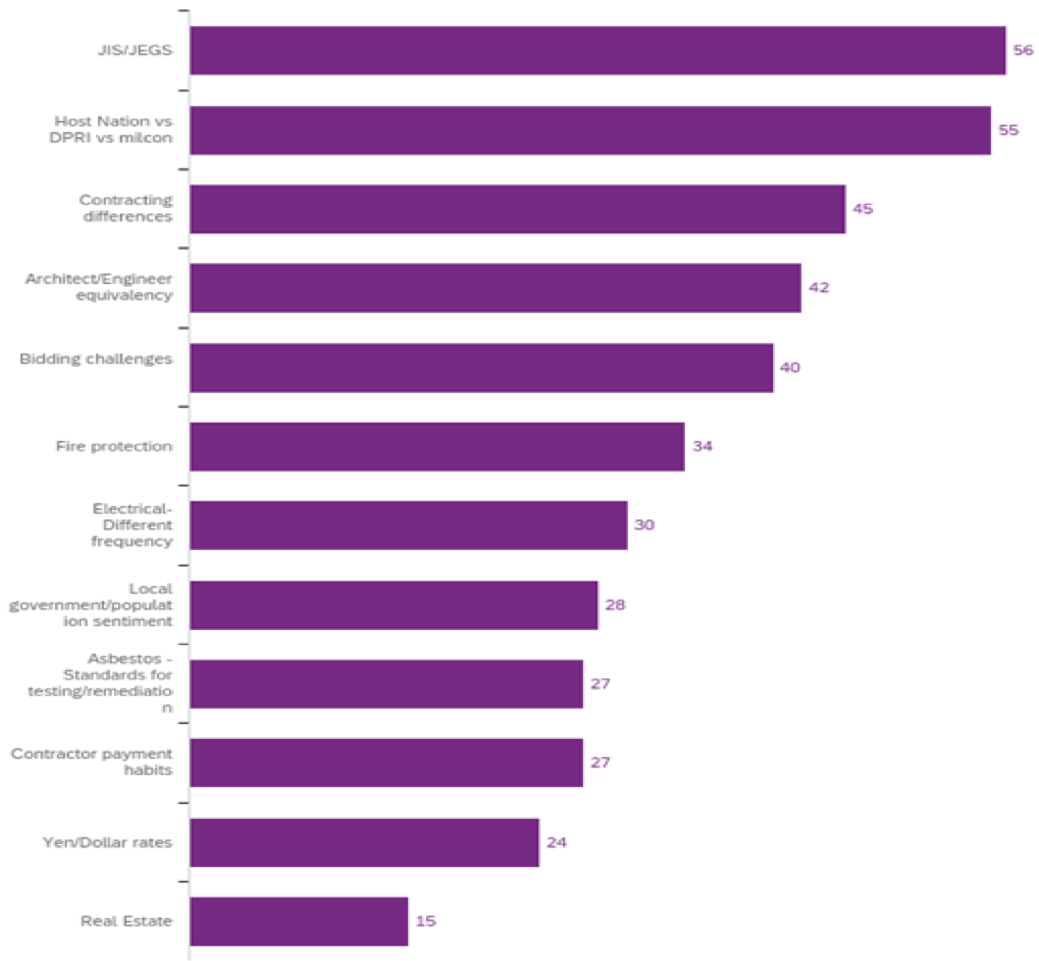

Figure 1: Helpful JED orientation material ranked by response rate

The next step in SMARTbook development would be in the hands of JED leadership. Time and ultimately funding would be required to populate the framework with current and accurate data. Participation from current subject matter experts would be required in order to ensure current market and standard operating procedures are capture within the SMARTbook framework. The interest and need from the end users is there as shown from the survey results. These findings will be disseminate with JED leadership. The decision for further development and cost effectiveness of distribution would come from JED command.

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GIS and Open Data for Sustainable Construction and Risk Analysis: The Case Study of a School in Zambia

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Abstract

GIS and open data are clearly an asset for the construction sector, especially during the planning phase and for logistic. Sustainability is a topic that cannot be disregarded anymore and particularly relevant for the construction sector as one of the most energy and material consuming sectors. In areas where climate change is already a reality and pre-conditions already challenging, the use of available technologies might make a vital difference if properly adopted in projects. This paper presents the result of a preliminary study conducted in collaboration with the Architects Without Borders, Sweden, for a boarding school in Zambia. Results show how GIS and free open data have been used to forecast the project's socio-economic impact on the local population, suggest sustainable materials for construction and foreseen climate change consequences on the project's location and in particular on the natural resources' supply.

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Keywords: climate change, GIS, open data, risk analysis, sustainability.

1. Introduction

Creating and managing digital information about the built environment in Geographical Information Systems (GIS) environments is not new, but rather GIS' common applications which bring together spatial data and associated information, and provide a central database to store, update and interrogate these data [1]. The use of GIS in early stages has been confirmed by a great deal of studies. In the last years, new uses of GIS, often integrated with other tools, software or systems, opened for new possibilities. For instance, GIS integrated with Building Information Modelling (BIM) seemed to provide an asset for the construction phase. Zavari et al. (2022) claim that GIS, integrated with Building Information Modelling (BIM), is practical and beneficial for optimizing the construction site layout planning, decreasing the total on-site traveling distance and developing a more realistic model using BIM and GIS together for acquiring the spatial data, navigating dynamically, and considering available indoor and outdoor space continuously [2]. BIM-GIS integration and its applications represent an active research topic for the future development of society, especially in the field of the sustainable built environment [3].

Sustainability issues are well known to the construction sector and the scientific community interest on the topic increased exponentially in the last years. Very similar the trend that sees GIS connected to Sustainability. Usually, while the construction sector's activities are pointed out as the cause for un-sustainable energy and materials consumption, GIS is presented as a tool to analyse, forecast and to support decision-making phases. GIS can be defined as "a system that creates, manages, analyses, and maps all types of data. GIS connects data to a map, integrating location data [...] with all types of descriptive information […] used to identify problems, monitor change, manage and respond to events, perform forecasting, set priorities, understand trends” [4].

GIS is indeed a great asset, but data and geodata are needed. In the last years, numerous initiatives have been dealing with the provision of open, and often free, data and geodata. The availability of open data has grown significantly, with pressure being placed on all kinds of public organizations to release their raw data [5]. Finding free and open data and geodata is therefore not difficult, however, information quality issues such as lack of information, lack of accuracy of the information, incomplete information, only part of the total picture shown or only a certain range and obsolete and non-valid data must be taken into serious consideration [5].

The Arkitekter Utan Gränser, Sweden (Architecture Sans Frontières (ASF) Sweden), is a non-profit, religiously unaffiliated, non-political organisation that aims to create and improve access to a safe, sustainable and equitable development of the built environment for all [6]. Once a project idea is approved by the ASF's board, the preliminary study phase can start. This includes the delivery of a report that must comprehend a clear and deep description of: initiative, location, project's sustainability (ecological, social, economic analysis), community needs, analysis, partnerships and collaborations, project's financing, risk analysis, project's effects. Moreover, in order to finalize the preliminary study, a visit to the project's location is considered necessary. From the very beginning of 2022, because of Covid-19 pandemic, travel became from difficult to almost impossible, especially to developing countries, and many of the ASF's projects were set to a pause.

On March the 11th, 2020, the World Health Organization declared Covid-19 a pandemic. To contain the pandemic, most countries took a two-pronged approach. First, they attempted to slow the spread of the disease internally by implementing various non-pharmacological interventions, such as social distancing, using face coverings, and closing businesses and schools. Second, they attempted to reduce the number of imported cases by implementing travel restrictions [7]. While travel restriction measures had some benefits on the already feeble heath system of many developing countries, factors such as restrictions of travel into and within countries, quarantining and other restrictions on group activities and increased bureaucratic hurdles by governments and other actors, have acted against humanitarian access and delivery and international organizations have had to scale back the number of international staff in field locations as they managed travel and quarantine restrictions [8].

During the same period, a close collaboration between ASF, Sweden, and the School of Engineering, Jönköping University, Sweden, was established. The collaboration encompasses the engagement of students in ASF's preliminary studies with the attempt to supply the impossibility to collect onsite data. Students have been involved within GIS and Industrial Placement programs' courses. So far, three successful examples of students' contributions to ASF's preliminary studies have been recorded for: a hospital in Taita–Taveta County, Kenya; Kamakwie hospital infrastructures' improvement, Karene District, Sierra Leone; and a boarding school in Chirundu District, Zambia.

In this paper, the results of the preliminary study conducted in collaboration with the ASF, Sweden, for a boarding school in Chirundu District, Zambia are presented. The aim of the paper is to show how GIS and open data can be used for sustainability and humanitarian purposes and they served as assets to bypass the unforeseen obstacles caused by the Covid-19 pandemic.

Results show how GIS software and free open data have been processed to forecast the project's socio-economic impact on the local population, suggest sustainable materials for construction and foreseen climate changes consequences on the project's location and in particular on the natural resource supply.

2. Research method

For this research, the preliminary study for the project named “Build a classroom”, a boarding school in Chirundu District, Zambia, served as case study. “Build a classroom” is a project initiated by the Zambian Children In Crisis, a non-governmental organization registered under the Ministry of Community Development and Social Services in May 2020 and supported by the ASF, Sweden. What started as a “Build a Classroom" initiative, became the project for 500 pupils boarding school on about five hectares land in the village of Kapulurila Chief Sikaongo of Goba village, 10 Km from Chirundu, Chirundu District. The local communities made possible to choose among two plots of land (A and B in Fig. 1) situated few Kilometers from the banks of the Kafue and the Zambezi rivers (Fig. 1). Both plots are still under analysis and a final decision on which has not been taken yet.

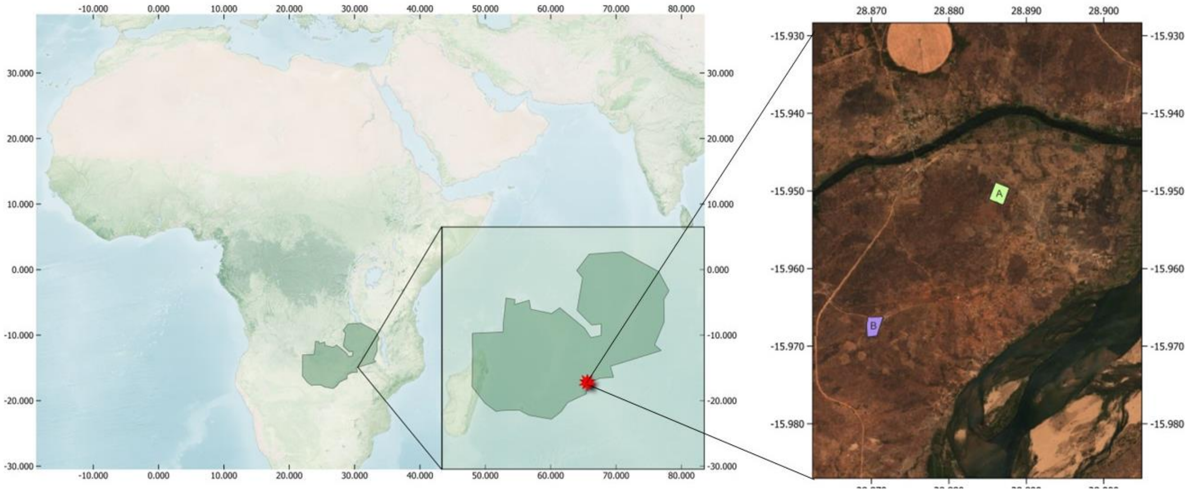


Fig. 1. Project location and the two possible land plots for the school (A and B).

Geodata have been downloaded mainly as Shapefiles, JSON, GeoJSON, Excel, TIFF and geoTIFF from databases that allow free access and downloading such as those showed in Table 1.

Table 1. Used open and free geodatabases.

Database	Data	Website
AmeriGEOSS	Mineral resources	www.amerigeoss.org/
Humanitarian Data Exchange	Installations, infrastructures, and demographic	data.humdata.org
European Soil Data Centre (ESDAC)	Soil diversity	esdac.jrc.ec.europa.eu
geo7	African geology	geo7.ch
Berkeley Library GeoData	Electricity gris and dams' conditions	geodata.lib.berkeley.ed u
Global Solar Atlas	Information for solar energy	globalsolaratlas.info
GRID^3	Social risk indicators, operational points, demography	grid3.org
The Landscapes Portal	Land use, vegetation, crops, soils	landscapeportal.org
Sentinel Hub - Playground	Orthophotos	apps.sentinel-hub.com
FEOW	Hydrographic watershed	www.feow.org/
British Geological Survey	Africa's groundwater	www2.bgs.ac.uk
WorldData.info	Zambia's energy consumption	www.worlddata.info/
World Bank Open Data	Climate	data.worldbank.org/
National Oceanic and Atmospheric Administration (NOAA)	Weather and climate	www.noaa.gov

To visualize and analyzed geodata, both the free and open-source Quantum GIS and Esri's ArcGIS Pro (and its base maps) have been used.

In April 2022, when in Zambia the Covid-19 restrictions have been partially lifted, a visit to the project location was conducted to validate the remotely retrieved data. Onsite surveys and unstructured interviews were conducted. Interviews targeted the main projects' actors: Children in Crisis board, school pupils aged from five to sixteen, teachers, and local communities, and included questions about needs, expectations, and daily issues that the project aims to solve or mitigate. Questions were asked during workshops' activities and answers were gathered differently based on the respondents' age and literacy background: interviews with the NGO border's members and teachers were more formal; school pupils were asked to draw their answers on A4 white paper and post-it; local communities were interviewed with the help of an interpret to overcome linguistic and cultural barriers (Fig. 2).

Fig. 2. Interview with one of the local communities.

3. Results

Free and open sourced geodata have been used to analyze the following aspects: location, topography, climate, geology and hydrology, land analysis, economic analysis, infrastructures in the country and in the project area, social structure, distribution of the population, tribes, languages, equality (classes and castes, household, gender equality), worship, education, sustainability of the project, local materials and construction techniques, renewable energy, community needs and risk analysis including climate change.

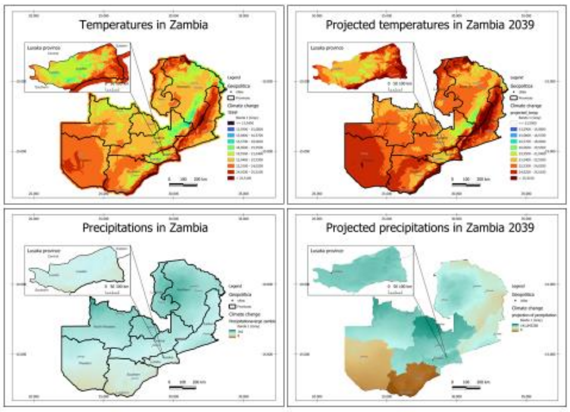
While some of the analyses are typically needed to understand the project's location, others such as local materials, renewable energy, and risk analysis, have been specifically conducted for construction purposes. The maps of land use, crops, vegetation coverage, geology and mineral resources provide a great understanding of the materials available for the project in a country where the materials used in rural areas, such as the project area, are and must be local.

During the analysis of the local materials, it was determinate that the site ground consists of conglomerates, sandstones, carbonaceous siltstones, and mudstones. These materials are used in the compressed earth blocks (CEB), a traditional construction technique in Zambia. The use of local materials fulfills all sustainable requirements and enables the employment of local workers who are familiar with traditional techniques.

The photovoltaic power potential average (KWh/m^2) raster was used to calculate the square meters of solar panels needed to support the schools. According to the WorldData.info website, the energy consumption per capita in Zambia is 600.52 KWh per year. Calculating the energy consumption for the 250 people who will reside in the boarding school, an average annual consumption of 150.250 KWh is needed. According to Fig. 4, the photovoltaic power average potential in the sites is 2291.1 KWh/m^2 per year. Dividing the energy needed by the photovoltaic power output (150.250 KWh/2291.1 KWh/m^2), it is reasonable to assume that 65,57 m^2 buildings' surface should be covered with solar panels. To calculate the exact surface area, the actual efficiency of the solar panel must be considered.

Climate change forecasts were made using map algebra by adding the predicted variations for temperature and precipitation for the year 2039. For this, the estimations from the Climate Change Knowledge Portal of the World Bank Open Data were added to the raster data of the current situation obtained from NOAA, using the raster calculations by region.

Fig 3. shows that the most affected areas are those in the southern part of the country where temperatures will increase more drastically, and rainfall will decrease. As a consequence, water in the Zambezi, Kafue and Luangwa River basins will reduce. The results of those analyses must be considered when choosing materials, construction, and the water supply systems during the design phase of the project. Also, buildings' orientation and architectonical techniques will be adopt to favor an appropriate indoor temperature.



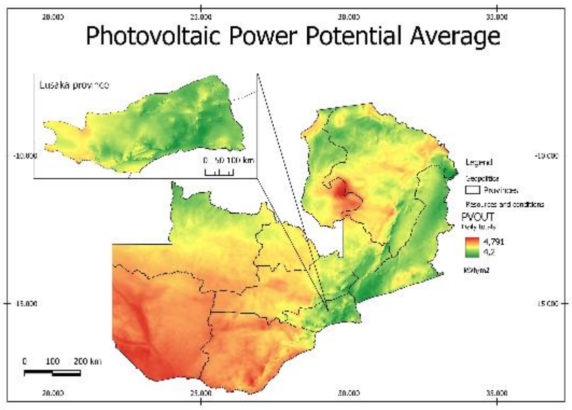


Fig. 3. Climate changes analysis maps.

Fig. 4. Photovoltaic power potential average map.

From the analysis of the topography, geology and hydrology geodata was found that the project area is located on the upper Karoo Supergroup formation which is a consolidated sedimentary aquifer with mixed intergranular and Fracture Flow and Karstic Flow, of High to Very High Productivity (CSIF- HV). Therefore, it is necessary to explore the possibility of constructing a borehole. In addition, the high difference from the Zambezi river was used to estimate the upper limit of groundwater and the depth of the well.

The assessment of the need for this project was also evaluated through maps of different social factors such as schooling rate, fertility rate, the Gini Index (which measures inequality in terms of income and wealth) and the WASH Index (measures the access to basic services such as water and communications). These maps were obtained from the Humanitarian Data Exchange website and from the digitization of data included in the Zambian Demographic and Health Survey 2018 [9].

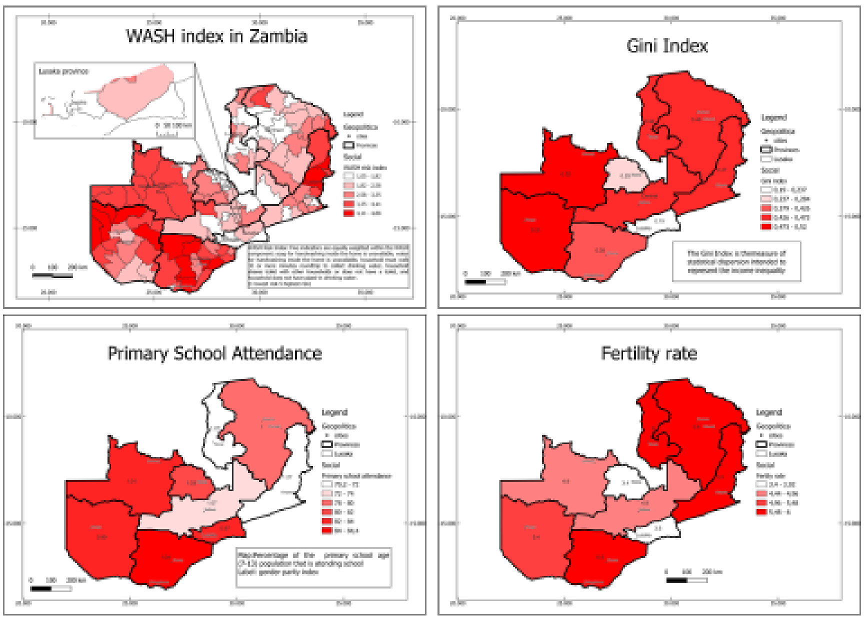


Fig. 5. A selection of the created demographic analysis maps.

Fig. 5 shows the results of the need evaluation for this project. In Zambia, children, especially orphans and girls, are vulnerable to many social risks. The majority of Zambians have no or some primary education. Specifically, 60% of females and 54% of males aged 6 years and older have no or only some primary education. The primary school net attendance ratio (NAR) for the population aged 7-13 years is 79% (81%

for girls and 77% for boys). The secondary school NAR drops sharply to 40% (38% for girls and 42% for boys). The variation in the secondary school by place of residence is large, with a 27% difference between urban (56%) and rural (29%) areas. Besides this, the risks derivate from not having proper sanitary installations, limited access to clean water and walking long distance unsupervised can be also mitigated with the realization of a boarding school.

In all the interviews, the need for the School was confirmed. During The interview with the NGO, a list of priorities to be phases during two phases of the project was drafted. Access to electricity and clean water was claimed as the top priority.

From the workshops with the pupils, their needs and challenges clearly emerged. School children need from legal requirements to go to school (for example uniforms and shoes) to the means to reach the school within an acceptable timeframe and in security. At school, basic teaching and learning tools such as tables, chairs, books, pencils, whiteboards, and chalks lack. Basic infrastructures such as toilets are, when existent, deficient. Children don't have proper playgrounds or a safe green areas close by the schools. Food is scarce and for several of the pupils attending Children in Crisis' schools, the meals provided by the teacher is often the only one they will eat during the whole day. The main challenges discussed with the children mirror the needs listed above. Some of them live far from the school and being in classroom every morning is difficult. Some don't have uniforms or shoes, therefore not even supposed to be at school. Difficulties faced home by some of those children have repercussions at school where inappropriate behaviour are sometimes imitated. The classes are full. Following a lesson is very difficult in a crowded, small, hot room. The lack of toilets and other sanitations facilities is indeed a problem.

Interviews were conducted with a number of the communities surrounding the project´s sites. The communities consist of about 100 families of circa 15 members each. Many of the interviewees claimed that that the way to the nearest school is too long. During the path, children encounter dangerous animals that often attack. During the rainy season, roads become very muddy and reaching schools become extremely difficult when not impossible. The boarding school would also be a way for young girls to avoid early pregnancies by avowing sexual assaults that often happen on the way to school, early marriage and indeed by empowering young girls with the knowledge the school can provide.

4. Discussion and conclusions

The aim of the paper is to present how GIS and free and open data have been used for sustainability and humanitarian purposes and how they served as assets to bypass the unforeseen obstacles caused by the Covid-19 pandemic. Despite the luck of some relevant data, those retrievable from online free and open databases allowed to deeply analyse project location, demographic parameters, materials and energy supply and risk analysis, including climate change.

A project's geographical location and topographic analysis are desirable for all construction projects [4], but fundamental for remote locations in developing countries where material supply and access to energy and water sources are, if existing, scarce or difficult to reach. Basic infrastructures are often unreliable, and transit is difficult. Therefore, local materials and material suppliers are the only possibility to build affordably.

Demographic analyses are needed to support the claim of the project's need and to justify the ASF's partnership on it. For this purpose, up-to-date, reliable data are needed.

In projects such as those supported and sponsored by ASF, the risk analysis is an indispensable tool for decision making and this must include climate change effects on the project's location and on the project itself. Especially in southern countries, the increase of temperatures constitutes a concrete danger that can be faced by taking right decisions during the first stages of a project (i.e. choose of materials, architectonic techniques, buildings orientation). Data such as the current climate data from NOAA and the climate projections and analyses in GIS environment, allowed a seventeen years forecast that will influence the above mentions decision matters.

In this project, free and open-source data and geodata played a central role. As underlined by [5], open databases provide many benefits, but the quality of the data must be assured. Furthermore, some data needed for the project do not exist or are not available on the used databases. Data such as animals most used paths were not found but would have been extremely useful for the project as one of the most reported natural problems by local communities is the danger posed by wild animals attacking people, including kids on their very long way to school. The same can be said for walking path used by children on the way to school, which often are through bushes, water streams and other unsafe paths. Finally, the rural and unsettle architecture is not always present in geodata (Fig. 6).

Fig. 6. A Google maps screenshot about the architectonical conformation nearby the project's area.

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Impact of Skill Proficiencies on Frontline Supervision Practices in the Construction Industry

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Abstract

Frontline supervisors play a crucial role in construction operations as they create a link between management and craft professionals, whereby they are expected to manage resources, plan and define work, communicate with workers, and create a safe working environment. Several studies indicate that adequate supervision is critical for field productivity and enhancing efficiency. While the importance and best practices of frontline supervision have been highlighted in existing work, no research has yet studied how different skills affect frontline supervision. The objective of this paper is to analyze and understand the impact of individual skill proficiencies on frontline supervision practices, specifically, investigating if skill proficiencies impact the time spent supervising craft professionals at the workface, and time spent on administrative and planning activities. To achieve the research objective, 1062 construction frontline supervisors were surveyed using an online questionnaire. The survey participants were asked to allocate what percent of time of their day they spend on the following tasks: “supervising craft professionals”, “administrative work”, “planning activities”, and “training workers”. The participants were additionally asked if they are proficient in specific “computer” skills, and “administrative” skills. The collected data was then analyzed. Key findings indicate that 5 of the 12 specific skill proficiencies had a statistically significant impact on time spent supervising workers. Additionally, 9 of the 12 specific skill proficiencies had a statistically significant impact on time spent on administrative work, and 4 of the 12 specific skill proficiencies had a statistically significant impact on time spent on planning activities. Only 1 of the 12 specific skill proficiencies had a statistically significant impact on time spent training workers.

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Keywords: administrative skills, craft professionals, computer skills, construction, frontline supervision practices

1. Introduction and Background

Frontline supervisors play a crucial role in construction operations as they create the link between management and craft professionals, whereby they are expected to manage resources, plan and define work, communicate with workers, create a safe working environment, and ensure field productivity [1]. Construction frontline supervisors have a critical responsibility of ensuring safe and healthy work practices [2]. A study on the factors that are most influential to productivity found that foremen-related factors were among the top three most influential categories [3]. Researchers in [4] stated that while many attribute low productivity to workers, in reality, the main issues stem from supervision and failure to support the labor with adequate planning, training, and motivation. A study by [5] reported, through focus groups, the ideal competencies for effective supervision, and identified 12 pillars for successful supervision, including communication skills, experience, leadership skills, and knowledge. A study of the Alberta construction industry found that inadequate supervision is the third most important factor that hinders productivity (lack of detailed planning, and worker experience and skills were the top two factors) [6]. A research study by [7] of the performance of construction professionals in the Alberta building construction projects highlighted the importance of the supervisor's skills, and found that foremen lacked sufficient supervisory skills, indicating the urgent need for training programs to improve their skill levels. An analysis by [8] indicated that despite the acknowledged importance of the role of the foremen in the execution of construction activities, their function has not received the attention it deserves. Their study of construction frontline supervisors in the United States (US) and Israel found that pre-planning can replace re-planning activities. Additionally, the study showed that supervisors in the US spend 35.1% of their time on supervisory activities which include giving instructions, monitoring, and inspecting the quality and pace of work.

As the significance of the role of construction frontline supervisors is well documented, it becomes critical to understand how proficiencies in different skills, including administrative skills and computer skills impact time allocation practices of supervisors. While previous research has highlighted the importance and best practices of frontline supervision, no research has yet studied how different skills affect frontline supervision. To understand this impact, 1,062 construction frontline supervisors were surveyed using an online questionnaire. The survey participants were asked to allocate what percent of time of their day they spend on the following tasks: "supervising craft professionals", "administrative work", "planning activities", and "training workers". The participants were additionally asked if they are proficient in specific "computer" skills, and "administrative" skills.

The primary objective of this paper is to understand the frontline supervisor's time allocation practices for different tasks, and study how different proficiencies in administrative and computer skills impact the percent of time spent on different tasks, and in particular, the amount of time spent supervising craft professionals at the workface, administrative work, planning activities, and training workers.

2. Methodology

In this study, a survey of construction frontline supervisors in the US was conducted using an online questionnaire published through "Qualtrics". Among other questions, the survey asks frontline supervisors about their time allocation practices for different tasks, as well as whether they are proficient in a list of different administrative and computer skills. The survey received 1,062 responses from all 50 states to the questions being studied, with the responses having a gender breakdown of 97.5% male and 2.0% female. Of the supervisors, 31% are foremen, 29% are superintendents, 17% are general foremen, 2% are craft superintendents, 2% are assistant superintendents, and 19% indicated that they have another title. The breakdown of the respondents by age showed that 33.2% of the respondents are over the age of 55, 33.2% are in the 45-54 age group, 25.3% are in the 35-44 age group, 8.0% are in the 25-34 age group, and 0.3% are under the age of 25. Figure 1 shows the breakdown of the respondents by job title and age.

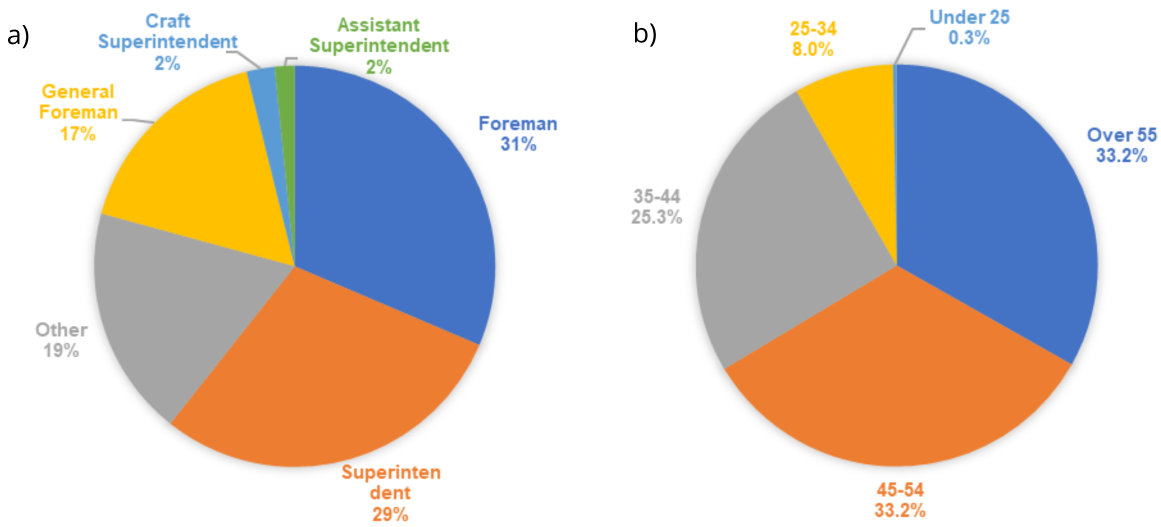

Figure 6: (a) Respondents breakdown by Job Title; (b) Respondents breakdown by age

The survey asked frontline supervisors to select all the administrative and computer skills they are proficient in. The following is a list of skills that can be selected:

- **Administrative Skills** included the following skills: cost management; scheduling; material management; request for information; estimating
- **Computer Skills** included the following skills: Email/Internet; word processing; spreadsheets; building information modelling; scheduling; estimating; material management

The survey additionally asked frontline supervisors to allocate percentages of time they spend on each task on average in their workday. All percentages must add up to 100. The following is the list of the tasks offered to the respondents.

- **Supervising crafts professionals** (e.g., assigning tasks and responsibilities for crew, toolbox meetings, task inspection, and resolving conflicts between workers)
- **Administration** (e.g., taking attendance, communicating and meeting from management, management and tracking of materials/equipment, progress reporting, and cost tracking)
- **Planning** (e.g., task planning, requesting information, safety planning and advising)
- **Training** (e.g., craft training, safety training, recruiting and hiring new craft)
- **Other**

To compare the time allocation practices spent on different tasks of supervisors based on their proficiencies of each skill, the data was grouped based on whether the supervisors are proficient in each skill or not. The average percentage of time spent on each task is then calculated for each group. To test if the difference between the two groups is statistically significant, a t-test was performed to obtain the p-value. A significance level, α, of 0.05 is considered for statistical significance in this analysis.

3. Results and Analysis

The time allocation practices on the four specified tasks of frontline supervisors (supervising craft professionals, administration, planning, and training) based on their skill proficiencies is presented in Tables 1 through 4. Each table shows the average percent of time spent on each task for frontline supervisors who are proficient in each administrative and computer skill, and those who are not proficient in the same skill. The results presented in these tables also show the p-value of a t-test to examine if the difference in the percent of time spent on the task based on skill proficiency is statistically significant.

Table 1 shows the percent of time spent on "supervising craft professionals" among supervisors based on their proficiencies in different administrative and computer skills.

Table 6: Percent of time spent on "Supervision" tasks among supervisors based on their proficiency in different skills

Skill	Average Percent of Time Spent on “Supervision” Tasks		P-Value
	Proficient	Not proficient	
Administrative: Cost Management	34.9%	39.7%	0.001*
Administrative: Scheduling	37.2%	38.8%	0.463
Administrative: Material Management	37.6%	36.0%	0.477
Administrative: Request for Information	36.5%	40.1%	0.033*
Administrative: Estimating	36.0%	38.5%	0.084
Computer: E-mail/Internet	37.3%	35.5%	0.737
Computer: Word Processing	35.3%	40.0%	0.001*
Computer: Spreadsheets	35.1%	40.5%	0.000*
Computer: Scheduling	37.0%	37.8%	0.588
Computer: Building Information Modeling	37.3%	37.3%	0.989
Computer: Estimating	34.6%	38.7%	0.006*
Computer: Material Management	37.0%	37.8%	0.582

**Difference in percent of time spent on task is statistically significant*

The results in Table 1 show that, supervisors who are proficient in in all skills except the *administrative material management* spend, on average, less time supervising craft professionals compared to those who are not proficient in same skills. Supervisors who are proficient in the “*administrative material management*” skill are found to spend, on average, more time supervising craft professionals; however, the difference is not statistically significant. Only five out of the 11 specified skills where supervisors spent, on average, less time on supervision, had a statistically significant impact on the percent of time spent on supervising craft professionals. The administrative skills that showed a statistically significant impact on the results include *cost management, and requests for information*. The computer skills that showed a statistically significant impact on the results include *word processing, spreadsheets, and estimating*.

Table 2 shows the percent of time spent on “administrative tasks” among supervisors based on their proficiencies in different administrative and computer skills.

Table 7: Percent of time spent on "Administrative" tasks among supervisors based on their proficiency in different skills

Skill	Average Percent of Time Spent on “Administrative” Tasks		P-Value
	Proficient	Not proficient	
Administrative: Cost Management	23.5%	18.8%	0.000*
Administrative: Scheduling	21.8%	16.2%	0.000*
Administrative: Material Management	21.3%	19.5%	0.210
Administrative: Request for Information	22.1%	18.0%	0.000*
Administrative: Estimating	22.2%	20.1%	0.038*
Computer: E-mail/Internet	20.7%	16.6%	0.254
Computer: Word processing	21.8%	19.0%	0.004*
Computer: Spreadsheets	22.5%	17.9%	0.000*
Computer: Scheduling	22.3%	17.5%	0.000*
Computer: Building Information Modeling	21.9%	20.3%	0.183
Computer: Estimating	22.1%	19.9%	0.029*
Computer: Material Management	22.2%	18.6%	0.000*

**Difference in percent of time spent on task is statistically significant*

The results in Table 2 show that supervisors who are proficient in each of all the specified skills spend, on average, more time on administrative tasks compared to those who are not proficient in same skills. Most skills (nine out of the 12) had a statistically significant impact on the percent of time spent on administrative tasks. The administrative skills that showed a statistically significant impact on the results include *cost management, scheduling, requests for information, and estimating*. The computer skills that showed a statistically significant impact on the results include *word processing, spreadsheets, scheduling, estimating, and material management*.

Table 3 shows the percent of time spent on “planning tasks” among supervisors based on their proficiencies in different administrative and computer skills.

The results in Table 3 show that, supervisors who are proficient in all skills except the *computer word processing* skill spend, on average, less time on planning tasks compared to those who are not proficient in same skills. Supervisors who are proficient in the “*computer word processing*” skill are found to spend, on average, more time on planning tasks; however, the difference is not statistically significant. Only four out of the 11 specified skills where supervisors spent, on average, more time on planning tasks, had a statistically significant impact on the percent of time spent on planning tasks. *Scheduling* is the only administrative skill that showed a statistically significant impact. The computer skills that showed a statistically significant impact on the results include *spreadsheets, scheduling, and estimating*.

Table 8: Percent of time spent on "Planning" tasks among supervisors based on their proficiency in different skills

Skill	Average Percent of Time Spent on “Planning” Tasks		P-Value
	Proficient	Not proficient	
Administrative: Cost Management	22.0%	20.9%	0.195
Administrative: Scheduling	21.9%	18.0%	0.005*
Administrative: Material Management	21.7%	19.7%	0.140
Administrative: Request for Information	21.8%	20.3%	0.165
Administrative: Estimating	22.2%	20.8%	0.126
Computer: E-mail/Internet	21.1%	17.7%	0.738
Computer: Word Processing	21.0%	21.1%	0.884
Computer: Spreadsheets	21.8%	20.0%	0.041*
Computer: Scheduling	22.0%	19.1%	0.002*
Computer: Building Information Modeling	22.3%	20.7%	0.148
Computer: Estimating	22.3%	20.3%	0.032*
Computer: Material Management	21.6%	20.3%	0.138

**Difference in percent of time spent on task is statistically significant*

Table 4 shows the percent of time spent on “training tasks” among supervisors based on their proficiencies in different administrative and computer skills.

Table 9: Percent of time spent on "Training workers" tasks among supervisors based on their proficiency in different skills

Skill	Average Percent of Time Spent on “Training” Tasks		P-Value
	Proficient	Not proficient	
Administrative: Cost Management	12.0%	12.3%	0.766
Administrative: Scheduling	12.0%	12.9%	0.585
Administrative: Material Management	11.8%	14.2%	0.139
Administrative: Request for Information	11.9%	12.8%	0.452
Administrative: Estimating	12.9%	11.5%	0.182

Computer: E-mail/Internet	12.2%	18.9%	0.090
Computer: Word Processing	13.4%	10.8%	0.015*
Computer: Spreadsheets	13.0%	11.4%	0.138
Computer: Scheduling	11.8%	13.3%	0.194
Computer: Building Information Modeling	14.2%	11.8%	0.073
Computer: Estimating	13.1%	11.9%	0.251
Computer: Material Management	12.4%	12.1%	0.818

**Difference in percent of time spent on task is statistically significant*

The results of Table 4 show that, supervisors who are proficient in six out of the 12 specified skills are found to spend, on average, less time on training tasks compared to those who are not proficient in same skills; Those skills include four administrative skills (*cost management, scheduling, material management and request for information*), and two computer skills (*E-mail/Internet and scheduling*); however, the difference is not statistically significant for any of those skills. Supervisors who are proficient in the remaining six skills are found to spend, on average, more time on training tasks; Those skills include one administrative skill (*estimating*), and five computer skills (*word processing, spreadsheets, building information modelling, estimating, material management*); however, the difference is not statistically significant in five of those six skills. *Word processing* is the only computer skill that showed a statistically significant impact on the results.

4. Conclusion and Future Work

Frontline supervisors play a vital role in construction operations where they are responsible for managing resources, workers, and time to ensure productivity and efficiency. This study focuses on how different administrative and computer skills impact the time supervisors allocate on different tasks throughout their workdays. The results of this analysis indicate that five out of the 12 specific skill proficiencies had a statistically significant impact on time spent supervising workers (administrative skills: *cost management, and requests for information*; computer skills: that showed a statistically significant impact on the results include *word processing, spreadsheets, and estimating*.), where those who are proficient in those skills spent less time on supervision tasks. Additionally, nine out of the 12 specific skill proficiencies had a statistically significant impact on time spent on administrative work (administrative skills: *cost management, scheduling, requests for information, and estimating*; computer skills: *word processing, spreadsheets, scheduling, estimating, and material management*), where those who are proficient in those skills spent more time on administrative, and four out of the 12 specific skill proficiencies had a statistically significant impact on time spent on planning activities (administrative skills: *scheduling*; computer skills: *spreadsheets, scheduling, and estimating*), where those who are proficient in those skills spent more time on planning tasks. However, only one of the 12 specific skill proficiencies (computer: *word processing*), had a statistically significant impact on time spent training workers. Future research will expand on this study and examine how skill proficiencies and time allocation practices analyzed in this study impact the performance of a supervisor. Additional work will aim to identify optimal time allocation practices for supervisors as a guide to increase field productivity in the construction industry.

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Necessity of Adopting Lean Techniques in Construction Projects

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Abstract

The world has witnessed large growth of projects development during last two decades, where Dubai in the UAE has witnessed big increase in construction projects. Some of these projects are completed and delivered on time while others have not delivered on time, due to some challenges and uncertainties that caused delay which impacted work progress of some major activities. Lean construction and lean techniques have been introduced in the UAE construction projects, but it is not adopted as mechanism to complete and deliver projects on time. Lean techniques in construction projects can be introduced as a philosophy that reduce project duration through the elimination of waste in process during design and construction. The study aims to introduce principles of lean management in construction projects and the benefits of applications of lean techniques in projects through investigating the level of implementing lean techniques in some construction projects. Principles of underpinning lean methodology is also investigated, and part of the study was to find out benefits of lean techniques implications.

Principles of the study results revealed the necessity of adopting lean process and techniques in construction projects that can be implemented. Responsibilities of project team to use available tools to support implementation of lean to minimize the waste of project processes is identified in the results. Barriers and factors of preventing project team to adopt lean techniques are identified as a main result in this study. Major conclusion of the study identified the necessity of understanding the concept of lean techniques in construction to control the uncertainty and eliminate the waste that may occur during any process. It is also recommended that construction firms must adopt the lean techniques to improve the productivity by eliminating the wastes, including but not limited to benefits of implementing lean

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Keywords: Constructability, Lean techniques, Methodology, Productivity, Process

1. General Introduction

Lean in construction projects is introduced as tool to reduce project duration through the elimination of waste either in process or methodology. Waste is any work element/activity that is not adding value to the work progress can be eliminated. The main goal of lean implementation in construction projects is to reduce the project execution time. Lean transformation aims to create a lean & effective process, remove the process noise, create an agile process capable of adjusting rapidly to changing circumstances, ensure project team is thinking with a divisional hat and have improved communication between project team. Also, it reflects the commitment to create a culture for continuous improvement. Lean is defined by those who works in construction firms as a set of systematic management practices to improve efficiency and effectiveness by eliminating waste where values can be delivered with less waste during construction. Benefits of lean adoption in construction industry is making the team to focus on activities that has a value which reduces the numbers of activities that cause a waste. Enhancing and improving productivity and work efficiency during project phases where staff and employees becomes more focused on delivering work values. Resource optimization and utilization will be a part of daily working process based on mechanism of waste elimination, reduction and work actual requirements. In addition, this technique is clearly streamlining the process that would deliver value to the client of the project where processes and activities without values can be minimized and eliminated. Work activities can be accelerated either during the design or construction based on removal of non-value activities after satisfaction of the client and project team. Project team including the work force will give more attention to the knowledge and innovation of lean implementation to create the required change that makes good value to the client requirements and needs. Many countries are started focusing on lean adoption based on analysis of work factors that lead them to eliminate the waste during design and construction mainly in design-build projects. The objective of the study is to present principles of lean management in construction industry and its benefits along with adopted tools based on feedback of developed questionnaire that is conducted during the research period. The conclusion of the research presented the necessity of understanding and adoption lean techniques in construction projects that can manage the uncertainty issues and can eliminate the waste that can happen during any of project life cycles where productivity can also be improved.

2. Literature Review

Lean principles of production have grown and were successfully implemented by Toyota Motor Company in Japan on forties of past century, The production system was considered by some to be the most efficient in the world, and it was claimed that their lean production principles could be applied not only to any other manufacturing process, but also to other business activities. These principles are being increasingly employed in many other commercial and industrial sectors. It can be categorized in terms of objectives, principles, and methods or tools. Lean has been judged to have improved construction project performance the world over due to its theoretical advantages and benefits. Leans has spread widely in manufacturing, moving far beyond the automobile sector where it originated and beyond the shop floor into white collar functions. Lean has also spread from manufacturing into product development, general services, aviation industry, ships and sub-marines' buildings, software development, health care delivery, and construction industry projects. The effective implementation of this concept in construction projects is rare in developing countries [1]. Adaptation of lean production concepts in the construction industry has been ongoing through fast development. Big, organized firms are becoming aware of benefits and outcomes of lean management in most kind of industries. The term "lean" is used consistently and is usually associated with lean manufacturing, lean thinking, lean production, and lean construction [2]. They further stated that lean practices were usually implemented based on some ideologies and scene that came up prior to the introduction of the lean concept. These ideologies include total quality management (TQM), as well as the just-in-time (JIT) production. The idea behind these ideologies [3] gave rise to the emergence of some of the key elements of lean which includes the focus on producing high quality products that are readily in need and relatively cost effective to users. This is based on proposals and discussions related to the improvement in quality and production. Lean construction according to [4] has of recent received audience as a way of improving construction performance and productivity. It has been presented to be the latest management concept that supporters for the minimization of waste in construction processes as well as changing the construction industry needs. Lean construction is a way of designing a production system that minimizes the waste of materials, time, and effort with a view to generating ample value within the construction process [5]. In general, Lean Construction projects are easier to manage, safer, completed sooner, cost less, and are of better quality.

Transformation and its management are a procedure of managing contracts and establishing quality and safety procedures which would ultimately lead to the increase in productivity and optimization of construction processes [6]. The senior managers and decision makers who works in big firms must focus on process review of contract management and requirements of their projects, so they can find out non added values of many activities which make them to eliminate the waste. Lean construction is a production management-based idea of delivering projects, the latest means of designing and building with a view to changing the previous ways of constructing [7]. So, senior managers must enhance communication process to enable the team work to create and develop effective lean process after removing invaluable activities. The team can be encouraged to think, participate, and propose where possibilities of adjustments can be accomplished. Customer satisfaction and quality improvement are two main factors for evaluating the progress and reputation of organization, but it also depends on the clients, their requirements and needs, and the types and scale of projects undertaken as large companies are often engaged in mega projects whereas small firms concentrate more on small scale construction like housing [8]. Some of them success but others are failed because lean adoption processes are not entirely successful. Lean construction as a movement arose from recognizing limitations of current project management and applying new production management or “lean production” to the construction industry projects according to [9]. This is maintained because in construction lean can effectively minimize the direct cost and it helps in expediting work process where time, cost and quality can be maintained. In construction industry, purpose of project control is to minimize negative variance from cost and schedule. This view leads to contract compliance which relies on managing contracts. In effect, work must be pushed. By contrast, the focus of management in lean construction depends on production starting with workflow reliability and valuable capacity. Managing combined effects of dependence and variations is the first concerns in lean construction [10]

3. Leans construction tools and techniques in projects

Lean construction can be introduced as a way of improving construction performance and productivity in project elements. It has been cited to be the latest management concept that supporters for the minimization of waste in construction processes as well as changing the construction industry needs. Lean construction is a methodology of developing system that minimizes the waste of materials, time and effort with a view to generating sufficient value within the construction process. Other than that performance of projects especially in construction will not be sufficient. Construction projects in the KSA normally have poor performance, which is mainly due to huge time and cost overruns [11]. Lean construction is a production management based idea of delivering projects on time, the latest means of designing and building with a view to changing the previous ways of constructing. In addition, massive environmental waste is also generated by the construction industry and the Saudi government issued a decree that requires all construction companies to meet new resource consumption standards to minimize the impact of waste in the construction industry [12]. All the various professionals in construction project can work together to enrich challenges experienced in a project. In applying the lean construction principles in construction projects, the process of design is carried out aim of achieving enhanced client satisfaction throughout the entire process. To address these challenges, lean construction has been introduced into the Saudi construction industry, and several contractors have realized the significance of implementing lean construction [13]. The lean construction concept is based on the Toyota Production System (TPS), which has been transformed into a newly systemized construction method all over the world. It aims to complete a project that meets customers’ requirements or client needs through waste reduction. Lean construction process is hinged on the following principles according to [14]:

(a) Reducing waste
(b) Specifying value from the perspective of the client.
(c) Clearly streamline the process that would deliver value to the client
(d) Minimize all non-value adding processes and activities
(e) Ensure that the client agrees to halt and accelerate activities when the need arises.
(f) Ensuring perfection is achieved via continuous improvement.
(g) Ensuring that there is a flow between all value adding processes devoid of interruptions in managing the interfaces between the steps and activities

Most construction related activities have been presented to a complex process of delivering kind product via the incorporation of a temporary and multi skilled team. Further stated that the two main contributors to lean construction are Transformation Flow Value (TFV) and Last Planner System (LPS) which were later followed by Lean Project Delivery System (LPDS).

Transformation Flow Value (TFV): The introduction of the ideas of lean thinking into construction was formulated through the transformation-flow-value (TFV) theory of production. The TFV theory of production when properly deployed, could lead to improved performance in construction projects. They see construction production as a continuation of conversion flow processes of eliminating waste while the traditional method of construction dwells more on conversion only and ignoring flow and value.

Last Planner System (LPS): To achieve lean goals of reducing waste, increasing productivity, and decreasing unpredictability, mainly through a social process, by trying to make planning a mutual attempt and by increasing the reliability of the commitment of team members. In construction, LPS was a method that forms workflow and deals with project variability.

Lean Project Delivery system (LPDS): The Lean Project Delivery System (LPDS) according to [15] was one of the outcomes of the lean construction institute (LCI) that was developed from the manufacturing industry and later metamorphosed into the construction industry. LPDS is a conceptual framework developed for purposes of guiding the implementation of lean construction on project related production system.

The below eight factors can be considered as a part of lean construction techniques which are the backbone of LC and have evolved since its adoption in the construction industry. Lean construction techniques are procedures, structures, conceptions, models, methodologies, and products which when implemented assists corporations apply lean across the workplace. [16]

- Bottle Neck Analysis (BNA): It is a structured way of looking at the processes and workflows for developing a product or service. Bottleneck analysis is also used to address both present and future issues, by identifying and addressing operational and process challenges. Utilizing Lean practices to spot and rectify a bottleneck saves companies time, energy, and money.
- Master Pulling Schedule (MPS): It is the complete project schedule with milestones. MPS is prepared based on the design criteria and standards that supports the client's project targets which is influenced by breaking the project into smaller activities and showing their successive relationships. It does not describe the run of demands between tasks or activities beyond simple successive relationships
- Phase Schedule (PS): The PS is developed by the teams involved in each phase and it is more practical than the preliminary optimal schedule which is the master schedule. It is like scrum where activities can be divided on weekly basis. It must be prepared minimum of 4 weeks before the number one activity. MPS produces the Reverse Phase Scheduling (RPS) which is a tool that develops the schedule
- Weekly Worked Plan (WWP): It is generated according to scheduled meetings covers quality issues, safety issues, weekly schedule, needs of material needs, methods of construction, reserves of prepared work and any difficulty that can come up in the field. Therefore, it improves quality, safety, flow of work and material, performance, and the relationship among stakeholders.
- Value Stream Mapping (VSM): This tool establishes the current state of the construction process or supply chain to identify the wastes. The future state helps to develop improvement strategies. It is a technique developed from Lean manufacturing. Organizations use it to create a visual guide of all the components necessary to deliver a product or service with the goal of analyzing and optimizing the entire process.
- Total Quality Management (TQM): Most of the substantial tools used to address construction performance issues are based on the concept of plan-do-act. Functions involve identification and evaluation of the problem, developing, and implementing solutions, and evaluating and measuring the results.

- Increased visualization (IV): Communicating key information effectively to the workforce through posting various signs and labels around the construction site; workers can remember elements such as workflow, performance targets, and specific required actions if they repeatedly see them.
- Just in time (JIT): It is a management philosophy that calls to produce what the customer/client wants, when they want it, in the quantities requested, where they want it, without it being delayed in inventory. So instead of building large stocks of what you think the customer might want you only make exactly what the customer asks for when they ask for it. Resources can be controlled.
- First Run Study (FRS): First-run studies are utilized to remodel important tasks. Operations are scrutinized thoroughly, and ideas and suggestions are raised to explore alternative ways of doing the task. The PDCA (plan, do, check, and act) cycle is used to build up the first-run study.
- Integrating quality into production (IQP): It is a part of making the production team's responsibilities; reducing as much of waste, defects, and errors as possible. This could also include stopping production to resolve quality problems rather than jeopardizing reproduction for defectiveness

The supporters of lean construction are not very interested in the systemic implications of forever focusing on short-term efficiency. A Joint public argument is that whereas the goals of lean construction and lean production may be similar, the approaches are different largely due to the project-based nature of construction, lean construction is a continuous process that applies throughout design, procurement, manufacture and construction. It is an 'integrated process' in which clients, designers, contractors, and suppliers must be committed to working together. This leads to a major improvement in the cost saving and quality. Lean construction also minimizes the direct cost of effective project delivery management and assists projects managers in making informed project decisions at all levels of the project. Lean construction promotes continuous improvement by encouraging reflection on lessons learned to eliminate the waste [17]. Lean construction is reported to lead to increased quality and productivity in the construction industry. Lean construction involves ways of designing production systems to minimize waste in materials, time, and human effort, with the aim of generating maximum cost-effective value [18]. Some of the theoretical and supposed principles behind lean construction are already founded and considered as a main supports factor for sustainable lean construction in the industry as explained and summarized in the general introduction and literature review, the factors are but not limited to the following:-

1. Eliminating waste and errors.
2. Direct and immediate involvement that lead to change.
3. Improving communication plans.
4. Improving work planning and forward scheduling.
5. Specifying value from the perspective of the customer.
6. Identifying the processes that deliver customer value (the value stream).
7. Eliminating activities that do not add value.
8. Increased visualization

4. Research Methodology

Comprehensive research method is adopted during the study where information of literature review is considered as a major data supported development of questionnaires. Projects Managers of big construction projects are requested to respond to the questionnaire to collect précised data related to necessity of adopting lean methodology, benefits, its construction and its tools. Primary data is generated based on the combination of finding the analysis of literature review and other different sources that has been approached through meetings, interviews and questionnaires.

4.1 Research Approach

Two approaches of data collection, qualitative and quantitative analysis has been approached to help the author developing proper analysis of the collected data through a detailed methodology.

4.2 Quantitative and qualitative analysis

Quantitative analysis is the assessment of data collected by means of survey techniques through statistical methods with the purpose of ensuring that the collected data are both reliable.

4.3 Data Collection

Primary and secondary date is the main types of data that has been collected by the researcher with the intention of developing the expected results. Collected date has been dealt with in turn in order to explain its necessity for this research.

5. Design of Questionnaires

A critical evaluation of the application of lean principles and techniques will help a creating a possibility and chance for value-adding and waste reduction in construction industry. The objective of this research is to identify the barriers to the adoption of lean in construction projects, and to find out if principles are adopted by project managers and rest of project team members. This study selected the quantitative research method to determine the benefits of adopting lean construction techniques in UAE by using primary and secondary data. Questionnaire surveys based on literature review are one of the methods to gather information/data. Questionnaires are developed to collect the required information and data for introducing principles of lean management in construction projects and the benefits of applications of lean techniques in construction as well, it is based on explanations of barriers of lean applications by project team. One hundred project managers of five big organizations specialized and serves in construction requested to respond to questions identified in table 1 that are related to tools of lean construction.

Key factors related to the adoption of lean construction and applications are listed in table 1, where the survey is prepared to evaluate the perceptions of project managers to the level of understanding and adoption applications of lean guidelines in their projects. The questionnaire is developed based on eight important factors/key areas that have been identified in the literature review and background of that study. Based on the feedback of participants, the level of meaning of each area has been identified as recorded in table 1. Major identified key areas are, related to waste elimination, communication, added value, scheduling and planning, risk identification, visualization, and stakeholders' needs.

Table 1. Key factors and tools of lean construction

SN	Questions and factors related to principles of tools and techniques of lean construction in projects	Validity	Means	Rendering	Standard deviation
1	Do you review the process to **eliminate waste** and error?	100	2.91	56 %	1.610
2	Are you involved during **design & built review process**?	100	3.12	61 %	2.102
3	How do you monitor administration of **project materials**?	100	3.62	64%	2.511
4	How do you improve **planning and scheduling** of lean?	100	3.89	67%	2.663
5	Do you discuss the **awaited added-value** with the client?	100	3.99	69%	2.799
6	How do you evaluate the **productivity** during the review?	100	4.01	71%	2.861
7	Do you prepare team **communication plan** of lean?	100	4.29	73%	2.992
8	Do you encourage to have BIM or any **visualized system**?	100	4.51	75%	3.012

6. Results and Discussions

6.1 Data Analysis and Findings

According to the analyzed data, it is observed that 67% of respondents are willing to practice lean tools and techniques during the life cycle of the projects they are managing. They do believe in lean tools and they are satisfied about its benefits in projects. The implementation of lean construction concepts increase the quality and productivity of construction projects [19]. 33% of respondents confirmed they are willing to practice lean, but they need to learn about it and understand its principles.

Regarding the first factor, eliminating the waste, 56% confirmed that they review the process during preparing construction methodology of each main activity, a lot of actions can be eliminated, while 44% of respondents they do not review due to some reasons such as knowledge, time constraints, and level of experience in lean tools. For second factor design and built review process 61% confirmed that they must review the process of work activities due to the nature of contract type where outcomes of design submittal must be very cost-effective design. 39% of others leave it to the design managers to review process of design management Regarding the third factor that is the project materials administration, 64 % of respondents confirmed that procurement process can be administered efficiently if process are reviewed based on value added consideration e.g. conditions of procurement, alternative materials, submittals and approval, etc. other 36% stated that they focus on approval process and issue of purchase order to bring the materials to the site without delay.

Forth factor, planning and scheduling, 67% confirmed that they review activities of each mile stone by focusing on the work process of each activity and resources required, while 33% stated that they work according to the planned schedule to achieve the mile stone without any delay. The awaited added-value that is fifth factor, 69% of correspondents confirmed that they focus on the added value of the client for the proposed project and they try to comply with the required efficient need of the project that will add the real value for the project, the remaining 31% of respondents stated that there duty is to complete the project according to the design criteria, drawings, specifications without any changes and they are not interested in changes during the design and construction. Lean Construction is a “way to design production systems to minimize waste of materials, time, and effort in order to generate the maximum possible amount of value [20]. Factors number 6, it is about productivity of the team in the project, 71% of respondents confirmed that they monitor the productivity of the resources and they mentor the resources to accomplish the desired productivity to avoid any waste during the work. 29% stated that they increase the resources to accomplish the deadline of any activity without looking to reasons that cause law productivity. Regarding factor number 7 which is the communication plan, 73% of respondents confirmed about necessity of preparing and reviewing the communication plan at the beginning of the project especially with the stakeholders by considering regular communication mainly reporting the updated information with each of project team, while 27% stated that it is the duty of document control to circulate the information and reports to the project team, it is not a major issue, as per “their confirmation”. Factor number 8, the necissety of BIM or visualized system, 75% of respondents confirmed that BIM or any digitalized system is very important and it helps project managers and the project team to check the design, interfaces, sections, openings, locations of ducts and other components in the project before construction start. It improve the process and eliminate the waste during the construction. Other 25% of respondents stated that they don’t have this technology and they have no time or support from the management to obtain any training for this new technology. Workers can remember elements such as workflow, performance targets, and specific required actions if they visualize them [21].

7. Conclusion

This study revealed the benefits of lean construction technique in construction industry, where lean must be considered as **a technique in construction projects at** project manager’s level to enhance and improve design and process efficiency, lean can be applied to any project in construction industry or in any production process. If lean mechanism is implemented correctly, it can create huge and big improvement in the efficiency of work process, time, quality, materials control and cost, and productivity of manpower in construction projects. The cost can be reduced and controlled where added value of the invested money in projects can be observed. Reducing process variability will also increase customer satisfaction and decreases the volume of non-value-adding activities as stated by [22].

Lean methodology and techniques can eliminate the waste, the non-value added, and unnecessary component of any working process. The increased visualization lean tool is about communicating key information effectively to the workforce through posting various signs and labels around the construction site. This includes signs related to safety, schedule, and quality. This tool is like the lean manufacturing tool, visual controls, which is a continuous improvement activity that relates to the process control.

Lean construction is considered as a powerful tool to enhance productivity by reducing wastage. Lean construction techniques and mechanism are not implemented in gulf rejoin compared to other countries. One of important tools that support the implementation of lean construction in projects can be computer aided design, CAD; and building information modeling, BIM, visual inspection, health and safety program, preventive and predictive maintenance, continuous improvement, design of target value, implementation of total quality management, just-in-time approach, and the work environment.

The word lean has been used most often and it is associated with lean thinking, lean manufacturing, lean construction and lean production [23]. The technique can also be used during design development in special contracts like design-build contract in construction industry. Lean construction involves ways of designing production systems to minimize waste in materials, time, and human effort, with the aim of generating maximum cost-effective value [24]

8. Recommendation

Managing construction projects always requires special techniques, e.g. lean construction techniques is one of the best tools can be used to minimize the waste during design and construction. Managing construction waste is one of the most necessary management processes to achieve project objectives which makes the senior managers of construction projects to focus on this tool to identify and analyze all the waste to improve productivity of project resources, minimize time and accidents, improve reliability, improve quality and ensure client satisfaction with a confirmed added-value for the project. Clear guidelines can be developed by experts in this field to encourage the adoption of lean construction.

It is extremely important to use modelling and visualization techniques to improve design, planning and communication. Early planning can improve the work flow that will be focused on the achievable tasks and avoiding mistakes and duplicated efforts where activities that not adding values can be eliminated. Value management techniques and just in time product item can be planned to help in maintaining risk management techniques where last planner system can be considered as well.

It is recommended that researches can develop further studies to determine how lean construction tools/techniques can be applied to eliminate the different types of waste in the construction projects in gulf rejoin. In addition, further studies can be investigated to find out the barriers of adopting lean construction in construction firms.

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The Influence of Human Capital on Construction Projects' Management

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Abstract

Financial, physical, and intangible assets represent most of a corporation's assets. Human capital is the most valuable intangible resource, and activities aimed at increasing productivity have expanded dramatically. Several studies show a close connection between an organization's human capital and its overall performance. According to businesses, an organization's market value is less dependent on tangible than intangible resources, such as its human capital. Today, many emerging economies lack financial and human capital, despite having an adequate labor force. To overcome a human capital shortage, companies must consistently increase their investments in employee development, ensuring that their human capital procedures are in place to ensure the project's success. Knowledge, skills, and capacities are essential success criteria contributing to a project's timely completion. The project's success depends on various elements, including physical and financial capital, technology, and people. As a result, human resources receive less attention throughout the initial stages of the project, which is a design flaw on the part of the project's creator. Human capital methods may help people get the essential knowledge, skills, and capabilities. These tactics not only create human capital but also help projects run smoothly. These characteristics are crucial for project success. Even though human capital practices are critical to the project's success, they have received little attention. The interference of project management and human capital is an under-researched area. The authors review the role and impact of human capital on project management. The research links human capital and project success by examining the effect of human capital development techniques. Following a general introduction, the relationship and interaction between human capital and project success are discussed based on the most recent literature. Despite the limited literature, the authors also attempt to explore the link with the construction sector.

Keywords: construction project, human capital, project management, project success.

1. Introduction

Today's construction industry values human capital. Hence, human capital is considered across industries; hence, its meanings vary. This study investigates how human capital theory has changed through time, affects industry success and competitiveness, affects construction performance, and the growth of the construction industry's success. Human capital investment boosts employee happiness, culture, and productivity.

2. Project Management

Customer quality expectations require better project management. The project manager must identify critical success criteria. Managing projects and operations in unconventional circumstances require project managers to learn rapidly and communicate effectively [1]. Project managers have both technical and interpersonal duties [2]. 60% of initiatives fail due to inadequate HR management, making it the most challenging issue [1].

The project manager's principal goal is speed. Each project ends. Meeting deadlines is crucial for competitive advantage, shareholder value, and revenue [3,4]. Identifying the most crucial variables means finishing a project faster and making the most of project resources. Success, efficiency, and production will all increase. Business success requires quickly identifying important success characteristics.

Management responsibilities have risen due to socioeconomic and technological advancements in the workplace. The human capital development and upkeep are crucial for project success [5]. Human capital, emotional intelligence, project manager emotional competency, and employee well-being have received minimal attention [1,2].

3. Human capital

Adam Smith (1776), in his book The Wealth of Nations, said that health care education is crucial in all cultures to develop skills and knowledge. This philosophy created the "human capital" theory, encompassing talents, knowledge, health, and creativity [2].

The building business generates new financial resources and improves infrastructure, helping governments attain socioeconomic goals [6]. For long-term growth and sustainability, expertise is required from the beginning to the end of construction projects, impacting the economy and construction [3].

A company's assets are mostly money, equipment, and intangible assets [1,3]. The most valuable intangible asset is human capital [2], with the skills of education, competence, and experience [1], which require formal education and on-the-job training.

Banik and Bhaumik define capital as three assets [2]: physical, economic, and human capital. Physical capital comprises land, buildings, factories, and machinery that produce goods and services [2]. Financial capital alone cannot make products. Human capital can be divided into general HC (transferrable abilities) and specific HC (training and education-based skills and knowledge required for a particular occupation). Investing in this crucial component of economic activity increases the company's assets.

There is a massive labor force in emerging economies but a scarcity of human capital [2]. Completing a project requires knowledge, skills, and talents [1], and additional training is necessary to ensure the project's success [1–3]. Project management requires EQ [3]. A team's performance depends on the project manager's motivation, which influences team success [3].

Even though the employees' well-being implies emotional intelligence and skill, and team satisfaction enhances project achievement, this topic is still understudied [1,3,5]. In a reciprocal relationship, human capital enhances human resources (HR), while HR values hardworking employees [1,7]. Human capital improves employee and business productivity [1,7], and its policies and procedures encourage competitive thinking and behavior [1,7].

4. Leadership

Leadership influences the organization's growth and viability [8–10]. Business and academia do not comprehend what constitutes a successful project or how to lead one [1,10–12]. Even though MBTI, Belbin, and 16PF are not leadership tests, they are employed by project managers to investigate the impact that management styles have on the outcomes of their endeavors [13].

Several studies on leadership include leader traits and job performance [10,12]. More focus has been placed on leaders' activities, interactions with followers, organizational culture, emotional intelligence, and team engagement [10].

Leadership theory focuses on influential leaders [10]. Dulewicz and Higgs (2003) selected 15 leadership skills based on approaches and measures to examine this phenomenon because skills, knowledge, and personality affect performance [12]. The primary project manager skills are problem-solving, results-focused, self-confidence, and good communication [9,12,14].

Even though emotional intelligence is crucial to project performance, some authors, such as Geoghegan and Dulewicz (2008) and Maqbool et al. (2017), claim that research on the factors that contribute to a project's success undervalues the role of the project manager [15].

5. Project Success

Research modifies the project success definition. This technique first prioritized the Iron Triangle (cost, time, and quality), but early in the 21st century, a project's success was determined by its contribution to achieving business objectives, focusing on the satisfaction of customers and enterprises, as well as the effectiveness of short-term and long-term projects [10].

A project's performance depends on financial, physical, and procedural factors. Since objectives and criteria influence project outcomes, managers must establish success criteria, prioritizing tasks to be completed on time and within budget [1,7].

In 1995, Wateridge discovered the requirements for success: earning money, making users happy, adhering to a budget, and having a specific goal; and in 2006, Turner and Müller founded PEM, a model with eight success criteria factors to evaluate how leadership impacts project success [10].

6. Project Type

More projects require innovative methods. Various projects differ in size, complexity, and technology, among other characteristics. Classifying projects permits a comparison of how they are managed , and organizing them into categories facilitates their connection to company objectives and improves project management [5].

Some projects improve an existing product or service, bringing in more money for the business. A project manager's leadership and effectiveness are affected by the project's characteristics, and the ability to execute a project depends on its strategic significance and degree of complexity [10].

7. Human Capital and Construction Project Success Through Emotional Intelligence

Project managers are confronted with a dynamic and complex environment every day. Emotional intelligence is one of the skills that, when enhanced, will significantly impact project success [9,10]. Researchers analyzed the correlation between training, teamwork, trust, and project success metrics like delivering on time and within budget [1,7].

In order to succeed in today's cutthroat trading environment, companies must complete projects on schedule and under budget. The success of a project depends on people, technology, physical space, and financial capital. Even though HC affects project success, it is disregarded early in a project [16].

Human capital is essential for optimizing other resources. Employees are the source of any organization's or project's success and profits. HC must aid in completing a project by ensuring that the team employs effective human resource procedures and has effective training programs. Businesses must modernize their human capital policies and procedures to boost employee performance and complete more tasks [1].

A combination of characteristics, including responsibility, success, charisma, and communication skills, is necessary for effective leadership [10]. The success or failure of a group or organization depends almost entirely on its chief executive's personality and leadership abilities [1,3,10]. The administration and execution of projects necessitate managerial leadership competencies and emotional intelligence, with leadership roles requiring greater emotional intelligence levels [10].

To encourage economic progress and improve people's lives, HC invests in acquiring knowledge and expertise. Its success depends on the quality of the work performed by its employees. The human capital approach, which emphasizes education, is associated with increased productivity [9,10,16]. Knowledge, abilities, and other forms of human capital make up the HC theoretical framework. Training construction employees benefit greatly from [3]. Scientists say that people are more likely to be successful if they have more education. HC needs to be flexible, knowledgeable, and quick on its feet to keep up with the evolving construction industry. In HC's view, increased output in the business sector directly results from graduating students' acquiring the requisite skills.

8. Conclusion

This research looked at how the human capital theory influences employment opportunities for recent college grads in the construction industry. Industrialized nations' GDP relies on worker training, which has led to increased knowledge and productivity. HC's societal benefits have an impact on economic growth over the long term.

HC encourages individuals to expand their horizons and acquire the skills necessary to improve their quality of life, increase their income, and alleviate or avoid poverty. To combat capitalism, human forces are essential. The literature on HC growth demonstrates a connection to the construction sector as well as other consequences.

Smart investments in HC development can improve construction sector efficiency, quality, and competitiveness in developing nations. To keep up with globalization and IT, businesses and stakeholders must review and revise their people development policies.

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The Role of Friction in Complex Organization Networks

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Abstract

We assume an organization comprising a vast number of participants with varying interests and skills. In order to contribute to a common project, the members are interconnected to each other impacting adjacent players by their own attitude via nonlinear functions. Hence, an organization is modelled using systems theory as nodes representing the single variables and local interaction functions impacting next neighbours. Any such system starts with arbitrary values, i.e., a random starting state vector, and eventually develops towards equilibrium in a system-specific manner. While a purely determined system follows the given differential equation systems and, therefore, exhibits at least some principally causal character, realistic models need to take in stochastic variations on all variables representing local ideas, constraints, likes and dislikes, therewith bringing in the most important aspect of creativity. This add-on enforces non-linear interaction aspects raising the unpredictability of the development paths to possibly chaotic behaviour. The aim of this research is to investigate the developing character of systems close to these limits of determinability where unimpeded development tends to instable and finally chaotic behaviour. Based on the fundamental concepts of controlling loops, the loss of determinism is elaborated and a principal limit of controlling strength based on the local complexity is described. On this background, the role of friction within an organizational system formed by the fundamental delay to all interactions is investigated. The introduction of some additional artificial friction is furthermore proposed to help stabilizing the system in the long run. May this even slow down the local stabilizing processes, friction is expected to dampen random side effects to some degree and, hence, providing some safety margins against fundamental instability plays a crucial role.

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Keywords: Organization Theory, Controlling, Systems Theory, Lean Management, Construction Management.

1. Introduction

The central task of any organization is to bring together a vast number of participants aiming at the optimal solution of a complex situation, comprising a number of issues connected by their mutual relationships while furthermore observing numerous boundary conditions [1, 2, 3].

With respect to construction projects, these "issues" are given by a huge number of technical, legal, economical, aesthetical, etc., parameters which are forming the actual physical construction as well as the processes of creating. They clearly depend on each other in numerous ways and range within certain boundaries given by external strict rules or just by more or less strongly pursued preferences. Numerous players are furthermore involved contributing to the definition or execution of these issues, also bringing in a number of parameters which as well are depending on many others. Clearly, most of the parameters are initially standing in contradiction to others and, hence, the situation is not acceptable and needs to be developed efficiently into a more agreeable version. In the end, a set of parameters is expected to be elaborated which meets all conditions simultaneously and is accepted by all participants as satisfactory [4].

In case of project organization, this would not be a long-term task but is put together in advance while expecting the organization to develop towards the optimal solution on the first attempt consuming the least possible volume of resources.

1.1. Exploring Equilibrium States

A favourable state would primarily be given by the fulfilment of all given boundary conditions and with all dependencies completely observed [5]. Since this is certainly impossible to achieve, a state of optimal fulfilment is aimed at where all requirements are at least fulfilled to a degree where in total every loss is balanced by respective gain, i.e., the set of parameters is representing a state of equilibrium.

Stability is furthermore achieved if any deviation from this state leads to an unbalanced situation which develops by itself towards the equilibrium. This behaviour refers to the inherent mechanisms of the organization to change parameters which is driven by the multiple targeted dependencies. Practically, this is to some degree a consequence of dependencies where a target value is simply determined by the source values, e.g., cost would be plainly given by the product of the required number and the price per unit. Beyond that, however, a significant number of dependencies are actively driven by the participating players' preferences, e.g., the investors pressure to finish in shortest possible time. The overall concept of economy is based on such driving effects and consolidating at states of stable equilibrium, e.g., equilibrium of markets [6, 7].

However, respective investigations [8, 9, 10, 11] reveal that stable systems need to be constructed carefully. Randomly generated structures will under no circumstances consolidate with some significant probability. This implies in particular two aspects:

First, parameters which need to be reliably held within a certain corridor need to be equipped with active controlling loops feeding back required modifications to the environment on respective deviations and so far, keeping the parameters close to the designed values [12, 13]. This applies, e.g., for the rate of consuming resources or the rate of producing a certain result. Such controlling mechanisms are in general not existing automatically but need to be carefully implemented in order to provide predictable stability.

Second, players need to bring in the personal readiness to adjusting their local parameters of preference [4, 14, 15, 16, 17]. Otherwise, no stability can be achieved. This can be encouraged by the use of respective contracts, in particular treating the issues of coordination and motivation allowing to helpfully provide maximizing their local utility functions. In reality, this aspect implies that each player is in fact interested in the project's outcome and invests a lot to adapt himself to the very needs. Such behaviour is identical to local controlling loops observing for differences to sensible values and adjusting accordingly. Obviously, controlling mechanisms need to be substantially stronger than the destabilizing effects of the system.

1.2. Introducing Time Delays Expressing Practicability

In order to negotiate these deviations, communication is required. Lean Management tends to favour fast and widely targeted communication while hierarchical approaches prefer strong separability and hence avoidance of long looped communication in order to have fast consolidating but starkly local communication clusters [18, 19, 20, 21]. The preference of the one or the other is not to be discussed here, however, we need to agree on the existence of a not vanishing time pattern of communication. Even under ideal circumstances, a player needs some time to survey and understand the requirements of the environment, to consider the local possibilities and to compile and initiate a respective offer. Hence, all kinds of reacting mechanisms required to develop consolidation will happen with a minimal but significant time delay [22, 23]. This very realistic property is expected to have the effect of slowing down communication, therewith slowing down the process of consolidating towards an equilibrium just in the same way as the term "friction" would describe in a very perfunctionary way.

1.3. Creativity

As already pointed out in section 1.1. [4], the willingness to adjust of any participant is required for consolidation. Considering in particular personalized players, not merely mathematical functions or inevitably occurring consequences are dictating the reaction on the needs of the environment, but in particular unthought-of solutions and proposals are expected, namely creative ideas. Creativity happens to the participants to their best knowledge and will. Semantically, this is a rather obvious conclusion. However, the actual effect of creativity with an organization has not been described up to now in detail and is to be investigated in this paper, providing a respective proposal.

2. Considerations of Potential Driven Motion

2.1. Model of an Organization as a System

In order to study the fundamental behaviour of organisations, typically models according to system's theory are used [24, 25, 26, 27, 28]. All participants, physical issues as well as persons, are represented by elements, i.e., nodes, while their interaction is given by unidirectional functions on the respective ties. On the most fundamental level, all nodes bear exactly one variable q_i which is the target of all inbound tie-functions determining required changes of the q_i. The state vector $\vec{Q}$ is spanned by the multiplicity of all variables q_i. Developing the tie-functions into Taylor series is used to linearize the system, which is applicable in the close proximity of equilibrium vectors as long as the functions are sufficiently differentiable. Then, the impact of the in-ties on a single variable is linearly cumulated as well:

$$\frac{\partial q_i}{\partial t} = \sum c_{i,j} q_j \tag{1}$$

Since absolute values of a state vector are of no interest when investigating the dynamical behaviour close to states of equilibrium, a respective transformation of the coordinate system can be applied where the origin represents the state of equilibrium $\vec{Q} = \vec{0}$. This approach considers in particular the changing characteristics, i.e., adjustability of local parameters towards the requirements of the adjoining system for each participant regardless of their absolute value. This approach leads to linear differential equation systems where the solutions are given as exponential functions. These allow for damping as well as for escalating behaviour depending on the sign of the tie strength $c_{i,j}$ in case of complex number also for oscillation which may as well be damped or escalate [23, 29].

2.2. Concept of a Potential

A system comprising vast numbers of interactions between the respective variables initially represents a state of discrepancy where most conditions are not fulfilled, i.e., far from equilibrium [30]. However, interactions are not merely stating the local inconsistency but include a mechanism to modify target elements towards an improved situation where less discrepancy is observed. This is the inherent working of a system to develop towards equilibrium, where either all relationships are completely fulfilled or at least are fulfilled to some degree where all impacts are compensating for each other at every node [31].

Hence, the degree of overall discrepancy as a function of all n variables q_i semantically plays the role of a n- dimensional potential $\Omega(q_i)$ which is to be minimized. A global minimum reflects the particular state vector where the cumulative discrepancy is minimal and cannot be improved further. No external means need to be established developing the state towards this vector but the impact functions themselves take care of the respective modification of their targets leading to equilibrium.

Classical algorithms searching for a minimum state on a multidimensional potential likewise operate simultaneously on all variables q_i (i.e., coordinates of the space of states) and take small modifying steps into the direction of the gradient $-\nabla\Omega(q_i)$. Therewith, a path "downward" the potential is taken, finally ending at the respective minimum where the gradient is zero $-\nabla\Omega(q_i) = 0$and no more sensible steps can be derived. Using a physical understanding, the negative gradient is used as a virtual "force" driving the particular variables towards the minimum where no more directional "forces" are in effect.

Remark: This understanding resembles physical potentials, however, is not the same. In this context we discuss the applicability of the physical terms like "potentials", "forces, "energy" etc. and their properties on the development of an organizational system. Therefore, all needed properties need to be explicitly derived from the given differential equations rather than unreflectedly taken from well-known physics.

2.3. Linearized Interaction

Restricting interactions to linear functions leads to the well-known differential equation system of control which provides exponential solutions - oscillating or monotonously escalating or damped.

In the present discussion we reduce the multidimensional linear differential system exemplarily to a single control loop instead of considering the feed-back impact of numerous multi-step loops implying no restriction to generality. The overall character of motion is then given by the magnitude and the sign of the combined controlling strength β which might be a complex number.

$$\frac{\partial q_i}{\partial t} = -\beta q_i \quad \Rightarrow \quad q_i \sim e^{-\beta t} \tag{2}$$

On this background, the generalized force inducing the respective modification is defined by

$$F_i = \frac{\partial q_i}{\partial t} = -\beta q_i \quad \text{leading to the potential} \quad \Omega(q_i) = -\int F_i \, dq_i = -\int -\beta q_i \, dq_i = \frac{\beta}{2} {q_i}^2 \tag{3}$$

This is a positive square potential where generalized forces $F_i(q_i) = -\partial\Omega(q_i)/\partial q_i$are consequently leading towards the equilibrium state $q_i = 0$.

In particular is to be noted that the generalized force in question is explicitly set by the differential equation as a function of the value q_i only, completely disregarding any possible previous value. Therefore, no issues of "history" are maintained.

From this we take the general understanding of a potential in the controlling context: Assuming a closed system, completely determined by the potential, all acting forces are taken exclusively from the gradient. Hence, at any location q forces are given, triggering a modification of q which lead to a new state where the potential yields a lower level. This reduction of potential (representing the improvement of the state regarding optimization) can never be reversed since forces always lead "downwards" (negative sign), unless there were means to "store" this potential difference somewhere and retrieve later being a different source of forces possibly driving states upwards a potential. However, in the case considered here the linear differential equation provides only the one given generalized force and no means of storage. Hence, this will not happen on the controlled system discussed here. Correspondingly, such virtual forces are understood as being "static" while "dynamic" forces resulting from history are not existing.

Remark: Obviously, the potential reflects the physical potential energy, while "storing" would be correspondent to kinetic energy.

2.4. Introducing Inertia and Friction

As pointed out in [23], any controlling delay due to finite detection patterns, time consuming considerations and finally the required time to get consequences into action is absolutely realistic and has the effect of virtual inertia as well as virtual friction. Therefore, sensible equations of motion are complete only if taking these terms into account as well:

Subjected to some substantial time delay$\Delta t$the integral controller differential equation

$$\frac{\partial Q}{\partial t} = -k_C Q \quad \text{develops into} \quad \frac{\partial Q(t)}{\partial t} = -k_C Q(t - \Delta t) \tag{4}$$

A second order Taylor development of Q close to the point of time t leads to

$$Q(t-\Delta t) \simeq Q(t) - \Delta t \frac{dQ}{dt} + \frac{\Delta t^2}{2}\frac{d^2Q}{dt^2} + \ldots \text{and} \frac{d^2Q}{dt^2} = \frac{-2k_C}{k_C \Delta t^2} Q + \frac{2(k_C\Delta t - 1)}{k_C \Delta t^2}\frac{dQ}{dt} \quad (5)$$

In close analogy to the physical description of a harmonic oscillator the coefficients of the terms can be identified

$$\frac{\partial^2 Q}{\partial t^2} = -\frac{\beta}{\mu} Q - \frac{\rho}{\mu}\frac{\partial Q}{\partial t} \text{ and result in } \mu = \frac{\Delta t^2}{\tau_C} \quad \beta = \frac{2}{\tau_C} \quad \rho = 2\left(1 - \frac{\Delta t}{\tau_C}\right) \quad (6)$$

Remark: The formal solutions of this differential equation reflect the observed behaviour of controlling mechanisms very well, allowing for escalating or damped monotonous or oscillating functions [32].

In addition to the recognisable term of retarding force β a mechanism of "inertia" reflects the ability of a variable to maintain the recent rate of modification ("motion") for some time and implies a "storing" memory effect. The therefrom resulting generalized forces go with the second derivation of q and are controlled by the parameterμ. A second derivative implies that the previously given rate of modification is maintained, however, just infinitesimally modified by this term. Hence, the "history" of the situation plays a significant role as the development is principally continued, only small changes are made to the speed. Here, "dynamic" generalized forces come into play.

Furthermore, a "friction" term turns up, proportional to any present modification of q, i.e., proportional to the first derivative of q, in particular with negative sign, i.e., continuously reducing speed of motion. This is also a dynamic force, since it derives from the past speed of modification. However, if this term dominates over the inertia term, the differential equation can be reduced to the undelayed situation. Otherwise, the friction term contributes a certain share to the inertia term (i.e., setting a friction-modified change to the current rate of development), in the end leading to the observed damping effects on the oscillating solutions.

This background clarifies that in controlling structures "friction" is closely coupled to "inertia" and cannot be understood separately. Any time delay leads to inertia forcing oscillations as well as to friction reducing such behaviour.

Remark: The magnitude of these effects is, however, controlled independently by the time delay Δt and the controlling time constant τ_C. As expected, reducing the time delay to zero leads to vanishing inertia and constant friction, reducing the differential equation to the original first-order form:

$$\Delta t \to 0: \quad \mu\frac{\partial^2 Q}{\partial t^2} = -\beta Q - \rho\frac{\partial Q}{\partial t} \quad \Rightarrow \quad 0 = -\frac{2}{\tau_C}Q - 2\frac{\partial Q}{\partial t} \quad \Rightarrow \quad \frac{\partial Q}{\partial t} = -\frac{1}{\tau_C}Q \quad (7)$$

On the other hand, raisingτ_C produces increased friction up to a constant value while reducing inertia as well as (naturally) the controlling strengthβ:

$$\tau_C{}^{-1}(= k_C) \to 0: \quad \mu \to \mu \cdot k_C \quad \beta \to \beta \cdot k_C \quad \rho = \rho_0 - \rho_v \to 2 - \rho_v \cdot k_C \quad (8)$$

Potential approach: The so far extended differential equation requires a different setting when attempting a potential approach. Obviously, three terms represent the respectively acting forces "acceleration", retarding forces and "frictional" forces. Typically, non-conservative forces like (dissipative) friction cannot be described by potentials and need to be treated separately. Nevertheless, at least the inertia part is available:

$$\mu\frac{\partial^2 q_i}{\partial t^2} = -\beta q_i - \rho\frac{\partial q_i}{\partial t} \overset{\rho \to 0}{\Rightarrow} \frac{\partial^2 q_i}{\partial t^2} = -\frac{\beta}{\mu} q_i \qquad q_i \sim e^{i\omega t} \quad \omega = \sqrt{\beta/\mu} \quad (9)$$

Such second order potentials are known as a situation effectuating undamped oscillations as are observed.

The potential is then also a positive square (however, generalized forces are defined different from the previous section).

$$F_i \sim \frac{\partial^2 q_i}{\partial t^2} = -\frac{\beta}{\mu} q_i \quad \Omega_i = -\int F_i dq = -\int -\frac{\beta}{\mu} q_i dq = \frac{\beta}{2\mu} {q_i}^2 \tag{10}$$

Understanding dynamical forces/storing on potentials: On this background, the dynamical aspect renders comprehensible. Since the differential equation just sets the change of the modification rate (and not the modification rate itself), any force derived from the potential, i.e., from reducing the potential level, goes into a new dynamic state, i.e., the rate of change. This implies, that changes of this rate need a gradient of the potential to be created. Then, clearly, reducing the rate of change also requires a gradient of the potential which is only possible if this mechanism works *vice versa* as well. As a consequence, a rate of change "stores" the reduction of the potential, which originally created the rate, while a negative reduction of the potential level, i.e., a rise of potential, follows from emptying the “rate” storage, i.e., reducing the rate of change. Hence, a respective storage mechanism is available in this setting.

Understanding of friction on the potential: The effect of friction as a term proportional to the rate of change contributes to the virtual forces. Hence, this term is not depending on the location$q$but on the motion and can therefore not be modelled using a potential. However, the friction term creates nonetheless a generalized force which is to be understood as a well-defined decrease of potential, though not in dependence of q (but of $\partial q/\partial t$ which is history). Hence, friction can be denoted as a reduction of the potential which occurs at any location$q$. This share of diminishing the potential value can clearly not be stored somewhere and is understood as being “lost”.

3. The Effect of Creative Ideas and Friction on Minimizing Potential

3.1. Interdependency of Inertia and Friction

As soon as storing mechanisms enter the system, changes of the state vectors become reversible. Therewith, infinitely unstable situations are not only possible but represent the fundamental solution of the differential equation systems. Only unstorable fractions allow for dissipating reductions of the potential, i.e., damping effects leading finally to stable equilibrium states.

The functionality of the friction term on a potential approach is easily understood as each bit of gained potential improvement is stored with the inertia term, however, reduced to some degree by the friction impact. Thus, stored and, hence, from storage retrieved shares are always less than the original amount. This effect principally impedes reaching any formerly attained state vectors and therewith reduces any rate of change over the time and eventually brings all changes to a halt.

As pointed out in section 2.4., inertia effects are caused by reaction delays which also provide the damping friction. Hence, depending on the ratio of these effects with the introduction of oscillations also the solution is brought in. According to [22] stable equilibrium is achieved if the controlling time constant τ_C exceeds the time delay Δt significantly providing a measure of stability $S_N < 1$.

$$S \sim \frac{1}{\tau_C - \Delta t} \frac{Q}{\dot{Q}} \overset{Normalized\ Q}{\Rightarrow} S_N = \frac{1}{\tau_C - \Delta t} \text{ and } S_N := 1 \quad \Rightarrow \quad \tau_C^{stab} = 2\Delta t \tag{11}$$

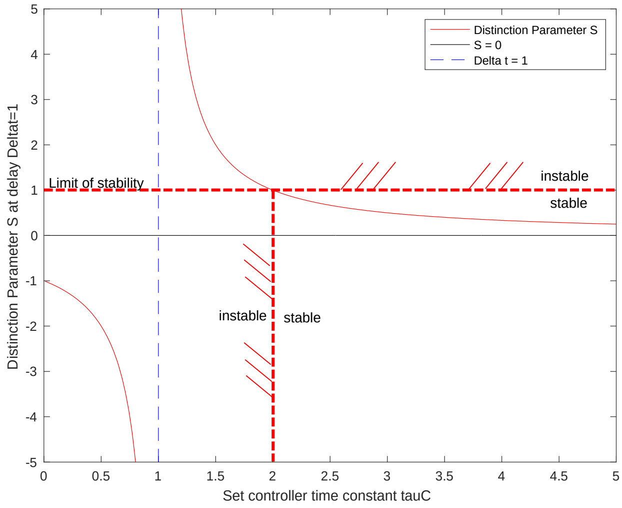

Figure 1. Development of distinguishing parameter S with $\tau_c$close to Δt

3.2. Creativity: Nonlinearity - Destabilizing Character - Chaos - Sub-optima

Accepting the bringing in of creative ideas implies a high degree of independence of a participant's reaction to the current situation. Thus, the restriction to linearity turns out to be a very limiting condition which no longer holds.

On this background, linear differential equation systems no longer reflect the true behaviour of the system. As a first consequence, so far induced situations lie far away from equilibrium where linear approximations provide only poor results. However, as long as dependencies are monotonous and differentiable, at least the given directions of approach are still valid, though stabilization time constants are no more reliably available. Furthermore, chaotic behaviour is likely to occur on nonlinear equation systems as soon as feed-back strengths are rising to substantial values. Such a scenario is clearly a realistic case, if a participant is reacting on an upcoming new idea with an innovative proposal himself. This may lead - as expected - to a completely new situation, where previously unknown characteristics are to be considered and explored. Therewith, the upcoming of multiple sub-optima as a consequence of nonlinear interaction is noted and needs to be tackled further in finding a globally optimal scenario.

3.3. Creative Modifications in Linear Systems

Creative modifications to a state vector have no directly corresponding counterparts in the linear differential equations. In particular, they cannot be described by generalized forces since the rate of change is in no way modified but solely the state vector is changed in no time. Furthermore, the reason, magnitude or direction of change cannot be derived from the present situation, e.g., the recent state vector determining the potential or any derivative. Hence, creative changes need to be understood as stochastically given, i.e., a random noise vector Q_{Rnd} added to the state vector at random times.

Investigating the impact on the stabilizing behaviour reveals easily that principally no stable equilibrium can be reached since continuously new ideas are coming up and need to be integrated (or damped away). Just adding a random constant vector to the state with each consolidation step simply adds the given uncertainty to the individual values as well as to the average result (and the final equilibrium state vector).

3.4. Proposed Approach - Simulated Annealing

If linearity is not given, an intermediary situation may be investigated and reveals some of the properties close enough to equilibrium to follow the differential equations, however, far enough away to allow for creative ideas. Hence, as known, e.g., from [26], the local environment is assumed to be subjectable to first-order-Taylor-development providing sensible stabilizing mechanisms, while arbitrary creative moves are allowed to shift the situation to completely different locations.

In this case the known equations may apply, however, at least the existence of a vast number of multidimensional sub-optima needs to be taken into account. As a consequence, the given differential equation system may be applicable but in need of further assistance to stabilize on global optima rather than local minima. At this point, creativity comes into play helpfully by providing the random noise required for appropriate travelling away from local sub-optima in order to reach globally optimal values (Simulated Annealing [33]).

This concept is named “Simulated Annealing” used for optimizing a state vector on a potential which is characterized by numerous sub-optima. During the execution of classical hill-climbing algorithms a random modification is added on the state-vector (resembling Brownian motion) which inhibits sticking to local minima and allows for pushes towards a global solution. Over the optimizing process the magnitude of the add-on is reduced to zero forcing a stable equilibrium once it is reached. This corresponds to the cooling down process, diminishing the Brownian motion, hence the term “annealing”. In order to avoid repeated jumps, i.e., artificial oscillations, a single criterion is to be observed: A Brownian jump will only be taken if the newly achieved state-vector leads to a significantly improved potential. Hence, no jump back is possible, due to some “loss” of potential, which corresponds to the functionality of friction.

3.5. Friction Representing the Decisive Criterion

The organization system considered here suffers from the existence of numerous sub-optima where the global minimum is searched for. Approximating the interacting functions by the use of the first Taylor terms allows for developing towards an optimum resembling the classical hill-climbing algorithm. However, creative ideas are required to be brought in in order to avoid stuck situations which correspond to sub-optima. Allowing for such erratic moves changes the situation and continually opens unconsidered options. Though, permittance of such moves also provides the same probability to worsen a given situation of temporary (local) agreement. At this point, artificially introduced friction terms limit the extent of creative ideas to such that are leading to an improved situation and, therewith, inhibit those ideas which worsen the situation. This concept corresponds to the method of simulated annealing.

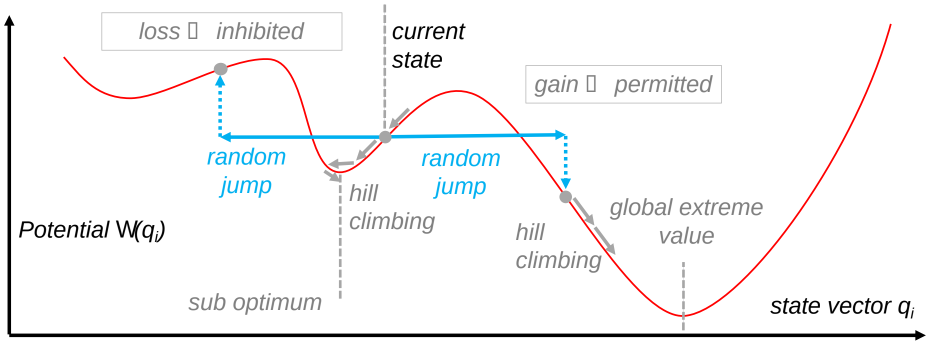

Figure 2. Random noise and friction on potentials with sub-optima.

However, friction on creative ideas is not the same as friction growing from controlling delays, though, serves the same purpose and has the same effect on potentials. In this case, friction does not originate automatically from the rate of change and is, therefore, not a dynamical force. Furthermore, creative moves are also not derived from the potential’s gradient nor from dynamical memory but are randomly injected. Hence, the therewith gained potential cannot be stored at all, and, using the same reasoning, a rise of the potential is not capable to inhibit such a move.

Any permission to run a creative move based on the required improvement of the potential is not accountable, since no direct measure for the potential value is available. Hence, in contrast to "simulated annealing" a mechanism of "try and error" is necessary, initiating a creative idea and possibly pulling back if not meeting the potential requirements, i.e., improving the local situation. To accomplish this, an artificially introduced mechanism is required.

3.6. Artificial Friction as Means to Handle Creativity

Creative moves are, though they are useful to escape from local sub-optimal traps, to be treated as disturbing artefacts which need to be damped down and ruled out through the existing controlling system. In this respect, they are forming additional noise which can be eliminated and brought to new equilibrium states only by dissipating terms, i.e., friction. Such terms are introduced by time delays, but their effect is to some degree also eaten up by the introduction of storing terms ("inertia"). Section 3.1. [22] described the limit of balance, where no friction effect is left for other purposes. Therefore, the controlling system needs to be designed in a way that the remaining friction suffices to dampen the brought in creative moves. Since constant noise added at a stable equilibrium state continuously fuzzifies the state vector, no improvement can be derived from further creative moves at this point. Thus, we state qualitatively the need to reduce the amplitude of noise over time once approaching the optimum ("annealing").

A suitable measure for these effects can be taken from the balance-limit mentioned above [22], where, however, the vectors Q are replaced by a representative component q_i:

$$S = \frac{\beta}{\rho}\frac{q_i}{q_i} = \frac{1}{\tau_C - \Delta t}\frac{q_i}{\dot{q}_i} \tag{12}$$

In this equation, q_i refers to the deviation of the respective variable to be ruled out. Any additional random noise on it is to be treated as an offset $q_i + \Delta q_i$. In order to compensate for the offset an increased distance between the controlling time constant $\tilde{\tau}_C$ and the controlling delay Δt maintaining the same degree of stability is required.

$$const = S = \frac{1}{(\tau_C - \Delta t)_{Mod}}\frac{q_i + \Delta q_i}{\dot{q}_i} \tag{13}$$

Clearly the magnitude of the random noise $\Delta q_i(q_i)$ as a function of the distance q_i determines the behaviour of the system approaching equilibrium and, hence, the demanded modification of $\tau_C \rightarrow \tilde{\tau}_C$ or $\Delta t \rightarrow \tilde{\Delta} t$ to compensate. Setting $\Delta q_i / q_i = \eta$, we need to investigate two border cases: Allowing for all kinds of creative moves, i.e., $\Delta q_i = const$ leads to hyperbolic development of $\eta(q_i)$ while forcing the noise to a limit proportional to q_i also limits η to $\eta(q_i) = const := \varepsilon - 1$

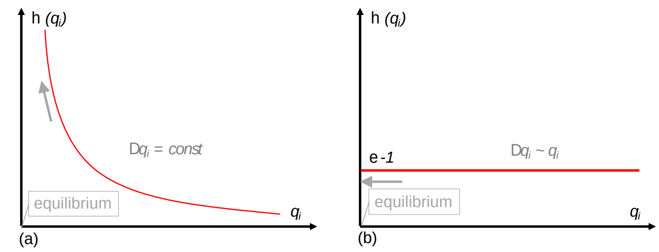

Figure 3. Requested compensation factor for constant (a) and proportional (b) noise.

$$const = S = \frac{1}{(\tau_C - \Delta t)_{Mod}}\frac{q_i + q_i\eta}{\dot{q}_i} = \frac{1}{(\tau_C - \Delta t)_{Mod}}\frac{q_i}{\dot{q}_i}(1 + \eta) \tag{14}$$

Obviously, constant offsets cannot be handled and would lead to the demand of infinitely large controlling time-constants $\tilde{\tau}_C$ to compensate. Demanding the limitation of offsets proportional to q_i requires limiting the absolute noise amplitude to a noise factor $q_i + \Delta q_i = (1 + \eta)q_i = \varepsilon q_i$. Then, the required compensation difference between the controlling delay and the controlling time constant is ruled by ε as well.

$$const = S = \frac{1}{(\tau_C - \Delta t)_{Mod}}\frac{q_i + \Delta q_i}{\dot{q}_i} = \frac{1}{(\tau_C - \Delta t)\varepsilon}\frac{\varepsilon q_i}{\dot{q}_i} \tag{15}$$

In particular, the original limit of stability is modified by either reduction of Δt or raising the reaction time constant $\tau_C$with slightly different effects. Combinations are possible, however, not considered here:

$$\tau_C = 2\Delta t \quad \rightarrow \quad \tilde{\tau}_C = (1+\varepsilon)\Delta t = \frac{1+\varepsilon}{2}\tau_C \text{ resp. } \Delta t = \frac{\tau_C}{2} \quad \rightarrow \quad \tilde{\Delta} t = \frac{\tau_C}{1+\varepsilon} = \Delta t \frac{2}{1+\varepsilon} \quad \varepsilon > 1 \qquad (16)$$

$$\text{abbreviated } \tilde{\tau}_C = \tau_C/\gamma \qquad \tilde{\Delta} t = \gamma \Delta t \qquad \gamma = \frac{2}{1+\varepsilon} < 1 \qquad (17)$$

As pointed out in section 2.4., both approaches allow compensating for a given value of εresp. γ. Table 1 shows the respective consequences on inertia, controlling strength and friction:

Table 1. Modification of parameters required for compensating for creative moves' amplitudes

	Modifying $\Delta t \rightarrow \tilde{\Delta} t = \gamma \Delta t$	Modifying $\tau_C \rightarrow \tilde{\tau}_C = \tau_C/\gamma$
Inertia $\mu = \Delta t^2/\tau_C$	$\mu \rightarrow \tilde{\mu} = \gamma^2 \mu$	$\mu \rightarrow \tilde{\mu} = \gamma \mu$
Contr. Strength $\beta = 2/\tau_C$	$\beta \rightarrow \tilde{\beta} = \beta$	$\beta \rightarrow \tilde{\beta} = \gamma \beta$
Friction $\rho = 2(1 - \Delta t/\tau_C)$	$\rho \rightarrow \tilde{\rho} = 2 - \gamma \rho_v$	$\rho \rightarrow \tilde{\rho} = 2 - \gamma \rho_v$

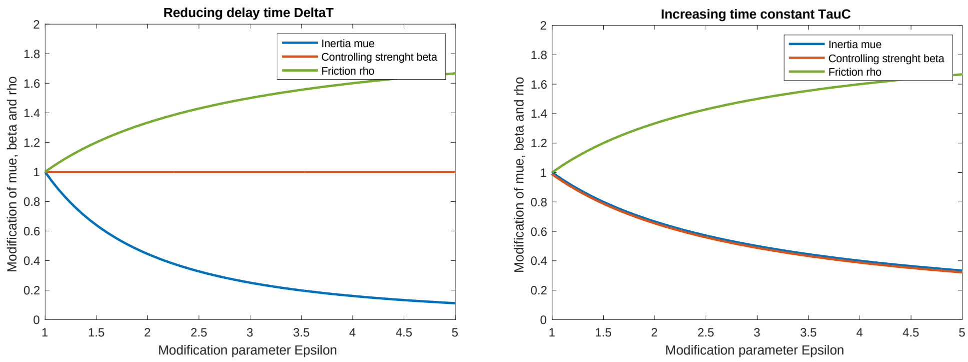

Figure 4. Development of inertia, controlling strength and friction at the limit of stability

Hence, both approaches are keeping the system in a sufficiently stable state. ModifyingΔtseems to be more promising as it provides the same amount of friction, strongly (power of 2) reducing inertia while inflicting no change to β. However, Δt is usually enforced by the given situation as well as by the invested resources of control and, hence, is rarely available for modification, in particular not reducible. In contrast, modifying the time constants $\tau_C$produces the same amount of friction, a little less reduction of inertia, but can easily be taken independently as this means to reduce the strength of coupling variables to each other.

4. Conclusion

Any organization of projects is in imperative need of strong mechanisms to approach a state of agreement regarding all the different aspects and participants. Preconditioned the willingness of all players to cooperate and contribute, resources as well as controlling processes need to be actively implemented and spent in order to achieve the project goal on the first attempt. Due to the strongly nonlinear complex nature of such systems, simple controlling mechanisms are principally under no circumstances sufficient for successful, i.e., cost- and time-efficient operation and finalizing. In particular, creative input is absolutely required to avoid sticking to suboptimal solutions while they are destabilizing the system on a principal basis. The need to operate delayed actions due to realistic considering and effectuating corrective actions follows the same pattern as it leads to oscillatory behaviour on the background of virtual inertia, but simultaneously introduces virtual friction allowing to dampen the resulting effects of instability. Overall, the therewith brought in concept of friction allows to handle the destabilizing effect of creative moves.

However, to make practical use of this, the magnitude of creative impact needs to be limited to values decreasing with approaching the final state, where no more proposals are permitted. This factor of proportionality is then used to compute the extension of the well-known limit of stability used for complex systems as a design criterion in order to keep the system capable of dealing with the respective creativity without losing its stability.

This proceeding leads to the requirement of weaker coupling, which is explicitly maintained by adapting all system variables to their sources, however, not fully but only to a limited percentage. Therewith, even while losing reaction time and, hence, agility, stability will be maintained and, thus, lead to earlier reaching states of equilibrium, which equals shorter project durations.

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Towards a Canvas for Construction 4.0 Implementation in AECO Organizations

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Abstract

Construction 4.0 has been steadily reshaping the Architecture, Engineering, Construction, and Operations (AECO) industry, especially as the industry transitions to a post-pandemic world. With the wave of technologies, tools, and principles that Construction 4.0 offers, organizations have been altering the ways they conduct their business and complete their projects. To succeful complete these changes, it becomes important to understand Construction 4.0 in order to develop a proper implementation vision that organizations can build on. Thus, this study proposes a five-step roadmap to develop a canvas that builds on existing readiness and maturity models to provide organizations with successful Construction 4.0 implementation practices across six distinct dimensions: people, environment, approaches, resources, leadership, and strategy (PEARLS). The proposed canvas is called "Construction 4.0 Implementation Canvas" or "ConIC 4.0". This paper presents preliminary results for the first three steps of the roadmap based on the existing research corpus. Findings will be validated with subject-matter experts in a future study that expands on the findings and presents the complete canvas.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2022.

Keywords: Construction 4.0, canvas, implementation practices, maturity, readiness.

1. Introduction

The fourth industrial revolution, commonly known as "Industry 4.0", introduced a wave of technologies, tools, and principles to allow industries to innovate and gain competitive advantage, increase productivity, achieve sustainability, and lower costs [1]. However, as industry 4.0 brought new opportunities to industries and organizations, the unexpected rapid spread of COVID-19 in 2020 had a dire effect on the global economy as it disturbed supply chains, decreased the global Gross Domestic Product (GDP), and created a financial toll on major industries [2]. As such, Industry 4.0 became a key vision in ensuring the survival of organizations during the pandemic, and continued to play a significant role in shortening the recovery phase, accelerating businesses return to normal, and providing a platform to develop new and resilient ways of doing business long-term [1].

In the case of the Architecture, Engineering, Construction, and Operations (AECO) industry, a notable recovery and renewal vision is "Construction 4.0" [3]. The concept of Construction 4.0 is modeled after Industry 4.0 and is inspired by the convergence of the physical and digital trends and technologies in the AECO industry [4,5]. Construction 4.0 can be defined as "digitization and industrialization of the industry that (1) enable real-time, horizontal, and vertical integration and connectivity of stakeholders across the construction project lifecycle, (2) promote the advancement of construction processes by employing mechanization and automation, and (3) bridge the gap between the physical and cyber environments" [6].

Because of the significance of Construction 4.0, it becomes important for AECO organizations to assess themselves with regard to the Construction 4.0 vision. Examples of such assessments can be "readiness" and "maturity". In context, "readiness" is defined as the "state of being ready or prepared", while "maturity" is defined as the "state of being mature" after having completed growth or development [7,8]. Considering AECO organizations and Construction 4.0, readiness can refer to the early development stages to assess the organization's level of preparedness for the Construction 4.0 vision. Maturity, on the other hand, can assess the evolutionary progress at any point in time using well-defined maturity levels or stages. Despite the different nature of the terms, both terms have been used interchangeably in literature, with some studies also considering readiness as a low-level or low-stage of maturity [9].

While readiness and maturity assessment methods exist for Industry 4.0, studies specific to the AECO industry have been tailored to technologies instead of Construction 4.0 as a stand-alone vision [10]. Examples include the various studies that evaluated Building Information Modelling (BIM) readiness and maturity. To the best of the authors' knowledge, only one study developed by Mansour et al. [11] attempted to fill the gap by presenting a "Construction Firm's Industry 4.0 Readiness Model" (ConFIRM), a model that computes the strategic readiness of a firm through evaluating a firm's human capital, structural capital, and relational capital [11].

While ConFIRM computes the organization's readiness for Industry 4.0 numerically and highlights the "red zones" that would require attention, the study does not provide a comprehensive set of recommendations or implementation practices that can guide AECO organizations in their Construction 4.0 journey. In fact, implementation practices that AECO organizations can reference in the early stages of developing a Construction 4.0 vision or at any point in time as this vision progresses are still missing from literature. Therefore, this study aims to address the gap by proposing a new canvas of Construction 4.0 implementation practices. The proposed canvas is called "Construction 4.0 Implementation Canvas" and will be referred to as "ConIC 4.0" (**C**onstruction **4.0** **I**mplementation **C**anvas) by the authors.

2. Methodology

To achieve the desired objective, this study adopts the methodology shown in Figure 1. While most studies refer to existing readiness and maturity models to develop new models or generate case studies, this study utilized existing models to identify implementation practices that can guide the Construction 4.0 vision AECO organizations are aiming towards. Findings discussed in this paper are limited to Step 1, Step 2, and preliminary analysis from Step 3.

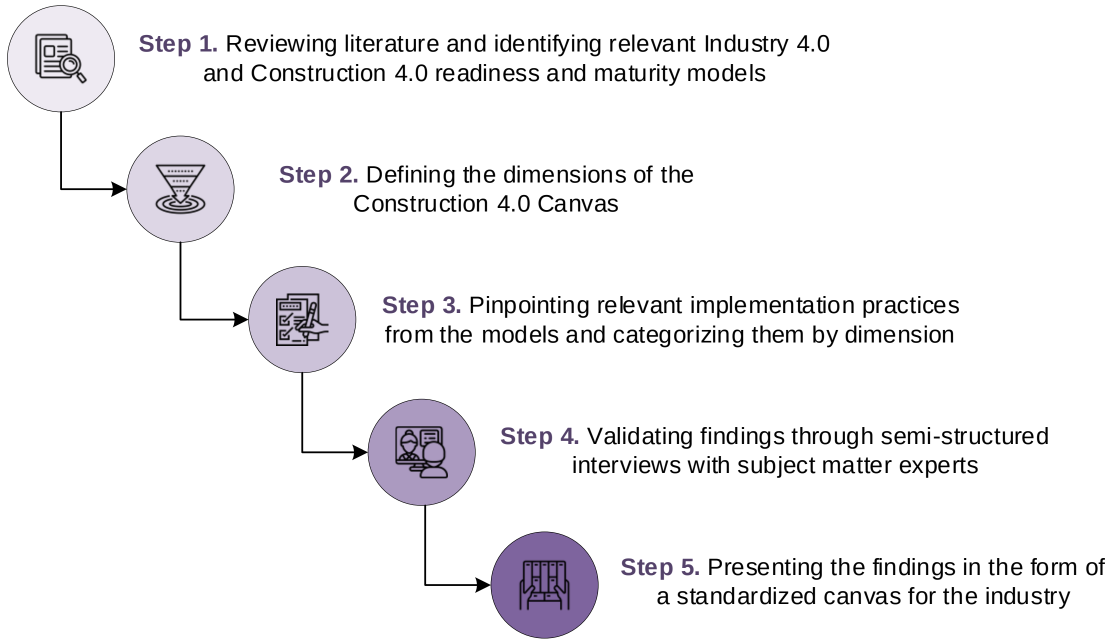


Fig. 1. Methodology of the proposed canvas (Icons used for Steps 1, 2, 3, 4, and 5 are respectively designed by rsetiawan from Flaticon, monkik from Flaticon, Eucalyp from Flaticon, juicy_fish from Flaticon, and GOWI from Flaticon).

3. Relevant Models from Literature – Step 1

A 2022 study conducted by Flamini & Naldi [9] performed a systematic literature review using Scopus and Web of science to identify and review all assessment campaigns published regarding Industry 4.0 across all industries. The paper reviewed 85 different models published between 2017 and 2021 and summarized the findings by identifying 11 assessments as "established models". Assessments were deemed “established” based on two criteria: whether they were employed by other studies at-least once, and whether they used questionnaires that were detailed, fully defined from literature, and described for future references with the aim to gain a wide diffusion.

Since Flamini & Naldi [9] executed a thorough and systematic literature review for all models published in the last five years, performing a new bibliometric analysis is highly unlikely to yield different results. Thus, this study will use the 11 established models that [9] identified. The models are explained below.

3.1.1. ACATECH Industrie 4.0 Maturity Index [12]

The aim of this index is to guide the introduction and implementation of the required Industry 4.0 digital transformation process using a six-stage maturity model starting from computerization (stage 1) to adaptability (stage 6), passing through connectivity (stage 2), visibility (stage 3), transparency (stage 4), and predictive capacity (stage 5). The index evaluates four key structural areas: resources, information systems, organizational structure, and culture.

3.1.2. Construction Firm’s Industry 4.0 Readiness Model (ConFIRM) [11]

The aim of this model is to present the potential issues that affect the success or failure of Industry 4.0 in the construction industry, evaluate the firm’s readiness against these issues, and identify where corrective actions are needed. The five-stage model utilizes Analytic Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and consists of three dimensions: (1) human capital or the people in the organization; (2) structural capital or the non-human resources like processes, procedures, information systems, and culture; and (3) relational capital or relationship with external entities like customers, suppliers, market networks, and governments.

3.1.3. IMPULS Industrie 4.0 Readiness Model [13]

The aim of this model is to evaluate the readiness of an organization for Industry 4.0. The model is based on measuring 18 fields using appropriate indicators. The fields are grouped into six dimensions: (1) Stategy and Organization with three fields including strategy, investment, and innovation management; (2) Smart

Factory with four fields including digital modeling, equipment infrastructure, data usage, and IT systems; (3) Smart Operations with five fields including cloud usage, Information Technology (IT) security, autonomous processes, and information sharing; (4) Smart Products with two fields including data analytics and Information and Communication Technology (Information Technology) add-ons; (5) Data-Driven Services with three fires including data-driven services, share of revenues, and share of used data; and (6) Employees with two fields including skill Acquisison and employee skill sets.

3.1.4. Industry 4.0 Adoption Maturity Model (AMM) [14]

The aim of AMM is to evaluate the maturity level of organizations Industry 4.0 efforts and assess the implementation process. AMM has eight maturity indicators distributed on three axes: (1) the strategy axis which includes the business strategy indicator, technology strategy indicator, and networking and integration indicator; (2) the maturity axis which includes the infrastructure indicator, analytical skills indicator, and absorptive capacity indicator; and (3) performance axis which includes efficiency impact and benefits impact (such as economic, social, and environmental).

3.1.5. Industry 4.0 Maturity Model [15]

This study proposes an "empirically grounded novel model" that asses Industry 4.0 maturity using 62 items distributed between nine dimensions: (1) strategy such as Industry 4.0 roadmap; (2) leadership such as management competencies; (3) customers such as data and digitalized sales; (4) products such as individualization; (5) operations such as modelling and simulations; (6) culture such as knowledge sharing; (7) people such as autonomy and competences; (8) governance such as labour regulations; and (9) technology such as mobile devices and information and communication technology (ICT).

3.1.6. Maturity and Readiness Model for Industry 4.0l [16]

The aim of this model is to help companies seeking to transform their business and operations for Industry 4.0 by evaluating the maturity level of their processes, products, and organizations. Four maturity levels were identified namely absence (level 0), existence (level 1), survival (level 2), and maturity (level 3). The maturity levels were used to evaluate three main dimensions: (1) smart products and service offerings; (2) smart business processes including functional operations; and (3) strategy and organization.

3.1.7. PwC Maturity Model [17]

The aim of this model is to evaluate the Industry 4.0 capabilities of an organization when mapping out the organization's Industry 4.0 strategy. The capabilities are divided into seven dimensions: (1) digital business models and customer access; (2) digitization of product and service offerings; (3) digitization and integration of vertical and horizontal value chains; (4) data and analytics as core capability; (5) agile IT architecture; (6) compliance security, legal, and tax; (7) organizational employees and digital culture. Evaluations of these dimensions are performed through four descriptive phases with digital novice being the first stage, followed by vertical integrator, then horizontal collaborator, and finally digital champion.

3.1.8. System Integration Maturity Model Industry 4.0 (SIMMI 4.0) [18]

The aim of this model is to assess the readiness of an organization's IT system landscape in terms of Industry 4.0. The model has four dimensions: (1) vertical integration, (2) horizontal integration, (3) digital product development, and (4) cross-sectional technology criteria. The model describes the different activities that an organization can perform to push the dimensions through four digitization stages: basic (level 1), cross-departmental (stage 2), horizontal and vertical (stage 3), full (stag 4), and optimized (stage 5).

3.1.9. Singapore Smart Industry Readiness Index (SIRI) [19]

The aim of this index is to guide organizations regardless of their size in developing a clear vision, stratify, and develop a systematic roadmap for the Industry 4.0 transformation. The index has three building blocks and eight pillars: (1) the process block with three pillars – operations, supply chain, and product lifecycle; (2) the technology block with three pillars: automation, connectivity, and intelligence; and (3) the organization block with two pillars – talent readiness and structure and management.

3.1.10. Smart SME Technology Readiness Assessment (SSTRA) [20]

The aim of this framework is to present Small and Medium Enterprises (SMEs) with techniques and methodologies to examine their readiness to implement Industry 4.0. The framework has three main criteria: (1) Real-Time Design System evaluated through the organization’s extent in using technology for data acquisition, data analytics, and data security; (2) Flexible Design System evaluated through the organizations extent in using technology for collaborative customization, agility, and collaborative design; and (3) Design Execution evaluated through the organizations extent in using technology for decision making, modelling, and prototyping.

3.1.11. Smartness Assessment Framework for Smart Factories [21]

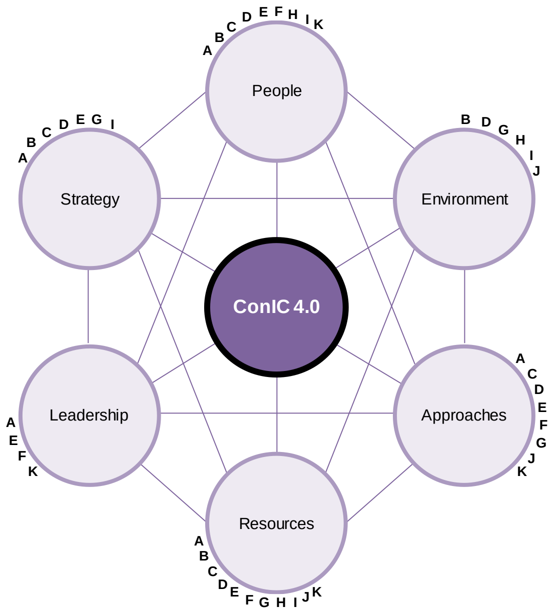
The aim of this framework is to evaluate the smartness of SMEs using analytic Network Process (ANP). The network model is formed of four main criteria: (1) Leadership assessed through leadership qualities and strategy; (2) Process assessed through product development, production planning, process control, quality control, facility management, and logistics management; (3) systems and automation assessed through information systems and facility automation; and (4) performance assessed through a set of performance passements including cost, productivity, quality, safety, lead time, and environment.

4. Canvas Dimensions and Preliminary Categorizations – Step 2 and Step 3

Following the review of the 11 existing models, the proposed holistic Construction 4.0 Implementation Canvas (ConIC4.0) consists of six dimensions: People, Environment, Approaches, Resources, Leadership, and Strategy (PEARLS). Each dimension is outlined below:

- People: People inside an organization are at the center of Construction 4.0, and no transformation can be successfully performed in the construction industry if people are not involved. Examples of implementation practices include skills, trust, collaboration, and openness to change.
- Environment: External factors and players surrounding the organization plays a significant role in driving change within the organization, especially with the dynamic and short-term nature of construction projects and the large number of parties involved. Implementation practices should target players such as technology vendors, clients, labour unions, and government.
- Approaches: Approaches include popular techniques, methods, and procedures that the organization adopts both in and across departments. Implementation practices should build on such existing approaches such as Cost Benefit Analysis, success stories, key performance indicators, approvals, and root cause analysis and tailor them to Construction 4.0.
- Resources: Non-human factors are essential for any change and a Construction 4.0 vision is no exception. Notable resources are financial assets, information systems, and existing technologies. Implementation practices should target deploying organization resources for piloting technologies, Construction 4.0 champions, data standards, and IT infrastructure.
- Leadership: Leadership provides the top- and mid-management support needed to plan transformation efforts and successfully implement changes. Examples of implementation practices include trust cultivation, open communication, and structure evaluation.
- Strategy: Incorporating the Construction 4.0 vision into the organization’s strategy can be the compass that drives the vision to success. Examples of implementation practices include long term thinking with short term goals, proactive reaction to anticipated changes, and switching from “project-thinking” to "process-thinking”.

Figure 2 below presents a schematic diagram of the “ConIC 4.0” dimensions. Each dimension is surrounded by letters that represent the models that have implementation practices that would contribute to the dimension.



(A) ACATECH Industrie 4.0 Maturity Index
(B) Construction Firm's Industry 4.0 Readiness Model (ConFIRM)
(C) IMPULS Industrie 4.0 Readiness Model
(D) Industry 4.0 Adoption Maturity Model
(E) Industry 4.0 Maturity Model
(F) Maturity and Readiness Model for Industry 4.0
(G) PwC Maturity Model
(H) System Integration Maturity Model Industry 4.0 (SIMMI 4.0)
(I) Singapore Smart Industry Readiness Index (SIRI)
(J) Smart SME Technology Readiness Assessment (SSTRA)
(K) Smartness Assessment Framework for Smart Factories

Fig. 2. "ConIC 4.0" dimensions and preliminary categorization are based on a preliminary scanning of the best practices of every model described above.

5. Conclusion and Further Studies

This paper proposed a blueprint for "ConIC 4.0", a Construction 4.0 Implementation Canvas that aims to provide implementation practices to guide AECO organizations towards a successful Construction 4.0 vision. The canvas consists of six dimensions, collectively referred to as PEARLS (People, Environment, Approaches, Resources, Leadership, and Strategy). Each dimension will consist of a set of practices that must be explored to enable both construction practitioners and researchers to better understand the key ingredients for the successful implementation of an organization's Construction 4.0 vision. This paper was limited to proposing "ConIC 4.0", explaining the methodology needed to develop it, presenting six dimensions of ConIC 4.0 – namely PEARLS, and identifying the models that will be used to capture the implementation practices. The next step of this study is to identify the practices in every dimension and validate them through a series of structured interviews with subject matter experts to complete the canvas and present it to the industry.

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How Point-to-Point Relations Change Influence Lines in Schedule Networks

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Abstract

Influence line diagrams depict the effect of changing the duration of a single activity on the whole project's duration. The behaviour of influence lines, transitions between criticality types were hitherto examined with certain limitations on the activities and the relations. Only the four end-point relationships were allowed, the finish-to-start, start-to-start, finish-to-finish, and the start-to-finish. This paper aims to extend the previous research by inspecting the influence lines and criticality types if not only these relations, but also point-to point relations are allowed.

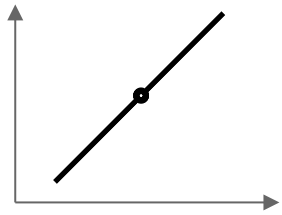
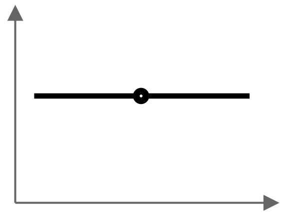
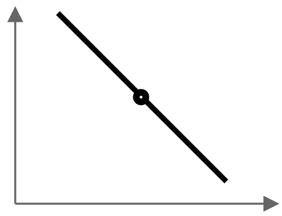
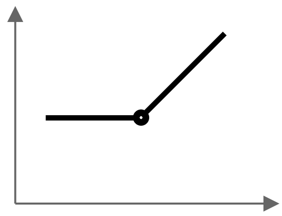
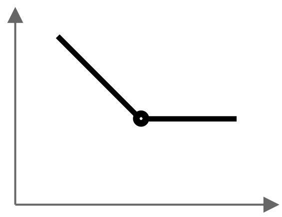
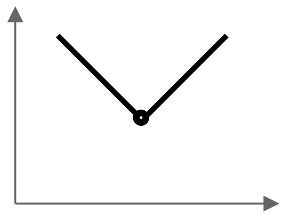
Keywords: CPM, Precedence Diagramming Method (PDM), Influence lines, Point-to-point relations

1. Introduction and literature review

Precedence Diagramming Method is the most widely used network technique due to its flexibility in modelling the task. However, most of the applications do not use all the possibilities of this technique, they stick to the findings of Roy [1] Fondahl [2] and IBM [3]. The endpoint relations of the traditional approach (start-to-start, start-to-finish, finish-to-start, finish-to-finish) limit the modelling capabilities of PDM, especially when handling overlapping activities. This problem was issued by several researchers, like Kim [4, 5], Francis and Miresco [6, 7], Plotnick [8] Ponce de Leon [9]. Finally Hajdu [10] gave a mathematical model and terminology of point-to-point relations which allow to define a relation between two arbitrary points of the activities These internal points can be described as the volume of work performed (if the activities are linear) or the time spent in percentage: 0% is the start of the activity, 100% is the end, and any point in between can be chosen. This allows a more precise work with overlapping activities, while the traditional endpoint relations still can be used.

Criticality of the activities in a PDM network has a great significance when a project's duration has to be shortened: changing activity duration on the critical path can result in speeding up the project, but it also can lengthen it in certain situations. The different behaviour of critical activities was described first by Weist [11], then extended by Hajdu [12]. Based on their findings, six criticality types exist, defined by the effects of the activity duration's modification on the project duration. Influence line diagrams depict this effect. The criticality types and the influence lines are summarised in table 1.

Table 1. Criticality types and their influence line diagrams, where horizontal axis represents activity duration, vertical axis represents project duration

Criticality type	Effect of increasing activity duration	Effect of decreasing activity duration	Influence line
Normal critical	Increasing project duration	Decreasing project duration	
Neutral critical	No effect on project duration	No effect on project duration	
Reverse critical	Decreasing project duration	Increasing project duration	
Increasing normal decreasing neutral critical	Increasing project duration	No effect on project duration	
Increasing neutral decreasing reverse critical	No effect on project duration	Increasing project duration	
Bi-critical	Increasing project duration	Increasing project duration	

Bokor and Hajdu have shown that the abovementioned criticality types are valid for networks with point-to point relations as well [13]. The main difference is the effect of changing the activity duration: in case only endpoint relations are allowed, changing the activity duration by one day changes the project duration also by one day (or zero). In case of point-to-point relations, the value of project duration's changes depends on the activity duration, as well as the points where the critical path enters and leaves the activity. The formula given by Bokor and Hajdu is valid also for endpoint relations, so it can be used for any activity.

Influence lines were introduced by Hajdu [14], and the internal rules shaping the form of influence lines were described by Lepel and Hajdu [15], with the following limitations:

- activities were assumed to be linear, non-splittable, and non-stretchable;
- only the four minimal end-point relationships were allowed;
- calendars were not allowed;
- hard constraints (such as Must Start at, Start Earlier than) were not allowed;
- resources and their limitations did not affect the results of the time analysis.

The research has shown that increasing and decreasing the duration of the activity can result in changing the criticality type of activities. Table 2. shows the possible transitions from a criticality type to another.

Table 2. Transitions between criticality types.

Criticality type	Increasing activity duration	Decreasing activity duration
Normal critical	no change	normal-neutral or bi-critical
Neutral critical	normal-neutral	neutral-reverse
Reverse critical	neutral-reverse or bi-critical	no change
Normal-neutral	normal	neutral-reverse
Neutral-reverse	neutral-normal	reverse
Bi-critical	normal	reverse

The goal of this research is to investigate the behaviour of influence lines in case of point-to-point relations.

1 Research goals and limitations

This research aims to extend the use of influence lines in PDM networks by allowing minimal point-to-point relations. Other generalisations, like non-linear, splittable or stretchable activities are not allowed. Calendars and hard constraints cannot be used either. Allowing one or more of these factors could serve as further research.

2 Influence lines in case of point-to point activities

As mentioned earlier, all six criticality types can be found in case of point-to-point relations. However, the behaviour of the influence lines is analogous, but not completely equivalent to the ones in case of endpoint relations.

1.1. Normal critical activities

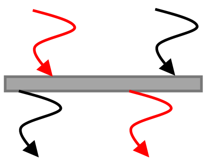


Figure 1. Critical and non-critical relations of a normal critical activity
(red arrows represent critical relations, black arrows represent non-critical relations)

In case of normal critical activities, the critical path enters at an arbitrary point of the activity and leaves at a point which is after the entering point. This can be inspected in Figure 1. Increasing normal critical activities' duration increases the project duration while a decrement in the activities' duration results in decreasing project duration. The value of this increment and decrement depends on the entering and leaving points' position and the activity duration. Thus, the gradient of the influence line can be 45°or lower.

If the activity duration of a normal critical activity is raised in case of endpoint relations, then it remains normal critical and the influence line does not change. In a network with point-to-point relations it is possible that increasing the activity duration results in changing of the critical path so that another connection becomes critical which leaves the activity at a later point than the previous. In this case the activity remains normal critical, but the gradient of the influence line changes. The changing critical relations are shown in Figure 2., the influence line is introduced in Figure 3. The example represents a network with three activities A, B and C. There are four point-to point relations, No. 1., 2., 3. and 4., where AB 50-90 15 reads as follows: The relation connects 50% point of activity A with 90% point of activity B and the lag is 15 days. The table shows the changes in the project duration caused by changing the duration of activity B. The changes of critical connections are also indicated, as the float of critical connections is zero. The example shows an activity with changing critical connections with an unaltered criticality type, the inflection is at activity duration 48.

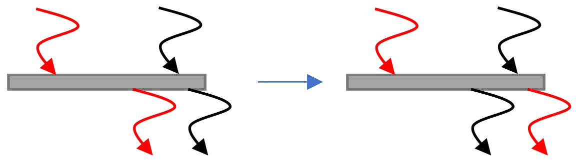
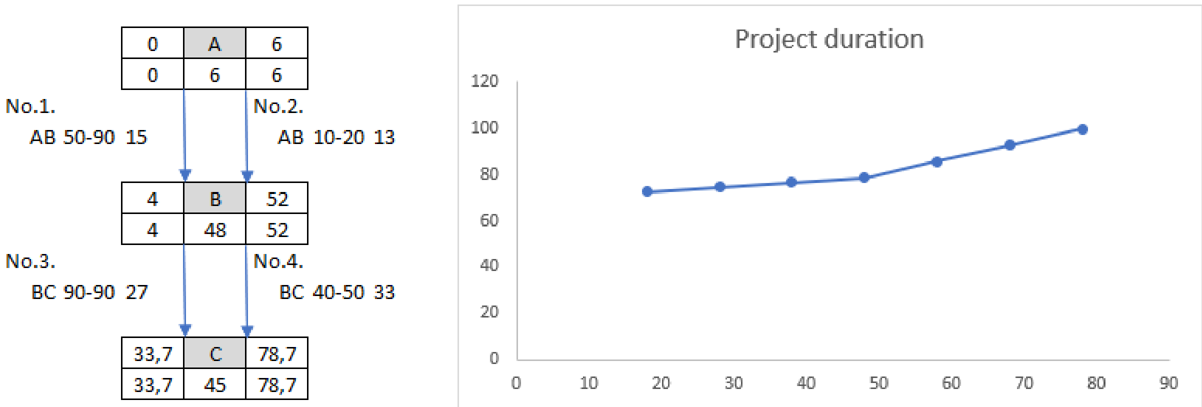


Figure 2. Changing of critical and non-critical relations of a normal critical activity – while the outgoing critical connection changes the activity remains normal critical.



		Decreasing the duration of B			Base	Increasing the duration of B		
Duration of B		18	28	38	48	58	68	78
Float of the connection	No.1.	8,2	15,2	22,2	29,2	36,2	43,2	50,2
	No.2.	0	0	0	0	0	0	0
	No.3.	15	10	5	0	0	0	0
	No.4.	0	0	0	0	5	10	15
Project duration		72,7	74,7	76,7	78,7	85,7	92,7	99,7

Figure 3. Influence line of a normal critical activity

1.2 *Neutral critical activities*

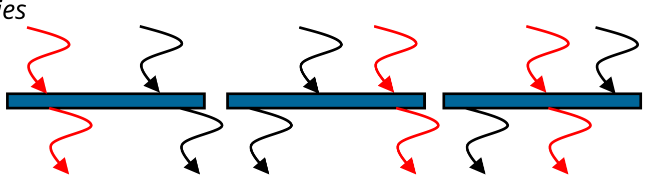
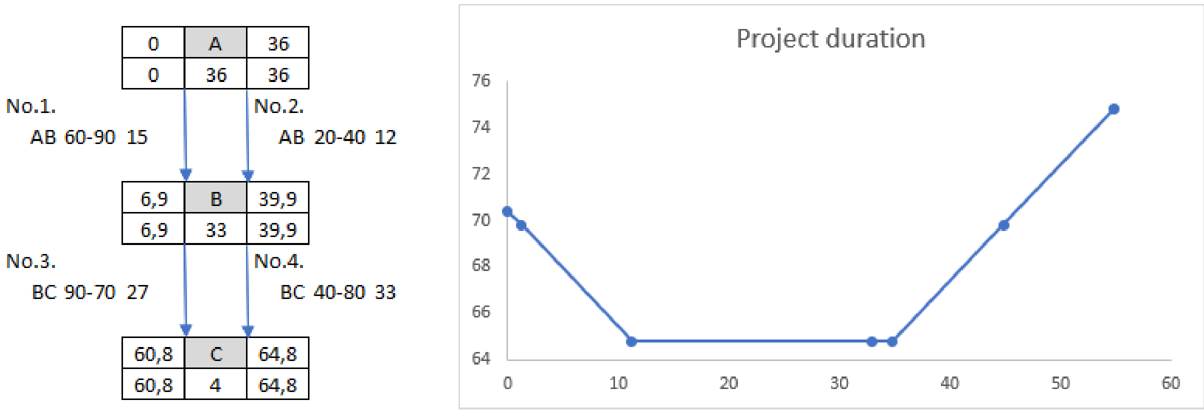


Figure 4. Critical and non-critical relations of a neutral critical activity

If the critical path enters and leaves the activity at the same point, wherever it is in the activity, the activity is called neutral critical activity. Fig. 4 illustrates some possible combinations. In this case, changing the activity's duration does not affect the project's duration until the point where a third relation becomes critical. The influence line of a neutral activity is horizontal, in case of endpoint relations and point-to-point relations alike. If the activity duration is modified to a point where a third relation turns critical, the activity becomes increasing normal decreasing neutral critical or increasing neutral decreasing reverse critical. The influence line of neutral critical activities is demonstrated in Figure 5. with a network, where the activity B is neutral at the inspected duration and between 1,2 and 34,8.



		Decreasing the duration of B			Base	Increasing the duration of B		
Duration of B		0	1,2	11,2	33	34,8	44,8	54,8
Float of the connection	No.1.	0	0	0	0	0	5	10
	No.2.	17,4	16,8	11,8	0,9	0	0	0
	No.3.	5,6	5	0	0	0	0	0
	No.4.	0	0	0	10,9	11,8	16,8	21,8
Project duration		70,4	69,8	64,8	64,8	64,8	69,8	74,8

Figure 5. Influence line of a neutral critical activity

1.3 Reverse critical activities

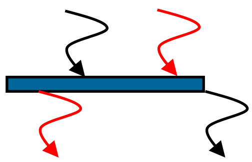


Figure 6. Critical and non-critical relations of a reverse critical activity

Reverse critical activities have the critical path entering at a later point than it is leaving that activity. Increasing a reverse critical activity's duration decreases the project duration. Decreasing the activity's duration, on the contrary, increases the project duration. The increment and decrement again depend on the activity duration and position of the incoming and outgoing points of the critical path. Similarly to the normal activities, the gradient of the influence line can be lower than 45°, and it can even change while the activity remains reverse critical. Figure 7. demonstrates one possible combination of changing critical connections while maintaining the criticality of the activity. Figure 8. shows the influence line in this situation, with an inflection at the duration of 13,6 and 82.

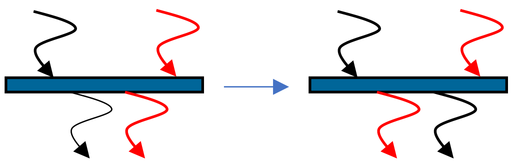
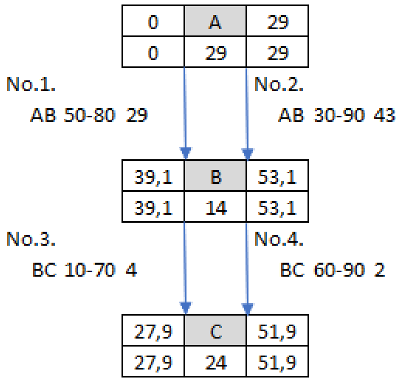
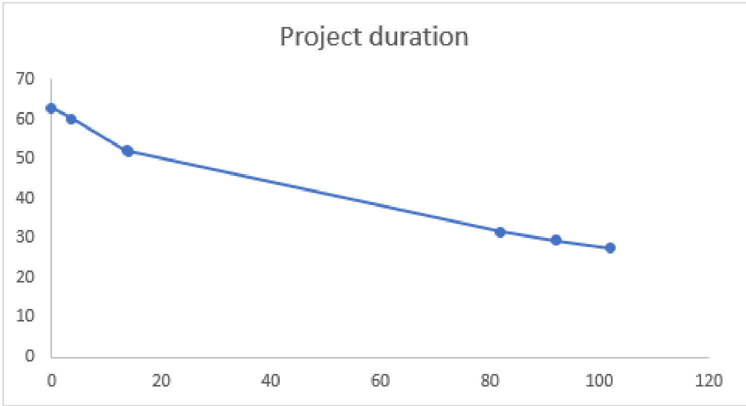


Figure 7. Changing of critical and non-critical relations of a reverse critical activity – while the outgoing critical connection changes the activity remains reverse critical.





		Decreasing the duration of B			Base	Increasing the duration of B		
Duration of B		0	3,6	13,6	14	82	92	102
Float of the connection	No.1.	8,2	7,84	6,84	6,8	0	0	0
	No.2.	0	0	0	0	0	1	2
	No.3.	0	0	0	0,2	34,2	39,2	44,2
	No.4.	6,8	5	0	0	0	0	0
Project duration		62,9	60,02	52,02	51,9	31,5	29,5	27,5

Figure 8. Influence line of a reverse critical activity

1.4 Increasing normal – decreasing neutral critical

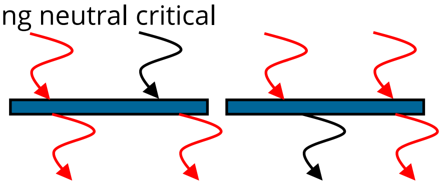
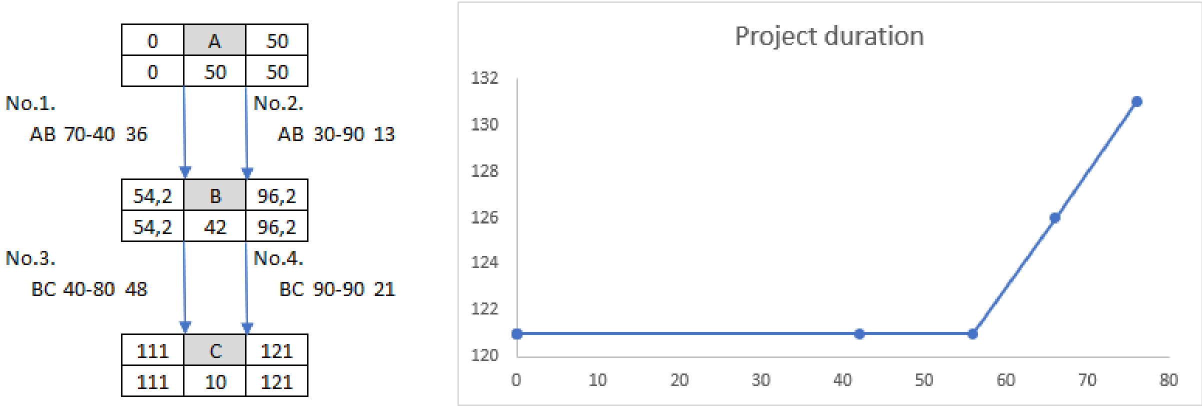


Figure 9. Critical and non-critical relations of an increasing normal – decreasing neutral critical activity

In case of increasing normal – decreasing neutral critical activities, the activity has three critical connections. There is one pair of critical connections, which point towards and out of the same point while the third critical connection creates the situation of the critical path leaving the activity later than entering it. Some possible connection combinations can be seen in Figure 9. This way, the activity becomes simultaneously a neutral and a normal critical activity, depending on the changes of the duration. The effect on the project duration is also the combination of normal and neural criticality: increasing the activity duration by one day increases the project duration by one day or less and decreasing the activity duration makes no change in the project duration. Figure 10. illustrates the influence line of an increasing normal – decreasing neutral critical activity. In the example the activity is increasing normal – decreasing neutral critical at the duration 56, below that, it is neutral, above that it is normal critical.



		Decreasing the duration of B			Base	Increasing the duration of B		
Duration of B		0	0	0	42	56	66	76
Float of the connection	No.1.	0	0	0	0	0	0	0
	No.2.	43	43	43	64	71	76	81
	No.3.	0	0	0	0	0	5	10
	No.4.	28	28	28	7	0	0	0
Project duration		121	121	121	121	121	126	131

Figure 10. Influence line of an increasing normal – decreasing neutral critical activity

1.5 Increasing neutral – decreasing reverse

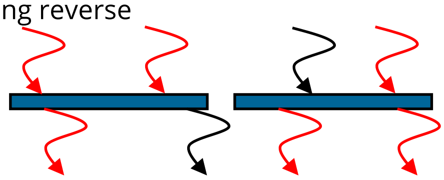
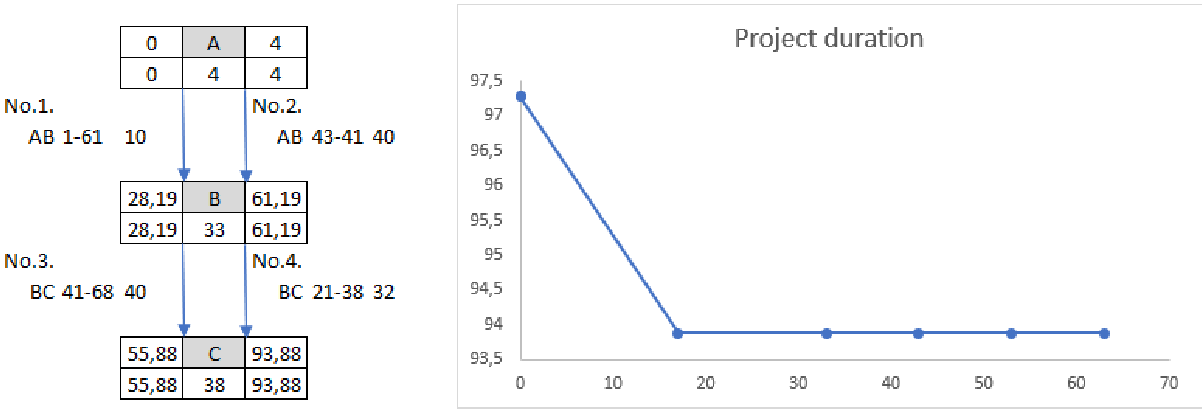


Figure 11. Critical and non-critical relations of an increasing neutral – decreasing reverse critical activity

Increasing neutral – decreasing reverse activities have combine the neutral and reverse criticalities: the critical path enters and leaves once at the same point and one of these connections with a third critical connection realises the combination that reverse critical activities have: the critical path leaving point precedes its entering point. The three critical connections result that increasing the activity duration does not affect the project duration, while decreasing the activity duration increases project duration. The gradient of the reverse section depends on the position of the critical path’s entering and leaving point and the activity duration. Figure 12 demonstrates the influence line of an activity which is increasing neutral – decreasing reverse critical at the duration 17, below that, it is reverse, above that it is neutral critical.



		Decreasing the duration of B			Base	Increasing the duration of B		
Duration of B		0	0	17	33	43	53	63
Float of the connection	No.1.	31,68	31,68	35,08	38,28	40,28	42,28	44,28
	No.2.	0	0	0	0	0	0	0
	No.3.	3,4	3,4	0	0	0	0	0
	No.4.	0	0	0	3,2	5,2	7,2	9,2
Project duration		97,28	97,28	93,88	93,88	93,88	93,88	93,88

Figure 12. Influence line of an increasing neutral – decreasing reverse critical activity

1.6 Bi-critical

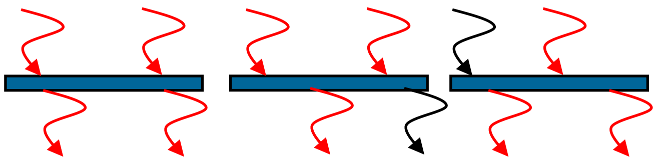
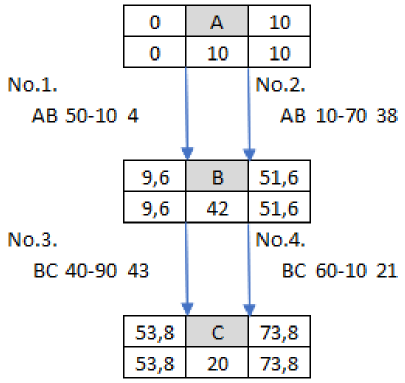
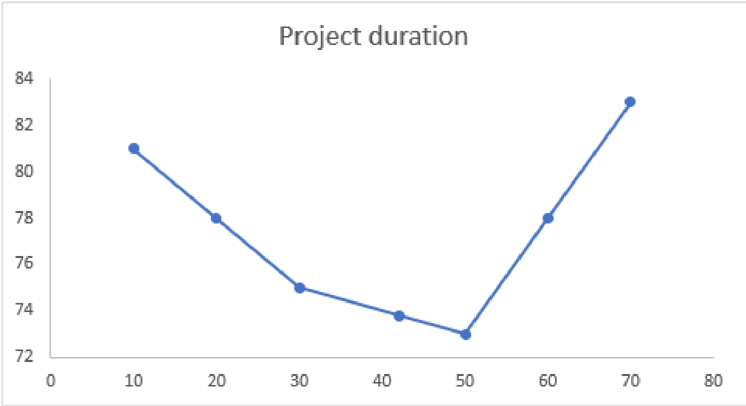


Figure 13. Critical and non-critical relations of a bi-critical activity

If the activity has four critical connections, and they in pairs point to and from two identical points, then the activity is bi-critical. The activity can be bi-critical in case of three critical connections: these have to produce the conditions of a normal and reverse activity simultaneously. One incoming critical connection is preceded and followed by two outgoing critical connections, or the one critical outgoing connection is preceded and followed by two incoming critical connections. These combinations are depicted by Figure 13. Increasing or decreasing a bi-critical activity's duration both result in increasing project duration, but it is possible that the gradients of the two sections are different. Figure 14. shows an example of an activity that is bi-critical at duration 50. If the duration is longer, it is normal critical, if it is shorter than 50 it is reverse critical with an inflection at 30.





		Decreasing the duration of B			Base	Increasing the duration of B		
Duration of B		10	20	30	42	50	60	70
Float of the connection	No.1.	24	18	12	4,8	0	0	0
	No.2.	0	0	0	0	0	6	12
	No.3.	0	0	0	2,4	4	6	8
	No.4.	4	2	0	0	0	0	0
Project duration		81	78	75	73,8	73	78	83

Figure 14. Influence line of bi-critical activity

2 Transitions between criticality types

Transitions between criticality types in networks with only endpoint relations are listed in Table 2. The possible transitions form the chain of reverse critical, then increasing neutral decreasing reverse, then neutral, then increasing normal decreasing neutral, then normal critical. If the neutral state is missing, then reverse critical, bi-critical, normal critical states follow each other. These transitions are illustrated in Figure 15 a) and b).

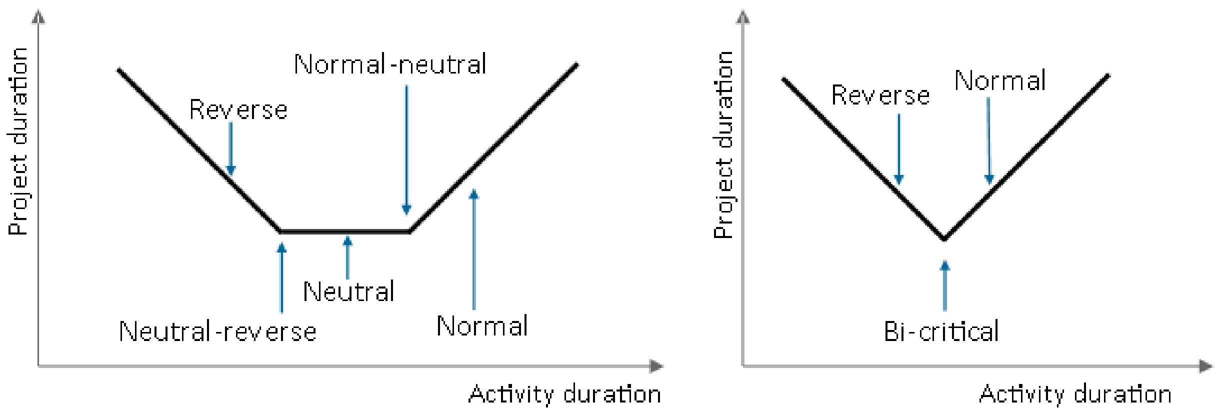


Figure 15. Transitions between influence lines in case of endpoint relations, with and without neutral critical state.

In case of point-to-point relations gradient changes within the normal critical and reverse critical state are possible, so the influence line diagram can be more complex in this case. As mentioned earlier, the gradient of the inclination and declination of the diagram depends on the activity duration and the positions of the incoming ang outgoing points of the critical path. Regardless of the relation types the chain is still reverse critical, then increasing neutral decreasing reverse, then neutral, then increasing normal decreasing neutral, then normal critical. The neutral state can be missing, then the chain is again reverse critical, bi-critical, normal critical. These two possibilities can be inspected in Figure 16 a) and b). It is more probable to reach the bi-critical state in case of point-to point relations than endpoint relations, as connections can point to or from any point of the activity and there are three combination possibilities versus one combination with only endpoint relations. Reaching neutral state is more probable when only the start or finish of an activity can serve as entering and leaving point of the critical path.

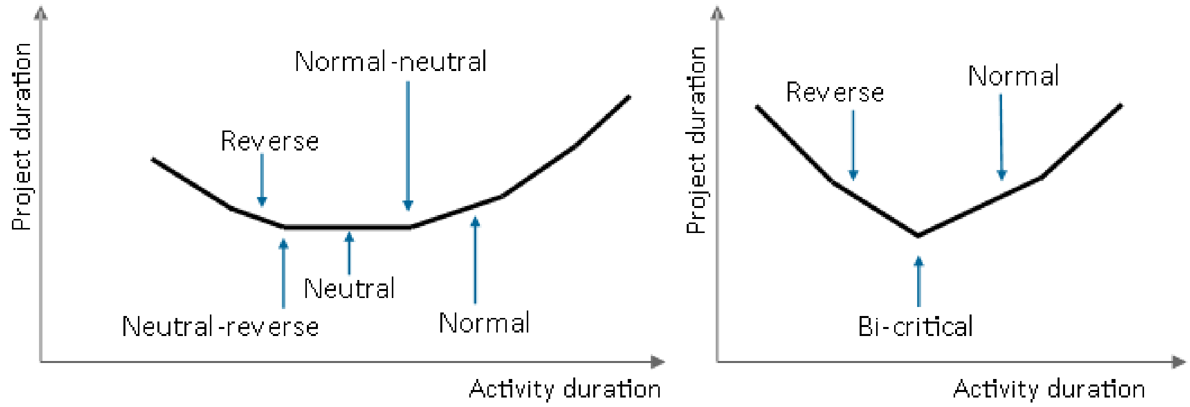


Figure 16. Transitions between influence lines in case of point-to-point relations, with and without neutral critical state.

3 Conclusions and further research

This research established that:

- Influence lines are convex even in case of point-to-point relations;
- In the case of point-to-point relationships the number of break-points depend on changes of critical and non-critical connections as these can produce a break-point even if the criticality type does not change. There can be zero break-point if the activity is normal critical, neutral critical or reverse critical, and changing the activity duration leaves the critical connections unchanged. There can be one breakpoint within one state in case of normal critical and reverse critical activities, and between criticality types at increasing normal decreasing neutral critical, increasing neutral decreasing reverse critical and bi-critical states. Two or more break-points can appear on the influence line within or between criticality types. Theoretically there can be infinite number of break-points.
- Influence lines are linear or piece-wise linear, and the gradient is maximum 45° (or 1/1) in both directions when activities are linear, non-splittable, non-stretchable.

Further research direction can be the description of the internal rules of influence lines where more of the generalizations listed in the 'Research objectives and limitations' section are allowed in the schedule network.

Acknowledgment

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Integrative Mixed Reality Sketching

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Abstract

In Architecture, Engineering and Construction (AEC), early design decisions have great impact. Sketching is a fast and immediate early design tool and means of communication. Communication with other professionals is challenging, because of varying professional languages.

We propose a novel integrative sketching application to improve communication. Our application uses mixed reality interaction to allow sketching directly into 3D space, capture the process as temporal data, utilise animation in form-finding. We describe an exemplary workflow that integrates parametric geometry generation and digital manufacturing domain expert feedback into the early design phase of sketching via real-time data exchange.

The workflow is evaluated by architectural design experts. Our findings indicate that the immediate domain expert feedback coupled with the novel 4D freehand sketching approach is a highly proficient way of aiding design decisions and streamlining AEC processes, improving communication between designers and mathematicians.

Keywords: architectural collaboration, concept design, design methods, reflection on design processes, mixed reality

1. Introduction

AEC is a collaborative workflow. It is the combined effort of numerous experts with different professional skills, backgrounds, methodologies, and communication cultures. in practice, the flow of information between these professionals is often temporally displaced. As a result, feedback and the exchange of ideas is not direct and immediate. By improving communication, we can also improve the design process workflow. By improving the workflow of the design process, we might improve the quality of the design itself.

Decisions made in the early design phases are particularly important. These decisions can have a far-reaching impact. If problems are discovered late, adjustments and corrections can have significant temporal and financial implications. To ensure that all professionals involved can contribute their expertise in the most effective manner, a workflow and communication process must be established that provides a common platform for the exchange. In practice, this often proves difficult: The professionals involved usually have different working conventions, terminology, and toolkits, which hinders seamless communication. Some professionals are only involved at a later stage of a project and cannot contribute to decision making in the early design phases.

To improve the efficiency of AEC processes, a central integrative communication platform is necessary. Such a platform must be centred around early design tools, ensuring the highest impact of informed decisions. The most formative of early design methods is sketching. Sketching is the earliest stage in the iterative process of architectural form-finding. It involves a multitude of techniques beyond the commonly associated pencil-on-paper modus. Sketching is fast, immediate, and expressive, it is a strategy, a selection procedure, and a form of communication. It is more than just a design tool. Sketching is thinking: thinking about form, about shape and about different realisations thereof. To truly enable thinking about form, sketching should not be limited or hindered by its tools.

A truly impactful tool for architectural design is one that allows the creation of informed sketches: unhindered expression of form, enriched with domain expert feedback to supplement decision making. Consideration this, we propose the creation of a sketching application that can act as a central integrative platform throughout the entire design process. Our goal is to seamlessly integrate and visualise domain expert feedback on the feasibility, cost-effectiveness, and potential uses from different AEC professionals in the earliest stages of design. With the help of domain expert feedback, we can offer alternatives and new form concepts from the first draft iteration, which the designer can consider when developing the project. Creating sketches directly in 3D space offers significant advantages in individual form finding work, making extent and shapes immediately discernible by providing a sense of spatiality. It is of even greater value in a collaborative workflow. With spatial visualisation, the design can be better communicated to other stakeholders.

There are established best practices for communicating spatial data across multiple applications, like computer aided design (CAD) and building information modelling (BIM). However, the tools of 3D CAD modelling hinder the advantages of sketching, losing its immediacy, spontaneity, and unobstructed expression. The "sketching is thinking" paradigm cannot be achieved through the mediation of such instruments. In these paradigms, freehand drawing and the creation of a spatial model are two separate work stages, and the feedback into the iterative form-finding is not directly coupled.

Our proposed sketching application aims to bridge this gap by incorporating interaction paradigms that enable the creation of spatial models with the immediacy of freehand drawing. The application can be used primarily on portable devices. The primary stylus-on-tablet input method provides intuitive stroke control, with a familiar sketching experience that is similar to the still ubiquitous pencil-on-paper paradigm.

2. Related Work

2.1. Digital Sketching in Three Dimensions

Digital sketching in two dimensions (2D) is available in multiple commercial and open-source applications. Sketching in three dimensions (3D) is an ongoing research topic, as there are still difficulties to solve: How to use 2D input devices for sketching directly in 3D? How to create sketches with a context of real objects? To use 2D input devices (stylus-on-tablet), several approaches create a canvas (e.g., planes or curved surfaces) in 3D and project the 2D strokes onto the 3D canvas [4; 8; 17]. Some approaches track the location and orientation of the input tablet device to generate a 3D canvas [9]. Others use hand tracking to define a 3D canvas [7]. Sketching applications using a virtual reality paradigm rely on 6 degrees of freedom (DOF) tracked input devices. Google Tilt Brush [6] became well known for allowing 3D painting in virtual reality

(VR) with inputs via tracked VR controllers. An overview of several painting applications in VR is given by Ramsier [11]. Arora et al. [2] have shown that a challenge for precise drawing in 3D is the lack of haptic feedback. Müller et al. [9] address this issue by using a Phantom device. Drey et al. [5] propose a design tool for 3D VR sketching with a hybrid stylus-on-tablet and 6DoF tracked pen interaction.

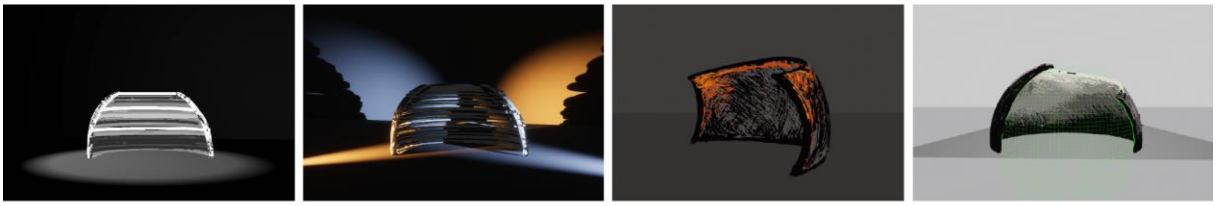

Fig. 1. Form study of curved walls in the sketching application.

2.2. AR Paradigms for 3D Sketching

A crucial hurdle in allowing sketching 3D content on a 2D surface is to define the plane (or, more generally: the surface) where the sketched lines are inserted into 3D space. Xin et al. [15] propose a handheld AR system for 3D sketching using stylus input and marker tracking. They approach involves an intermediate, separate canvas definition step before drawing. Arora et al. [1] describe a technique for combining 2D and 3D sketching for in-situ design. They too propose a 2-step solution. First, the designer defines a drawing canvas as a patch surface fitted to multiple freeform 3D mid-air sketch lines created via a 6 DOF motion tracked pen. In the second step, sketching onto the tablet surface projects the sketched lines on the predefined drawing canvas. Yee et al. [16], Berging et al. [3], Paczkowski et al. [10] and Wacker et al. [14] provide further examples of sketching within a context using augmented reality (AR) techniques.

3. The sketching application

3.1. 3D sketching

Drawing directly into 3D space presents the aforementioned challenges. To draw without obstruction, the designer must be always aware of two factors: Where are they located, how are they oriented in space (viewport pose) and where exactly will the pen stroke be inserted into space (line input pose)?

We propose a novel solution for this challenge: the use of viewport-affixed drawing surfaces (canvases). The method is based on affixing a surface in front of the viewport (camera) at a certain default distance. We refer to this surface as the drawing canvas, because during sketching, lines drawn onto the surface of the tablet device are projected onto the virtual surface of the canvas geometry.

To make the spatial relationship between the drawing canvas and the viewpoint evident, we use different interaction techniques, such as canvas-centric spatial navigation, direct canvas control and different canvas visualisations (semi-transparent grid, intersection highlighting). The application includes multiple scalable canvas geometries (plane, sphere, cube) and allows the import of arbitrary meshes to use as canvas. To support the user's spatial confidence, the application provides intuitive camera control schemes, including interactions based on mixed reality paradigms.

3.2. Mixed reality techniques

We implemented two distinct mixed reality interaction modes. The viewport-affixed drawing canvas can be used in augmented reality (AR) mode. In this mode, the camera position is adjusted via 6 DOF inside-out tracking using the built-in LiDAR scanner of the tablet device. Drawing canvas visualisations and control are still available in this mode.

The LiDAR scanner also enables spatial mapping and meshing the geometry of the physical environment. In this mode, the geometry of the scanned physical environment provides the surface for sketching. This allows the designer to draw directly over physical objects. Akin to the tangible user interface paradigm, physical objects can be used as drawing guides.

We use additional MR, AR and VR platforms and techniques to visualise sketches at different scales and in different contexts. Our application supports collaborative design and visualisation tasks, allowing room-scale visualisations of 3D architectural sketches previously created via stylus-on-tablet interaction.

3.3. Central integrative platform

We are creating experimental implementations of the above techniques with the aim of providing tools for designers to directly generate data that enables real-time, instantaneous exchange. Processing, transforming, serialising, and transferring 3D sketches is a significantly simpler task than converting a two-dimensional freehand drawing into a 3D model in an intermediate step.

In terms of data exchange, two main challenges were identified: on the output side, the serialisation and transmission of sketch lines created in the application. On the input side, the reception, processing, and visualisation of mesh geometries. Based on the preliminary requirement analysis, we implemented proof-of-concept data exchange solutions for two popular applications. We integrated the Rhino/Grasshopper (GH) parametric modelling software and its headless Rhino.Compute REST geometry server, to generate parametric geometries from freehand drawing lines, and Blender, an open source 2D/3D content creation software, which serves as an intermediate data exchange platform and meshing tool.

4. Exemplary workflow

In this section, we show how our application can be used to conduct a specific exemplary workflow on the basic spatial element of a transformable kinetic wall. In this example, the designer is supported by immediate feedback from mathematician and digital manufacturing domain experts. We describe the specifics of the integration with Rhino/GH, including data processing, generation of a specific quadrilateral mesh type, the visualisation of the resulting expert feedback (geometry) and the preparations for digital manufacturing.

4.1. Sketching lines

Using our sketching application, the artist can create the first sketches of the wall directly in 3D space. To generate the quad-mesh, three planar curves must be provided as input. We send these curves to Rhino/GH using real-time network data exchange. The quad mesh generated via the GH script is sent back and visualised in the sketching app, where the designer can make immediate refinements.

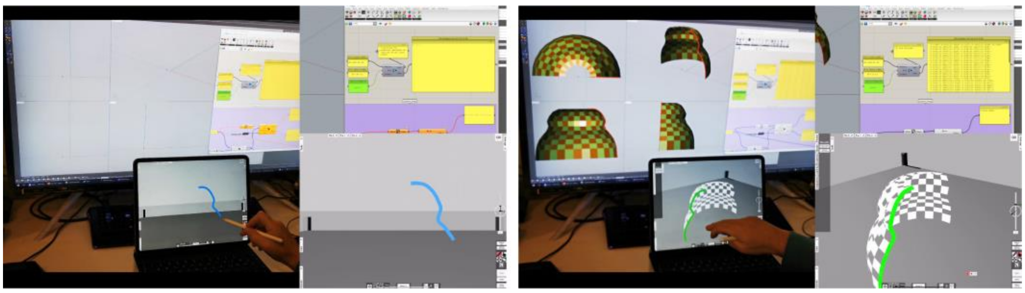

Fig. 2. Real-time data exchange between the sketching application and Rhino/Grasshopper. The designer sketches a curve on the tablet. A Rhino/GH instance running on a desktop computer receives the data, processes it, and generates a mesh. The mesh is then sent back and inserted into the sketch scene

4.2. Mesh generation for a kinetic wall

In this section, we give a rough introduction to the functionality of the GH plugin “Scutes”. It allows the designer to create a special class of flexible quadrilateral meshes known as T-hedra. Moreover, we point out some features of the plugin facilitating the construction process of physical models. Finally, we make some comments on the usability and performance advantages of "Scutes".

Triangulated meshes, in general, have several DOF, while a generic quad-mesh with planar faces, hinged by rotational joints in the combinatorics of a square grid, is rigid. However, there also exist certain geometries of such quad-meshes allowing a 1-dimensional flexibility. An important class of these flexible discrete surfaces is constituted by trapezoidal quad-meshes, as they allow direct access to their spatial shape, which makes them suitable for design tasks. These so-called T-hedra can be considered as a generalisation of discrete surfaces of revolution so that the axis of rotation is not fixed at one point but sweeping a polyline path on the base plane. Moreover, the action does not need to be a pure rotation but can be combined with an axial dilatation. After applying these transformations to the breakpoints of a particular discrete profile curve, we obtain a flexible mesh with trapezoidal faces. Therefore, the design space of T-hedra also includes discretised translational surfaces and moulding surfaces. These subclasses, beside the already mentioned rotation surfaces, are all widely used in the application context. For a more detailed geometric description of T-hedra we refer to [12; 13].

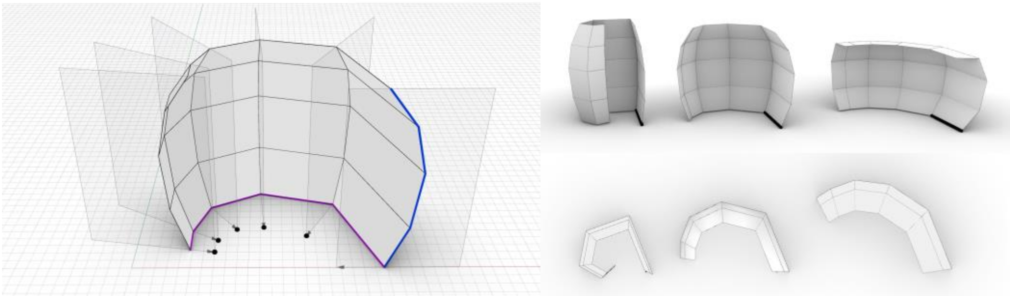

Fig. 3. (a) T-hedron of the most general type. Profile curve (blue), trajectory curve (purple), and direction points (black dots), (b) T-hedron and its relative motion into flexion limits regarding the fixed edge (thick black segment) on the base plane.

"Scutes" is an interactive plugin for Rhino/GH implemented in C#, which makes the design space of T-hedra accessible for designers. It enables the user to design a T-hedron interactively and visualise its deformation in real-time. The visualisation is updated based on a recursive parameterization of the quad-mesh vertices under the associated isometric deformation. The main mesh-generator component generates a T-hedron based on two planar boundary polygons (the so-called profile and trajectory polyline (cf. Fig. 3.a) and a list of direction points identifying the carrier planes, which are orthogonal to the base plane of the stretch-rotated/translated profile). Moreover, "Scutes" visualises the flexion of the T-hedron as set by a deformation parameter slider. For more details on "Scutes", we refer the interested reader to [13], where features are explained in greater length (e.g., the visualisation of the closeness to flexion limits or of the force transmission throughout the quad-mesh).

To facilitate the construction process of flexible physical models, we implemented additional features/components, such as the output of minimum and maximum dihedral angles for customised hinges with rotational restriction, edge selection of the trajectory polyline, which remains fixed under the deformation (cf. Fig. 3.b), and computation/visualisation of the resulting path-curves of points of the trajectory polyline, which is used for guiding rails.

As a conclusion of this exemplary workflow, we now provide details on the realisation of the designs created with our sketching application, for which we employed digital fabrication technologies.

4.3. Digital manufacturing

To digitally manufacture a movable flexible scale model of the sketched and computed, it was necessary to extract the information required for manufacturing from the virtual 3D model. Each face in the 3D model has zero material thickness, is unique in geometry and additionally each element in space has a different position in relation to adjacent elements. The first step of manufacturing is defining a material with a specific thickness and designing hinges for a smooth transition from the start to the end position. We chose opaque acrylic glass with 3mm thickness for the scale model (consisting of twenty faces) due to its high stiffness and ability to be laser cut precisely. We developed mass customised hinges to use as connectors between the faces.

To ensure that the hinges can move properly, we made a GH definition containing the real material thickness and our hinge design. Using a virtual 3D movable model, it was possible to detect collision problems in the movement caused by material thickness and the restriction in the rotation range of the hinges. We extracted the geometry and position of each face within the mesh. To achieve an undistorted contour curve of each planar face, we developed the 3D mesh into a 2D line drawing and orientated it onto the XY plane. All faces were offset by a safety distance of 2.5 mm towards the inside (red) to avoid collision with adjacent faces. We labelled each face with an ID (blue), marking its orientation for easier assembly (cf. Fig. 4).

In the next step, we used the GH definition to determine the minimum and maximum position of each hinge. For this model, the rotation angles range from 0.3° to 87.77°. Parametrically constructed hinges allowed the implementation of the boundary values as physical boundaries for each hinge. Material thickness, hinge mounting, and the diameter of the rotating part of the hinges had to match precisely, as any other position of the rotation axis would have caused the mesh to block. We designed the hinges under the constraint that the axis of rotation must be positioned exactly along the interior edges of the mesh. A total of thirty-one hinges were needed to connect all faces together as well as one large hinge to connect the first face, the lower edge of which is fixed in position. All other elements have a complex relative motion to the ground plate. We custom manufactured each hinge from grey coloured ABS filament using a 3D printer. We made the ground plate with four slits acting as guiding rails for the physical model using a laser cutter. These rails were generated by the path-curves of the midpoints of the four non-fixed edges of the trajectory polyline. We added small pivots in the form of pins to these midpoints. Note that the proposed construction takes advantage of the fact that the trajectory polyline remains planar during the deformation.

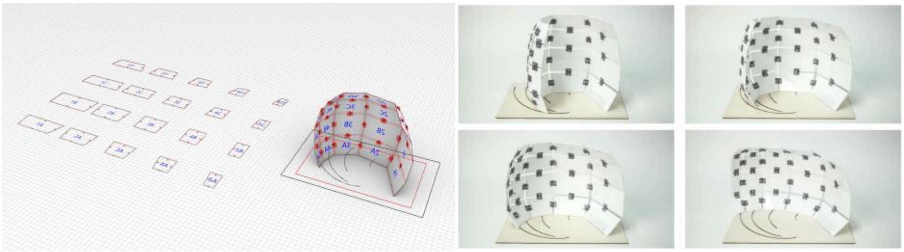

Fig. 4. (a) Drawing of extracted geometry and additional IDs ready to be laser cutted, (b) Picture of the physical model

5. Conclusion and future work

Improving communication between domain experts with different professional languages leads to an increase in the quality of the design process and subsequently to an increased quality of the design itself. Our integrative mixed reality sketching application provides a solution to achieve this improvement. We have created an experimental implementation and assessed its integrative capabilities on a use case aimed at designing a kinetic wall structure. We realised and described an experimental design workflow in which architects, mathematicians and digital manufacturing experts can communicate through a central integrative platform. With the help of our 3D sketching technique, the designer can create spatial freehand sketches in an immediate and intuitive manner. These sketches can be used as input for parametric design methods. We have shown that through real-time data exchange, immediate domain expert feedback can be provided to the designer. This helps to involve experts from across the AEC workflow in the earliest phases of a design project. Our experimental workflow shows improved professional communication from the first stylus strokes to the manufacturing of a physical structure.

We are in the process of conducting user evaluation with architecture students. The evaluation is based around performing specific design tasks and reporting user experience about form-finding, expression, and communication of design ideas. In this step, we are evaluating the 3D sketching aspect of our platform. The usability and design-related potential of the "Scutes" plugin was also evaluated in a seminar course for architectural students, with favourable feedback. Following evaluation rounds will involve students and professionals from different domains and will concentrate on interdisciplinary communication.

The exemplary workflow presented in this paper is one of the many integration possibilities that we are exploring. We aim to find and characterise communication bottlenecks in AEC processes and provide integration solutions to alleviate them. We are developing cross-platform annotation tools to enrich sketches with semantics. Our research project continues to explore, develop, and evaluate experimental tools for computational design, AEC communication support and mixed reality techniques for early architectural design contexts.

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Methodology to Improve Labor Productivity in Construction: A Housing Project of Highly Repetitive Processes Case Study

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Abstract

The purpose of this article is to present a methodology to identify and reduce waste considering Lean construction tools, time and motions study techniques. This investigation was carried out during the construction of 1,392 housing units located in Lima, Perú. The present case study focused on the analysis of highly repetitive processes during the structuring and finishing phases. The methodology presented has different stages. First, we used direct field observation to describe the current state of the work structuring. Second, we applied Value Stream Mapping (VSM) and Flow Process Chart in order to identify the productive stream, focusing in the identification of value adding activities and waste: no value adding necessary activities and no value adding unnecessary activities. Then we prepared and analyzed the information. Finally, with the lessons learned, we ideated and tested improvements in the organization of the work and design of the flows of labor, materials and equipment, among others. The success of this methodology is reflected on the reduction of waste and the improvement of labor productivity obtained in the final measurements and in the improvement opportunities identified.

Keywords: work structuring, productivity, time and motions study, Value stream mapping, flow process chart

1. Introduction

The construction industry is one of the largest industries with a high impact on the economy. However, its productivity is considerably low when compared to other industries [1]. Improving the effectiveness of production control has attracted the interest of researchers and lean construction practitioners over the years. In Lean construction, production activities improved continuously with respect to waste and value [2].

Lean construction, has been implemented to enhance construction systems, with the main goal of improving competitiveness and performance [3]. Also, Lean construction seeks to increase productivity and reduce waste in the construction industry [4]. However, the greatest obstacle to waste removal is the lack of attention of site management to determining waste [5]. One reason that waste is not properly recognized, is the absence of appropriate tools for measuring waste or value. Traditional process models in construction are not sufficient to distinguish between value adding and non-value adding activities [6].

In particular, waste is generally associated with waste of materials in the construction processes while non value adding activities such as inspection, delays, transportation of materials and others are not recognized as waste [7]. Most of these waste activities are intangible [8] and hidden [9]. Process analysis is a simple and effective tool that can be used to identify waste. This alternative investigates the overall flow of steps in a process and provides a method to improve the flow by making continuous improvements [10].

The purpose of this article is to present a methodology to identify and reduce waste considering Lean construction tools and time and motions study techniques. The present case study focused on the analysis of highly repetitive processes during the structuring and finishing phases.

2. Background

This section will review the main concepts and tools used during the case study.

2.1 Gemba Walk

Gemba is the Japanese word for actual place, and lean practitioners use it to refer to the place where value is created in production [11, 12]. This concept was developed in the Lean manufacturing paradigm into the practice of Gemba walks. Ohno described as a practice of Toyota Production System, the routine of going and seeing how the work happens at the shop floor [12,13].

It is essential to understand the importance of going and seeing for the construction process [14, 15]. Kerem brought an important insight considering that the managers discovered that none of the wastes they observed had ever been reported to management, and they would have remained unidentified if not for the Gemba session [13]. After the application of Gemba walk, several managers said that even though they had heard and learned about lean in the past, they had never been able to link it to their daily work [12, 13].

2.2 Work structuring

The purpose of work structuring is the breakdown of both product and process into chunks, separate sequences and assignments in order to make work flow more reliable and quicker while delivering value to the customer [16].

2.3 Value-adding activities and wastes

The definition of value-adding was made by Koskela. Value adding activity is an activity that transforms material or information towards that is required by the costumer and non-value adding activity is an activity that takes time, resources or space but does not add value [2]. Taiichi Ohno identified seven wastes: overproduction, time on hand, transportation, processing itself, stock on hand, motions an making defective products [12]. Subsequently, researchers suggested more waste types like making do [17], not using people´s full abilities [18] and behavioral waste [19].

A first interpretation of flow in construction is part of the TFV theory of production [20] which views production as a flow composed of value adding activities (transformation) and non-value adding activities (waiting, inspection and moving) [21]. The flow concept views production as a flow, which means, that in addition to transformation there is no value adding activities. It is main objective is to eliminate or minimize the share of non-value adding activities. As a result, it is expected some improvement such as lead time reduction, variability reduction, flexibility and transparency [20]. Lean construction represents a way to design production systems to discourage, minimize and eventually eliminate wastes of material, time and effort and emphasizes reduction of non-value adding activities as a means of value improvement [20, 21, 22]

2.4 *Value Stream Mapping*

Value stream mapping consists of all actions (both value-added and non-value-added) needed to bring a product through the production flow from the raw material to the client delivery [23, 24]. VSM permits a systemic view of the value flow in the production process, identification of problems and wastes, lessons learned and continuous improvement [25]. Value stream mapping is a powerful lean tool to improve the productivity of manufacturing industries [26, 27].

2.5 Flow process chart

The flow process chart is a modeling and simulation tool that aims to list all phases of a productive process, allowing quick visualization and understanding, facilitating its analysis. [28]. This tool shows several types of symbols utilized in process flowcharts, each one with a different characteristic that changes the way to analyze an activity, it´s up to the professional to define which one fits best the studied process [28]. The flow process chart makes it possible to create a common understanding, clarify the steps in a process, identify hidden productive costs such as distance traveled, delays and inventory. Once these are identified, the analysts can take steps to minimize them and then reduce their costs [28, 29]. Construction process analysis implements process charts and top-view flow diagrams common among process analysis techniques [30, 31]. The process chart records each step of a construction operation and also records flow within a unit, a section, a department or between departments. Flow may include the sequence of the flow of a product or an equipment or a worker [32].

2.6 Time study

A time study consists of to determinate the time required to complete a process, activity, task or step [33]. Frederick Taylor began the time study associated with work activities and developed the task concept. Around the same time, Frank and Lilian Gilberth, conducted the motions studies [34]. There are two basic procedures to make a time measure: (1) Reading continuous; (2) Return to zero or repetitive reading [29]. In the first procedure, we activate the chronometer, without stopping it, until the end point of the study. In the second one, we activate the chronometer and disactivate it for each element, task or step and then returned it to zero. This is done constantly until the end point of the study [29]. The time study, with a chronometer, is an old technique of work measurement that measures the time it takes an average worker to complete a task [35, 36, 37]. The objective of work measurement is to determinate the standard time and to increase the efficiency of work [38]. In addition to the use of a chronometer, other tools are used for the time, for example, video camera, computers, barcodes, specialized software, among others [39, 40]. Time and motion study can be employed to construction sector with promising results [41].

3. Methodology

This investigation was conducted during the construction of 1,392 housing units located in Lima, Perú. The present case study focused on the analysis of a housing project of highly repetitive processes during the structuring and finishing phases. The methodology is described in the following stages.

3.1 Stage 1: Direct Field observation and work structuring

A first step is to conduct a Gemba walk in order to get a sense of material and process flow. We need to observe how the process is conducted, what kind of materials and tools are used for each process, and what activities could add value or not. Then, we used work structuring in order to divide the process into chunks and make work flow more reliable. For the present work we divided the tasks in processes, then in subprocesses and finally in microprocesses.

3.2 Stage 2: Recordings and registrations

The data collection was conducted by the researchers of the present investigation. For the time study we used the video camera, with this tool we recorded all the processes of this case study. The procedure used in this time study was the continuous reading, it means that we recorded all the processes since the beginning until the end of each one. In order to register all the time and motions, we were located in a strategic place of the project. Finally, we proceeded to watch all the recordings and we registered, second by second of the film, in an excel spreadsheet.

3.3 Stage 3: Value Stream Mapping

Based on the observations and data collected, it was possible to produce a Value Stream Mapping for a task. First, we defined a task to be analyzed. Second, we identified the processes, the relations between processes, suppliers, customers. Third, we registered the time for each process, time for preparation, number of workers, the time of inventory and finally we calculated the lead time and the added value. After that we analyzed the results obtained according with the transformation-flow-value theory of production.

3.4 Stage 4: Flow process Chart

Based on the observations, the recordings of time, motions and the structure of the work, it was possible to make a process flow chart. In this chart we registered the total time of the process, the productivity of the process, the subprocesses for each process, the total time for each subprocess, the materials, tools and equipment used for each subprocess and the constructive sequence for each subprocess. Likewise, it was possible to show a deeper analysis. With the previous collected data, we produced a flow subprocess chart. In this chart we registered the microprocesses for each subprocess, the total time for each microprocess, the materials, tools and equipment used for each microprocess. Then, with this information, we quantified wastes and the level of value adding activities.

3.5 Stage 5: Identifying opportunities for improvement

In this stage, with the information previously obtained, we focused on identifying opportunities to reduce or eliminate wastes. We used tools such as histograms and pareto diagrams to identify those wastes that consume more time. Also, we used tools such as cause and effect and 5 whys in order to analyze and identified the principal causes.

3.6 Stage 6: Development of improvement strategy and Implementation

In order to ideate an improvement strategy, we organized this stage as following: First, we had meetings with the participation of the construction staff and crew leaders. During these meetings we described all the wastes that we could identified. Also, we watched the recordings and we showed to all the participants the activities adding no value. Second, we asked for different alternatives for solution. In order to ideate them we used tools such as 4W (who, what, where and when), brainstorming and ECRS (eliminate, combine, rearrange and simplify). Third we conducted a brief discussion about the different alternatives and finally we voted for the ones that could work. The alternatives selected were implemented and the results were registered.

4. Results

4.1 Stage 1: Direct Field observation and work structuring

As a result of the observation during the structuring and finishing phases, we could breakdown the work into chunks. Figure 1 (a) shows an example of the slab concrete task. This task is divided in processes of preparation, transportation, slab concrete pouring and curing. Besides that, we can observe that the process of slab concrete pouring is divided in subprocesses of concrete pouring, vibration and finishing and finally we can notice that each subprocess is divided in what we called microprocesses. This work structure facilitated the identification of wastes.

4.2 Stage 2: Recordings and registrations

For this study we used a video camera in order to record the processes second by second. After these was filmed, the investigators of this study registered the information in excel spreadsheets. Figure 1 (b) shows an example of the data registration of the slab rebar installation. The spreadsheet registers the subprocesses, microprocesses, the time for each microprocess, number of workers, production and productivity of the process.

a

Task	Process	Subprocess	Microprocess
Slab concrete	Preparation		
	Transport		
	Slab concrete pouring	Concrete pouring	Waiting time Motion Transport Pouring Spreding Resting time
		Vibration	Motion Checking Transport Additive pouring Waiting time Vibration
		Finishing	Waiting time Additive pouring Coordinations Motion Spreading Checking
	Curing		

b

Process :	Slab rebar installation
Time (hrs)	3.13
Production (kg)	382.98
#Workers	2
Productivity (kg/Labour hours)	61.27

Subprocesss	sec acum	sec	min	Microprocess
Bar straightening	12.00	12.00	0.20	Transport
Bar straightening	15.00	3.00	0.05	Bar straightening
Bar straightening	16.00	1.00	0.02	Motion
Bar straightening	23.00	7.00	0.12	Bar straightening
Bar straightening	27.00	4.00	0.07	Motion
Bar straightening	34.00	7.00	0.12	Bar straightening
Bar straightening	39.00	5.00	0.08	Motion
Bar straightening	53.00	14.00	0.23	Bar straightening
Bar straightening	57.00	4.00	0.07	Motion

Fig. 1. (a) Concrete slab: process, subprocess and microprocess; (b) Spreadsheet for data registration

4.3 Stage 3: Value Stream Mapping

Based on the observations, it was possible to produce a VSM for each task analyzed. Figure 2 shows the door installation task for the production of one unit. As we can observe the greatest amount of time is concentrated on activities that do not add value. For example, there is a huge gap of 30 days within the processes of applying the second coat of paint and the second door installation. In compliance with the transformation-flow-value theory of production [42], among the main losses are: (1) Material loss: Rework of painting due to continue presence of crews for re-entrant flow; (2) Time loss: Waiting time due to the interruption of other activities. Also, there are many unprocessed materials, and a high rate of inventory loss; (3) Value loss: Lack of quality in doors and frames due marks of painting and dents produced by other crews. If we observe the Value Stream Map in figure 2, there is still a lot of room for improvement.

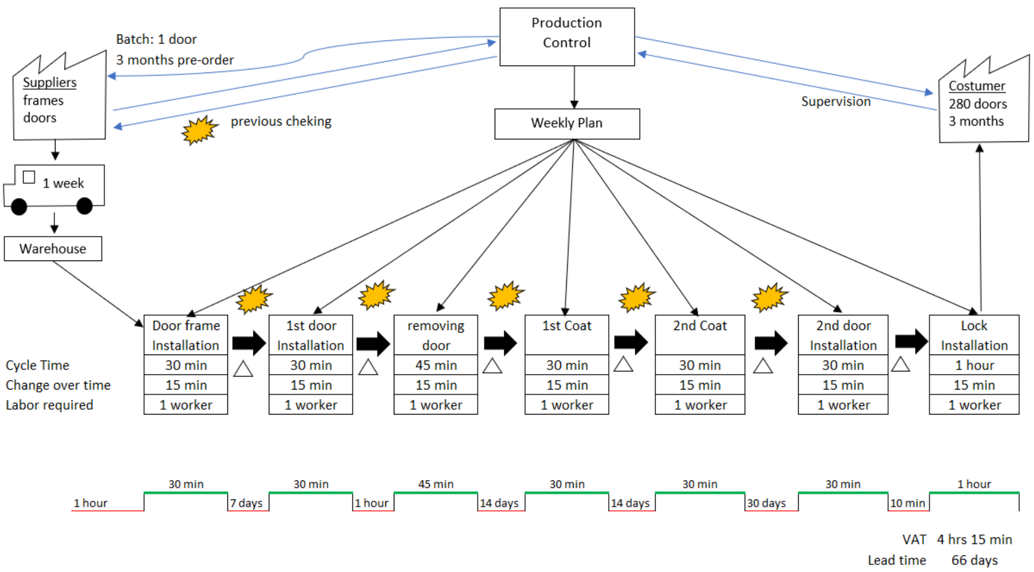

Fig. 2. Value stream mapping of door installation

4.4 Stage 4: Flow process Chart

Based on the observations and data collected, it was possible to produce a flow process chart. During the investigation it was observed that each process was composed of smaller elements that we called subprocesses and these had to be identified and measured. Figure 3(a) shows a flow process chart of the door frame installation process. This chart registers the total time, productivity, number of workers, production and time for each subprocess. This chart identifies, for example, that the subprocesses wood block placing and wall perforation, represent the majority of time with 25% and 15% of the total process time, respectively.

Also, we registered the microprocesses for each subprocess. For example, the Figure 3(b) shows the flow process chart of the subprocess frame installation. This chart registers the total time, productivity, number of workers, production and time for each microprocess. Also, this chart identifies that only 42% of the time are composed by activities that add value. Besides that, we calculated that the worker had more difficulty in the microprocess stoppers placing which presented the 33% of the total time of the subprocess. Finally, through these charts, it was possible to have a deeper analysis which allowed us to identify wastes, how time is spent and there is still much room for improvement.

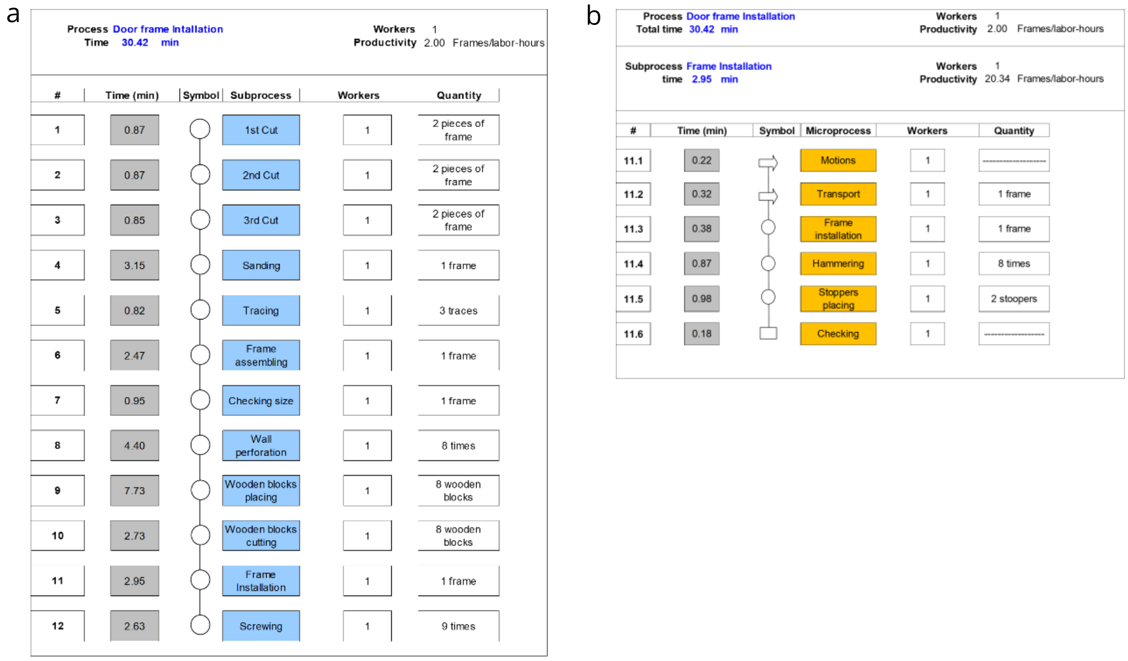

Fig 3. (a) Flow process chart: Frame Installation; (b) Flow subprocess chart: Frame Installation

4.5 Stage 5: Identifying opportunities for improvement

Based on the information and the previous analysis, it was possible to produce histograms, pareto charts, among others, in order to show the different opportunities for improvement. Figure 4(a) shows an example of the activities distribution adding and no adding value in the structuring phase. In this figure we can observe that the activities that add value (VA) are between 21% and 56% and have an average of 32% of the total time. As we can see the greatest amount of time is distributed in activities that do not add value. In order to know the type of wastes, Figure 4(b) shows the activities that do not add value but are necessary (NVAN) and the activities that do not add value and are not necessary (NVAU) during the wall rebar installation process. In this analysis 45% of time are NVAN and 22% are NVAU. Also, it was found that transport of material represented 27% (more than half time of NVAN) and motions 13% (more than half time of NVAU) of the total time of the process. In this example, we found that the principal cause for these wastes were that the workers had to move continuously to the warehouse which was far from the work placement, also there were not specific routes to return which made the work more difficult.

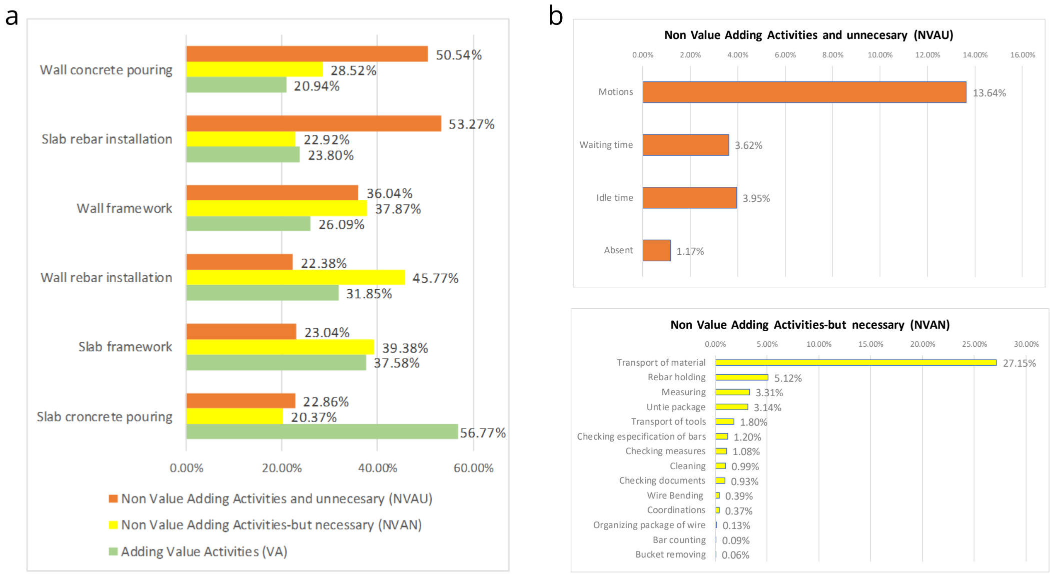

Fig 4. (a) VA and NVA in the phase of structure; (b) NVAU and NVAN in the wall rebar installation

4.6 Stage 6: Development of improvement strategy and Implementation

The different strategies were proposed during meetings by the investigators, the engineers of the project and by construction workers. At the end of the meetings several solutions were proposed by the participants and selected to be implemented in the processes, some examples of these are: (1) Wall and slab installation: The most relevant wastes were motions and transport of material. The suggestions proposed were: i) Arrange another temporary storage areas close to the crews; ii) Create a standard procedure and communicate it to workers iii) Provide panels with indications of the access routes. (2) Wall and slab frame work: In these processes, the most important wastes were transport of equipment and transport of tools. The suggestions were: i) Provide a basket to storage the tools and transport the basket by the tower crane; ii) Create a schedule of the tower crane and communicate it to workers. (3) Wall and slab concrete: the most relevant waste was waiting time. The suggestion was: i) Prepare a smaller volume of mix in the concrete plant to reduce the preparation time. (4) Patching walls: the most relevant wastes were transport of material and tools. The suggestion was: i) Create a simple equipment of transport to take the bucket fill of mix and the tools. (5) Door frame and door installation: the most important wastes were transport of tools and rework. The suggestions were: i) Provide a tool holder to reduce transport times; ii) Implement a control system on the site in order to bring access according to the weekly plan. Also, one important suggestion was to conduct weekly coordination meetings with all crew members in order to create a culture of continuous improvement. These suggestions were implemented in different processes during the execution of the project and then these were measured to evaluate the improvement. Table 1 shows some examples of the results. As we can see, it was possible to reduce waste. We achieved reductions of waste around 6% to 9.5%. Besides, we had an increase in labor productivity around 10.5% to 18.4%.

Table 1. Results of implementation.

Processes	Waste Initial (%)	Waste Final (%)	Productivity Initial	Productivity Final	Productivity Increase (%)
Wall rebar installation	68%	58.5%	65.3 kg/lh	77.3 kg/lh	18.4%
Wall framework installation	74%	68%	7.2 m2/lh	7.9 m2/lh	10.5%
Wall concrete pouring	79%	70.3%	1.1 m3/lh	1.3 m3/lh	13.6%
Patching walls	26%	19.8%	8.4 m2/lh	9.3 m2/lh	11.1%
Door frame installation	66%	58.7%	2.0 und/lh	2.3 und/lh	12.9%

5. Conclusions

This study shows that there is still a lot of room to continue reducing waste. We identified that no value adding activities represent the majority of time in the processes. For example, 62 % in the slab framework process, 66% in the door frame installation, 68% in the wall rebar installation, among others. In addition, by combining time and motion study tools and lean tools were very useful to identify wastes from different perspectives and contributed to the reduction or elimination of no value activities and improve labor productivity. We found that the majority of wastes were transportation, motions and rework. These wastes were due to a lack of management control. For example, transportation and motions wastes occurred because a bad distribution of the material and access routes not well defined. Rework wastes happened due to a lack of communication methods between engineers and crew members. The meetings with the crew members were very productive, each participant suggested alternative solutions that contributed to reduce waste in the processes. We considered that the implementation of meetings to ideate solutions focused in waste reduction should be scheduled weekly. The major advantage of this methodology is the simple steps that do not require extensive training and are useful to reduce wastes and improving processes. The keys for the success of this implementation are the continuous commitment of the participants at all levels of the project and having a culture of continuous improvement.

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Chronographical Modelling for Repetitive Project

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Abstract

Most building projects are scheduled using the Gantt/Precedence diagram. The lack of consideration of the sequence of work and traffic in the limited spaces of construction sites makes the resolution of conflicts more complex. Mathematical modeling and optimization techniques have been used to solve these problems. However, these solutions are less viable for application in real projects. There are too many parameters to be considered or processed with reasonable efforts and time. This paper presents an explanation of a repetitive spatiotemporal modeling solution and makes a clear distinction between these two different methods, namely, the linear and the repetitive methods. Linear methods are designed to graphically schedule a limited amount of activities in parallel to ensure continuity of resource use and support a stable and optimized production. Methods that are well-suited for planning linear projects as Roads, highways, railways, tunnels and pipelines. Repetitive models are more adapted to schedule building projects. For these projects, repeated tasks are assigned from unit to unit or from floor to floor. The paper also shows examples of modeling horizontal and vertical repetitive project.

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Keywords: scheduling, repetitive project, spatiotemporal, building, construction

1. Linear Projects

Linear methods are timeline diagram with two axes, time and space, that represent the movement of different teamwork through chaining. At any time, this method can visually define the location and spatiotemporal evolution of each resource on the project. This facilitates the visual optimization of the project and avoids conflicts or planning errors.

Linear methods are designed to ensure continuity of resource use and support a stable and optimized production. To ensure continuity of use of each type of resource, these methods propose to delay the start of specialties that have a faster rate of progression. This delay serves to adjust the completion dates of these specialties with those preceding them.

[1] mentions that schedules oriented by resources are more realistic than those dominated by activities. These methods show graphically any imbalance due to uneven progress of activities and quickly allow the manager to quantify the deviation [2].

Linear methods are therefore well-suited for planning linear projects. Roads, highways, railways, tunnels and pipelines projects are good examples. We note that within these projects the machinery and the work teams operate continuously in a linear way. The difference with the simulation methods based on CYCLONE is that simulation is used to optimize the production, versus a target of linearity and operating in parallel way between the successor activities for the linear methods. This concept could also be used for planning building projects. It was used for the construction of the Empire States Building in 1930.

Linear methods have been the subject of countless improvements either through their graphical design and their mathematical models. The Line of Balance method (LOB) was modified by [3] who showed an example of unbalanced progress of a housing construction project. It showed a distinction between the progress rate of a repetitive activity in the different units and the overall progress of the project.

In 1970, [2] demonstrated the application of the method for a manufacturing project to produce precast concrete beams. [4] applied the technique to housing unit construction projects. Subsequently [5] proposed the Vertical Production Method (VPM). In his proposal, he used CPM to represent nonrepetitive activities such as building foundations. The LOB was used for activities of a repetitive nature, represented in identical levels.

To model the variation in performance progression of a repetitive activity from one unit to another, several studies have been carried out [6, 7, 8]. The common-known name for these methods is the Linear Scheduling Method (LSM). The variation in progress rates may be due to the learning generally associated with the start of each activity, weather conditions or the particularity of a certain unit. [9] developed the Time Space Scheduling Method. This technique can be used to graphically schedule a limited amount of activities in parallel and to establish relationships between activities of the same unit.

In 1994, [10] define a scheduling method for multi-story buildings, called Horizontal and Vertical Logic Scheduling (HVLS). The progress of the activities has two directions: a horizontal direction that presents the sequence of activities on the same floor, and vertical constraints show the dependencies between activities taking place on different floors. Flood [11] propose a modeling paradigm suited for construction project planning that attain the simplicity of CPM, visual insight of linear scheduling, and the modeling versatility of simulation. Ioannou and Yang [12] classified projects as discrete (vertical for multistory buildings) and continuous (horizontal or linear, such as highways). Their modeling elements include three types of activities (line, block, and bar) and 10 types of relationships (links) between activities.

Most of the other developments of linear methods were oriented toward mathematical optimization aspects. Since this research concerns the study of the graphical modelling of repetitive methods, the bibliographical research concerning the mathematical developments exceeds the limits of this paper.

2. Repetitive Projects

Repetitive graphical models [13, 14] are more adapted to scheduling building projects. For these projects, repeated tasks are assigned from unit to unit or from floor to floor. This differentiates them from linear projects in which machinery is operating continuously. We can distinguish two types of repetitive projects: a) vertical projects, such as multi-story buildings and b) horizontal projects, such as the construction of several similar units. In repetitive vertical projects, some activities are non-repetitive activities, such as the foundation and the roof, while others are repeated from one floor to another, such as structure, architectural finishing and services. In repetitive horizontal projects, most activities are repetitive, and the work of several units can be planned simultaneously to accelerate the project schedule. The number of teams for each specialty can be calculated with the quotient of the time needed to complete a single unit by the total time available to complete the work of that specialty for all units [15].

Unlike purely algorithmic optimizations which are difficult for construction sites to implement due to their complexity and the number of parameters to be taken into account, the graphical methods help with visual optimization that is easily understood by the construction site.

The main goal of this research is to model the site operation and execution process for construction buildings projects based the Chronographic repetitive modelling. The aim is to ensure suitable rotation of the workforce in different spaces. It also ensures the continuity of work through linear production for the same team and parallel linearity between the various successor teams.

3. Graphical modelling for Repetitive Projects

3.1. Modeling a horizontal repetitive project

3.1.1. Calculation example

The example presented in the Figure 1 below shows the calculation model for a repetitive horizontal project. We could consider the repetitive approach as a combination between the network's techniques and the Linear Method. CPMs provide the logic and computation of the critical path, while linear methods demonstrate location and provide continuity of resource use and linearity of production. Thus, the activities, their relations and the executed units, can all be shown at the same time.

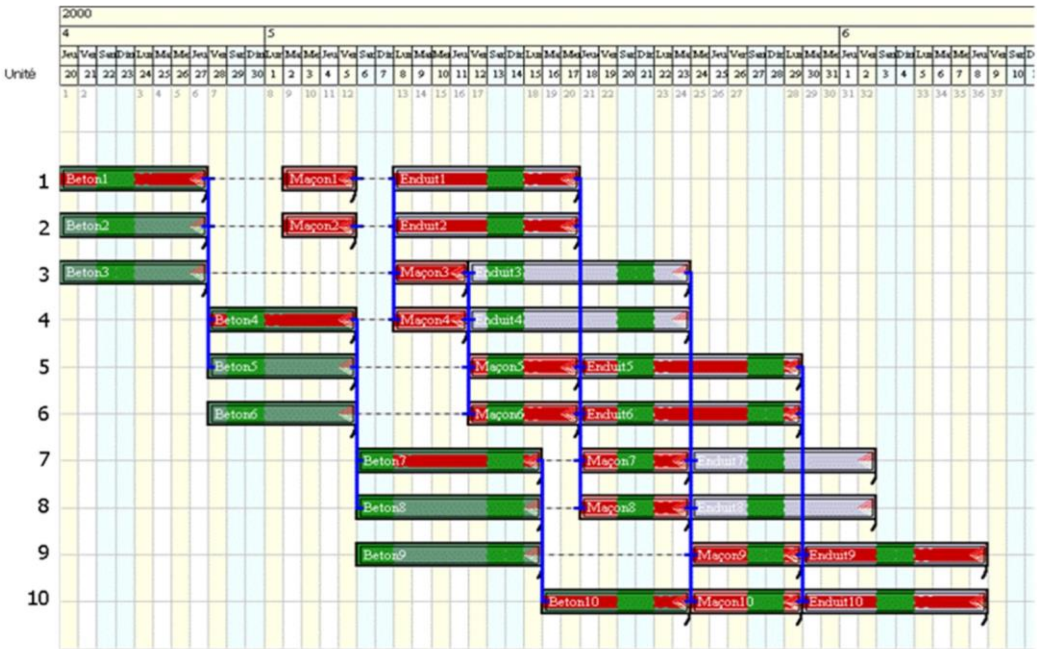

Fig. 1. Linearization of repetitive modeling.

The example presented in Figure 1 shows how one can Linearize the repetitive modeling. This project is made up of ten (10) units consisting of three (3) activities each. Usually, projects have deadlines and a total duration of projects are imposed. To respect this total duration, the general progress rate "Tp" of the project has to be calculated using the following formula:

$$Tp = \frac{Dp-Dr}{N-1}$$

N = number of units; Dp = expected duration of the project; and Dr = the needed duration in order to accomplish one unit

For this example, the target total duration is 38 days for the ten (10) units and each unit take 20 days to be executed. The general progress rate is then 2 days [(38-20)/9], which is means, we must, with the exception of the first unit, every two days complete a new unit

In repetitive horizontal projects, several units could be executed at the same time. For each activity, labor productivity is independently analyzed to estimate its specific rate of progress. The number of teams required for each specialty is calculated through the general progress rate of the project and the specific progress rate of the specialty.

The number of teams for each specialty "Ns" is calculated using the following formula:

$$Ns = \frac{Activity\ specific\ Duration}{Tp}$$

Non-critical activities can take advantage, as far as possible, of their own float in order to lighten the demand from the corresponding teams.

Thus, in figure 1, to respect the general progress rate of 2 days, three teams were used to make the foundations (Beton); two teams to do the masonry (Maçon) and four teams to do the finishing (Enduit) with a delayed start for the third and fourth teams.

3.1.2 Example of horizontal repetitive project

Figure 2 represents a repetitive horizontal project. This project is to build ten (10) units consisting of nine (9) activities each. The target total of the project duration is 48 days. Each unit take 28 days to be executed. The general progress rate "Tp" is 2.22 days [(48-28)/9], which means that a new unit must be completed, except for the first unit, at least every 2.22 days.

The number of required teams by specialty is the calculated by dividing its specific duration, to execute one unit, by the general progress rate. Activity B, for example, is performed by three teams (6 days / 2.22 days) for the first nine (9) units. Thus, the first three units are executed at the same time by three different teams and are represented by three bars in parallel. Units 4, 5 and 6 and units 7, 8 and 9 follow the same logic of the first three units. The tenth unit is performed by a single team.

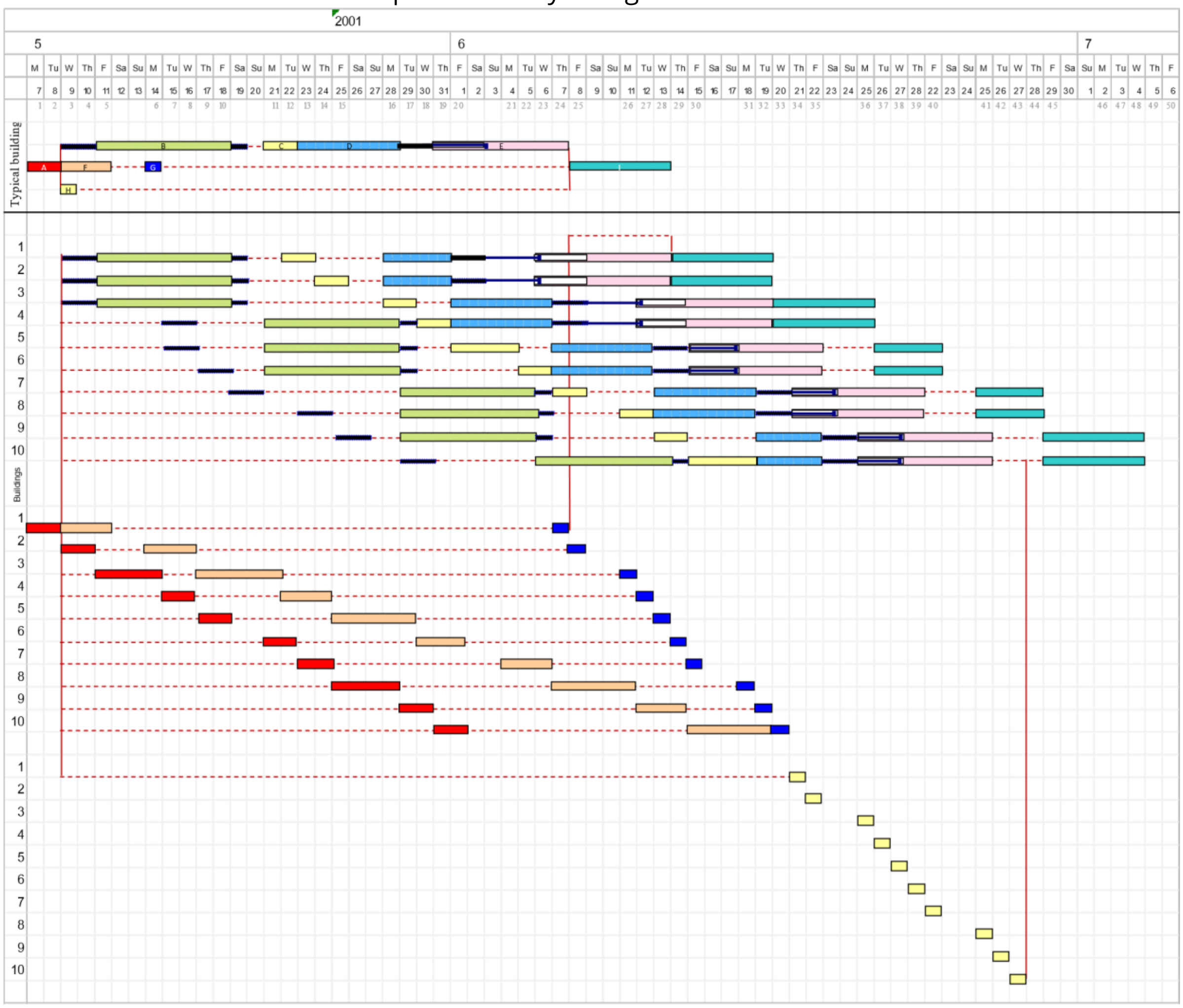

Fig. 2. Linearization of repetitive modeling.

3.2. Modeling a Vertical repetitive project

For repetitive vertical projects, most specialties are performed by a single team while some activities are non-repetitive activities, such as the foundation and the roof. The following figure shows a building reinforcement project with repetitive vertical planning modelling. The work on each floor focused on two areas.

Two differences between this modelling and the Gantt chart: 1) the vertical direction shows the spaces and not the WBS; and 2) the activities are modelled in series (several activities on the same line) and in parallel.

With these two specificities: i) the graphic modelling surface used (on screen or paper) by the schedule is better optimized and uses about 10% of the surface required to present the logic using a Gantt chart; ii) Teams rotation are easier to plan and track without complex calculations; (iii) resources are levelled from the first planning. No additional methods or procedures are needed to do a levelling; (iv) spatiotemporal locations of activities are easily identifiable; and v) conflicts of spaces are avoided and the use of the site is optimized. Thus, the project scheduling is optimized without the need for other complex theories to do so.

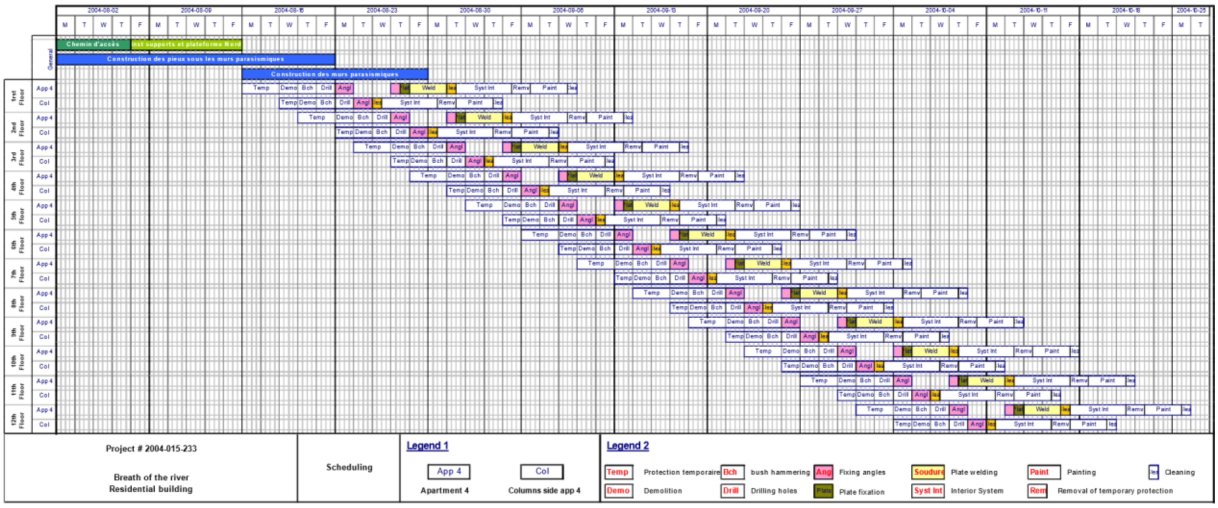

Fig. 3. Scheduling a repetitive project.

4. Conclusion

The limitations of the traditional scheduling methods result in unclear visualization and complexity in schedule analysis and optimization. The efficient use of site space is also neglected. These limitations result in non-optimal use of site resources and space, which affects the duration and cost of the project. Repetitive planning methods integrate the management of spaces, operations, and team rotation from the planning stage. Unlike purely algorithmic optimizations which are difficult for construction sites to implement due to their complexity and the number of parameters to be taken into account, the graphical methods help with visual optimization that is easily understood by the construction site. Despite its advantages, one of the main challenges stems from the lack of commercial software that enforces these strategies. Despite this, the method presented remains attractive and offers a visual communication that meets the needs of planners and resolves the limits of existing methods.

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Characterization of Concrete Exposed to Marine Environment

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Abstract

Concrete can be found in various types of environments during its service life. Marine environment is one of the most aggressive and complex due to its diverse actions and variable nature. Achieving designed service life with the least embodied energy for materials production, construction and maintenance of marine structures is an important task. To meet the criteria of economy and environmental protection, concrete is made of locally available cements and aggregates. Additional benefits to reduce energy consumption but also to prevent landfills can be achieved if part of the cement is replaced with by−products of other industries. A research project entitled *"Concrete development for sustainable construction in the marine environment"* aims to develop an optimized concrete mixes for Adriatic marine environment. This paper gives the overview of activities planned to achieve that goal. The project focuses on the design of the composition of the concrete mix, striving for an optimally sustainable solution between service life, energy consumption and environmental impact.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2022.

Keywords: concrete characterization, marine environment, optimization, sustainable construction.

1. Introduction

Concrete can be found in various types of environments during its service life, and one of the most aggressive and complex is the marine environment. The mechanisms of degradation in such an environment are numerous, and the most pronounced is the corrosion of reinforcement caused by the action of chlorides. The intensity and interaction of degradation mechanisms depend on the local specifics of each region - (micro) climatic and weather conditions, chemical composition of water, presence of local pollutants from industrial plants or seaports, changes and flow rates, use of maritime structures, etc. Typical salt content in seawater is about 3.5% (salinity of the Adriatic Sea is approximately 3.8%), and the majority are NaCl and $MgSO_4$. Sea water also contains dissolved gases (O_2, CO_2, H_2S) and numerous living organisms (mollusks, shellfish). Seawater temperature varies from -2°C (freezing point) in colder regions, to 30°C in tropical areas [1]. In warmer water, degradation of concrete is the result of chemical action, i.e., changes in the composition of cement caused by chlorides and sulfates. In colder water, the chemical action is less pronounced, and the main damage is caused by temperature fluctuations between water and air, which affect the moisture content and growth of marine organisms [2]. Concrete is exposed to cycles of wetting and drying, heating, and cooling, and freezing and thawing (colder climates) during high tide and low tide. Dissolved salts penetrate deeper and deeper into the pores of the concrete during the wetting and drying cycle. Winds, storms, and earthquakes can create high power waves. Structures exposed to waves show concrete degradation caused by erosion, abrasion, and cavitation, which manifests as surface wear of the material. It is important to mention sea dust, i.e., seawater particles formed by breaking waves and carried by the wind over long distances [1]. Degradation of concrete in the marine environment is caused by physical and chemical influences. Physical ones occur due to pressure due to crystallization of salt which creates cracks and opens the way to chemical influences, i.e., water penetration and initiation of chemical reactions of dissolved substances with hydration products of cement or aggregate [2]. Table 1 lists the most common participants in chemical reactions between seawater and concrete and their consequences on the durability of concrete.

Concern for sustainability is constantly posing new challenges in the areas of resource management and thus in the cement and concrete industry. The desire to reduce energy consumption for the construction and production of construction materials imposes the need for the most rational use of raw materials. Therefore, it is necessary to encourage the use of locally available materials and reduce the share of Portland cement in concrete at the expense of replacing part of the cement with by-products of industry. The use of by-products of other industries simultaneously protects the environment because it reduces the amount of deposited material and reduces the likelihood of environmental pollution. The implementation of these activities in the construction of structures located in the marine environment is a challenge for the concrete industry. This is the theme of the project entitled *"Concrete development for sustainable construction in the marine environment"* (RBOGMO) funded by the European Regional Development Fund. Research within the project is being conducted for the Adriatic coast of the Republic of Croatia. The project aims to include various parameters that are important for sustainable construction, such as local climatic specifics, identification of locally available aggregates, cements and secondary raw materials, their characterization and optimization of concrete composition. This paper presents the planned course of activities within the said project.

Table 1. Participants in chemical reactions between seawater and concrete, and their influences [2].

Reactants - seawater	Reactants - concrete	Products	Influence
$MgSO_4$, $CaSO_4$, K_2SO_4	C_3A, CH, C-S-H	$Ca_6Al_2(SO_4)_3(OH) \times 26H_2O$, $Mg(OH)_2$, $Al(OH)_3$, $CaSO_4$, $SiO_2 \times nH_2O$, M-S-H	Leaching, expansion, cracking
CO_2, H_2CO_3, Na_2CO_3, K_2CO_3	CH, $Ca_6Al_2(SO_4)_3(OH) \times 26H_2O$	$CaCO_3$	Local softening, disintegration, leaching, corrosion (carbonation)
K_2O, Na_2O	Silica or carbonate constituents of the aggregates	Na_2SiO_3, K_2SiO_3	Alkali-aggregate reaction, expansion, cracking
NaCl, $MgCl_2$	C_3A, CH, $Fe(OH)_2$	Chloraluminates, $Fe_2O_3 \times H_2O$	Corrosion of reinforcement

2. Research methodology

The activities envisaged by the research within the project are shown in Fig. 1. In the first phase of the project, data were collected on locally available sources of mineral admixtures that remain as a by-product of other industries, and their use in concrete is justified. In addition to mineral admixtures, data were collected on the types of cement produced within the nearby region. After the analysis of available raw materials, those materials that will be used in further research on the project will be selected, for which the possibility of contributing to the improvement of concrete properties will be assessed. Detailed characterization of selected materials by standardized and advanced test methods was performed to assess their suitability for use in concrete. In addition to the characterization of the material, a literature review was conducted aimed at investigating the interdependence of properties and composition of concrete and the resistance of concrete to actions from the marine environment. To properly select the materials to start with designing the composition of concrete and optimization, additional data collection (sampling and their characterization) was carried out from real existing structures built in the marine environment. The research is focused on structures for which data on the properties and composition of concrete and applied construction technology are known. In the final phase of the project, the collected data will be implemented in a database that will also be the basis for computer-aided design of concrete compositions.

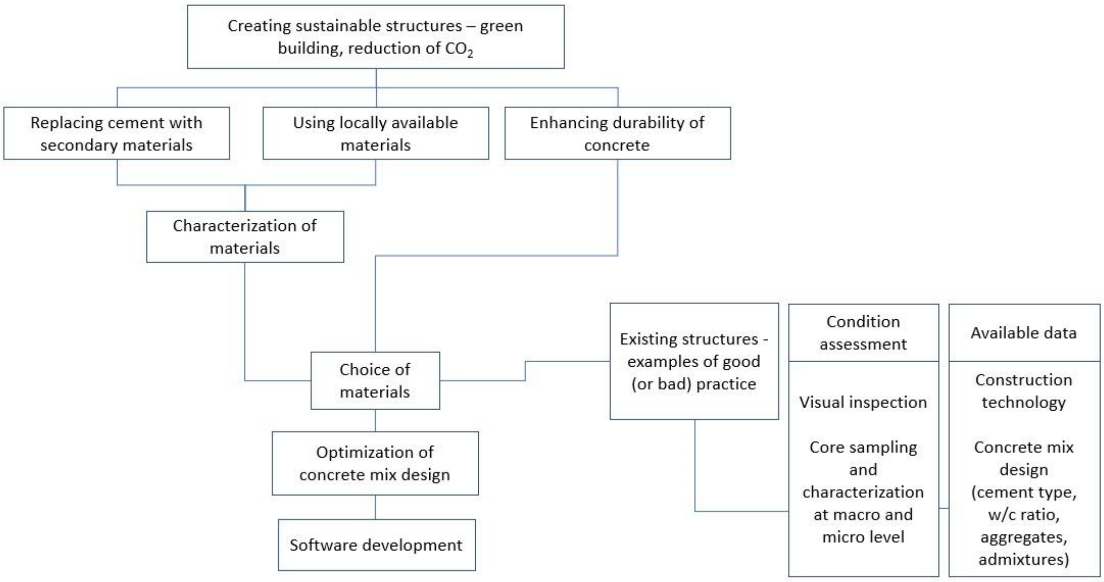

Fig. 1. Schematic representation of project activities.

2.1. Cement and mineral admixtures

There are two cement factories on the Adriatic coast that cover the needs of the local cement market, and in addition, there are two cement factories in neighbouring Bosnia and Herzegovina. All these cement factories produce Portland cements and certain types of metallurgical or pozzolanic cements. Reducing the amount of cement in concrete while achieving appropriate mechanical and durable properties can be achieved by replacing part of the cement with mineral admixtures. Significant amounts of fly ash from coal-fired thermal power plants have been found to be available from mineral supplements in the region. Flying ashes from several wood-fired thermal power plants are also available, and their use in concrete has been intensively investigated in recent times. In addition to fly ash, the possibility of using red sludge from a factory in Bosnia and Herzegovina will be analysed. In addition to these admixtures, the research will also include silica dust and metakaolin, which, although not locally available, play an important role in achieving better durability properties. Selected mineral admixtures have a justified application in concrete, especially those exposed to aggressive marine environment, as they improve its properties or give it special properties by various mechanisms of interaction between solid particles [3]. The use of selected mineral admixtures improves the workability of concrete by reducing the size and number of gaps between relatively large grains of cement, and releasing trapped water, which contributes to better fluidity [4]. Mineral admixtures reduce the permeability of concrete by improving the pore structure and increasing the pore density. This reduces the possibility of penetration of aggressive substances into concrete (especially chloride with a decrease in the diffusion coefficient) and the occurrence of alkaline-aggregate reaction. In addition, mineral admixtures contribute to increasing the compressive strength of concrete and its durability [3, 5, 6, 7, 8, 9]. The potentially negative contribution of mineral admixtures is reflected in the possibility of reducing the workability of concrete, which is often attributed to the increase in solid surface area due to the presence of fine particles that tend to adsorb water, replacement with filler containing large particles (> 45 μm) and open porosity of the particles which increases the specific surfaces [3, 4]. Also, mineral admixtures can have negative effects on concrete properties in the form of reduced early compressive strength which can lead to higher permeability and lowering the pH value of concrete in favor of corrosion, so it is necessary to pay attention to composition, selection and dosage of mineral admixtures [3, 10, 11]. In general, mineral admixtures act on the principle of pozzolanic reactivity, increasing the content of C-S-H gel that binds more cement and aggregate particles to form a cohesive structure, on the principle of filling (fillers) structures reducing permeability, and on the principle of nucleation [12].

2.2. Analysis of existing structures

The project will include tests on reinforced concrete from 5 seaports along the Adriatic coast in the territory of the Republic of Croatia (Fig. 2) to cover different microclimatic conditions (seawater composition, wind intensity and frequency, etc.). The choice of structures covered by the research is limited to those for which there is extensive data on the period, conditions and construction technology, concrete composition, control test results and data on the origin of concrete components, to establish a relationship with condition and properties.

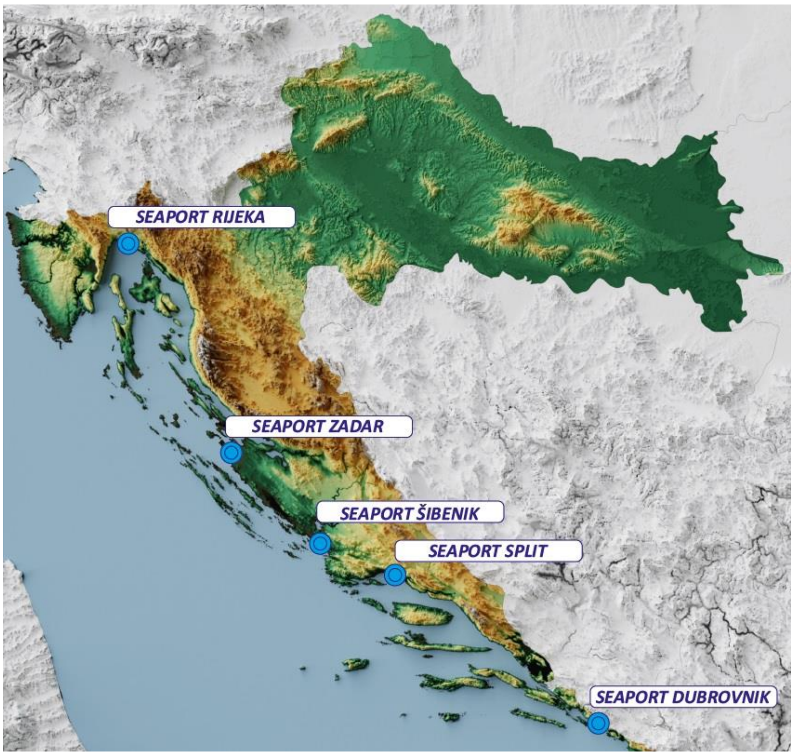

Fig. 2. Map of the Republic of Croatia showing the locations of seaports.

Pure Portland cements and Portland cements with the addition of slag or fly ash were used to produce concrete of selected structures, in quantities from minimum 340 kg (concrete element of seaport in Zadar) to maximum 430 kg (concrete element of seaport in Rijeka). Values of water-cement ratios vary from a minimum of 0.39 to a maximum of 0.45. The aggregates used are natural limestone, added in 3 different fractions: 0-4 mm (most of the total amount of aggregates), 8-16 mm, 16-32 mm. Various superplasticizers have also been added to the concrete mixes. In addition to the visual inspection and assessment of the condition of the structures, drilling of rollers was carried out for the purpose of characterizing the concrete. For each structure, three characteristic zones are analysed:

- 1st zone - part of the structure constantly immersed in sea water
- 2nd zone - part of the structure in the part of the tides
- 3rd zone - part of the structure constantly exposed to the atmosphere (air)

Characterization of concrete samples from selected structures will be conducted to gain insight into the current state. Comparison of compressive strength and measurement of chloride diffusion of concrete installed in the structure with the properties determined by control tests during construction are performed. In addition, to analyse porosity and chemical composition by depth, certain tests will be performed to determine the zone of influence of the marine environment.

a b

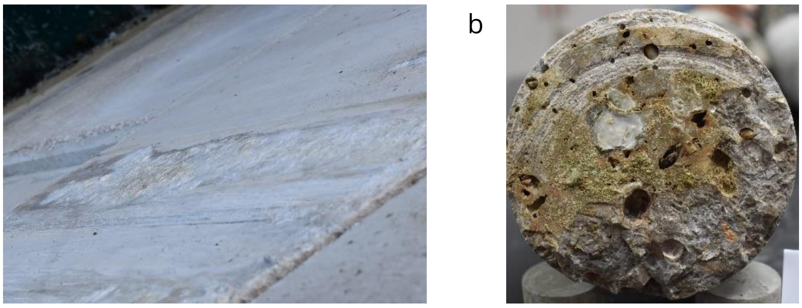

Fig. 3. (a) Degradation of concrete from analyzed marine structures caused by leaching on the surface in the splashing zone; (b) Degradation of concrete from analyzed marine structures caused by growth of shellfish in the area under the sea.

3. Optimization

The optimization process will include the preparation of test mixtures, varying the proportion of individual mineral admixtures. By optimizing the composition of concrete with selected mineral admixtures, efforts will be made to improve its durability and resistance when exposed to aggressive marine environment. During the optimization, different approaches to the design of concrete compositions will be considered, and the possibility of making self-compacting concrete will be explored as well. At the same time, a computer program for designing the composition of concrete exposed to the marine environment will be developed. A database with the properties of locally available concrete components will be integrated into the program.

4. Conclusion

The mechanisms of degradation of concrete exposed to the marine environment are numerous, and the most pronounced is certainly the corrosion of reinforcement caused by the action of chloride. To overcome this problem, efforts will be made to increase the resistance and, consequently, the durability of concrete exposed to the marine environment. Therefore, the main aim of the project entitled *"Concrete development for sustainable construction in the marine environment"* is to optimize the composition of concrete to improve its properties, and at the same time, to promote sustainable, green building. The optimization of concrete will be contributed by using locally available mineral admixtures as a replacement for part of the cement to keep its consumption as low as possible. Thus, the economic and environmental aspects gain in importance. Through the project, the aim is to develop a computer program to simplify the process of designing the composition of concrete and modelling its properties, which will ultimately make a positive contribution to optimizing the composition of concrete.

Acknowledgment

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A Review of Construction Safety and Health Laws in Lebanon

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Abstract

Despite being one of the most essential and prominent industries, the construction industry continues to be the world's most fatal. It is responsible for one in every five fatal occupational injuries in the European Union and the Unites States of America, and rates get even worse for developing countries. In Lebanon, a developing country in the Middle East, one in every three occupational fatalities is incurred by the Lebanese construction industry. These alarming fatality rates enhanced safety construction research, with many studies attempting to identify the root causes of injuries, investigate safety climate and culture in construction firms and sites, and analyze safety indicators. However, very few studies tend to critique the existing occupational and health safety laws adopted in their country. The main objective of this paper was to investigate the construction occupational safety and health laws in Lebanon. Upon examining the current decrees, and comparing them to foreign Ocupational Safety and Health (OSH) laws like Ocupational Safety and Health Adminsitration (OSHA), it became evident that the Lebanese laws are broad, lack specifics, and use weak terminology. Moreover, the status of the OSH inspectors in Lebanon needs to heavily improved to better implement the OSH laws and improve the safety situation. Findings of this paper can assist researchers in further understanding the safety status of the construction industry in Lebanon and similar developing countries.

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Keywords: construction industry; health and safety; laws; Lebanon; OSHA

1. Introduction and Background

The construction industry is home to millions of jobs globally and has significantly contributed to the global annual Gross Domestic Product (GDP). Despite its importance for the economy, the construction industry continues to be the world's most hazardous industry. According to the data released by the Occupational Health and Safety (OSHA) and Eurostat, the construction industry is responsible for 1 in 5 deaths across the United States and the European Union [1,2].

The Lebanese construction industry is no exception to the safety and health hazards. The industry is an important sector to the Lebanese economy and workforce, accounting to 6% of the country's GDP [3]. More specifically, this sector employs more than 110,000 active nationals, aged 15 and above, thereby accounting for 9% of the total Lebanese labour force and 12% of the entire Lebanese male working population [3]. The last attempt at analysing occupational injuries in Lebanon concluded that the construction industry incurred the highest number of injuries among all other industries, taking up around 43.7% of all occupational injuries, and responsible for 1 in every 3 occupational deaths [4]. As such, the alarming rate of deaths incurred triggered a number of studies that attempted to assess the safety status of the Lebanese construction industry. Major findings from those studies are summarized in Table 1.

Table 1. Summary of major safety studies on the Lebanese construction industry

Reference	Findings
[5,6]	• The size of the contracting firm and the implementation of Safety and Health Management Systems (SHMS) are correlated: only large sized contractors and half of the total number of medium and small sized ones adopt SHMS. • Top management of the studied firms were found to have a will to commit to safety procedures but were not ready to allocate enough resources. • No relationship was found between the years of experience of the contractor and the SHMS implementation. New contractors in Lebanon are not shifting towards the adoption of SHMS despite the rise of safety awareness worldwide. • Consultants impose the use of an SHMS only if required by owners. Besides the minimum safety requirements set by insurance companies, consultants usually do not provide incentives for contractors to adopt safety measures, and only few penalize for safety breaches. • While most of the owners claimed that they require safety implementation on their projects, only few appoint dedicated administrative to visit and inspect the worksite in person. • Insurance companies indicated that they could not recognize whether contractors emphasize safety standards or adopt safety manuals.
[7]	• Lebanese health and safety laws are outdated, and the government is not enforcing SHMS. • No measures are taken by the Lebanese Order of Engineers and Architects (OEA) to protect the construction labour. • Laborers are rarely provided with personal protective equipment (PPE), seldom trained on SHMS, and a majority of them do not know their health and safety rights.
[8]	• More than half of surveyed projects did not have safety-certified or trained field supervisors on their construction sites.
[9]	• The study assessed the application of ergonomics in the Lebanese construction industry: workers expressed the pain they face while performing certain activities and indicated their lack of engagement in decision making.
[10]	• The study assessed the application of ergonomics in the Lebanese construction industry: workers expressed the pain they face while performing certain activities and indicated their lack of engagement in decision making.
[11]	• Few large-scale sites use visual tools and follow safety regulations. Less construction injuries were reported on jobsites using visual management (VM) practices. Despite this fact, the majority of engineers or project managers don't emphasize the use of VM techniques.
[12]	• Insurance companies and contractors have different perspectives when it comes to implementing safety on construction sites. • Insurance companies cannot hold contractors accountable for safety injuries, especially with the absence of a multiplier such as the Experience Modification Rate (EMR) in USA.
[13]	• Empirical analysis on non-fatal and fatal injuries incurred by the construction industry showed that "falls from ladders, stairs, and scaffolds" was the highest cause of injuries, followed by "struck by falling objects or equipment" and "falling on the same level due to tripping".

2. Objective and Methodology

Findings summarized in Table 1 highlight the major safety problems in the Lebanese construction industry. The lack of government enforcement, misuse of SHMS, and absence of insurance multipliers has put the construction labour at risk and worsened safety on jobsites. Therefore, the objective of this paper is to dive into the safety and health laws of the Lebanese construction industry and highlight weaknesses and areas for improvement. The findings are sought to benefit practitioners and academicians researching health and safety in Lebanon.

To achieve the objective identified above, the study addresses issues in three specific task areas: (1) review the state-of-art of the Lebanese safety and health laws, (2) highlight the weaknesses of the construction safety and health laws implemented by the Lebanese government, and (3) discuss the laws with four subject-matter experts from two insurance companies. The practitioners work with contractors and have a deep understanding of construction safety and health laws and injuries.

3. State-of-Art of the Lebanese safety and health laws

Lebanon regulates Occupational Safety and Health (OSH) laws following pieces of legislations [14]:

- *Decree No. 4568 of 1960* related to health care in the enterprises
- *Decree No. 136 of 1983* related to occupational injuries and emergencies, employers' responsibilities, workers' compensation and sanctions for violations
- *Decree No. 129/2 of 2001* related to OSH labour inspection in private establishments
- *Decree No. 11802 of 2004* related to OSH regulations and precautions in the enterprises
- *Decree No. 11958 of 2004* related to safety and protection in the construction industry
- *Decree No. 14229 of 2005* that lists occupational diseases

The entire list of the aforementioned OSH decrees applies to working personnel in all Lebanese industries and workplaces. This paper, however, aims at reviewing articles and dissecting areas of improvement that affect the safety and health of construction personnel in particular. As such, the emphasis is *on Decree No. 11958 of 2004* which is exclusive for the construction industry.

Decree No. 11958 of 2004 targets safety and protection on construction sites. It applies to all construction activities, installations, demotion, digging, modification, renovation, maintenance, cleaning, and painting works that are carried out from site preparation to project termination. The decree is also applied to horizontal projects including highways, railways, bridges, arcades and tunnels, all works under and above water, and service works such as installation, codification, repair, maintenance and/or removal of telecommunication lines, networks, sewers, water, electricity and gas pipes. The decree hosts 52 articles divided into 17 provisions summarized in Table 2.

In addition to Table 2, other important mentions are Articles 41 and 50. Article 41 explicitly states that in case of injury, employers should "make the arrangements of transporting the workers who suffer from an accident or an unexpected disease to medical care centres during working hours" and "notify the Ministry of Labour of the work injuries within 24 hours at the latest from the occurrence of the accident." As for Article 50, it states that "the inspection staff of work, protection and security in the Ministry of Labour shall be entrusted to supervise and control the execution of the provisions of the present decree".

To monitor the application of the safety and health laws on jobsites, Lebanon implements a "Labour Inspection System". The system is under the Lebanese Ministry of Labour, which part of its duties is to monitor workplaces and ensure the health and safety of employees (as regulated by *Decree No. 3273 of 26 June 2000*). As stated in this latter decree, the Labour Inspection System "ensures the supervision of compliance with regulation regarding conditions of employment, protection of workers including OSH".

According to Lebanon's Labour Inspection Audit [15], there is a total of 96 labour inspectors in the country, where 72 are generic or administrative labour inspectors and 24 are OSH inspectors. The 72 administrative inspectors are divided between 26 senior administrative labour inspectors and 46 assistant labour ones. The OSH inspectors are divided into 12 labour health inspectors and 12 labour safety inspectors. The health inspectors should be physicians with a bachelor's degree in medicine and a member of the Lebanese

Medical Association, while labour safety inspectors are engineers with a bachelor's degree in engineering and members of the Lebanese Engineering Association. These inspectors are distributed geographically across the country and rotate every six months. They perform periodic visits or urgent ones when complains are issued.

Table 2. Articles in Decree No. 11958 of 2004 by provision

Article	Contents
№ 1	Provides the list of provisions
№ 2	indicates that sites must be protected by a barrier where only people with direct relationship can enter. Sites should also be equipped with "vehicles, supplies and equipment" made of "safe and sound materials" as set by their manufacturer and in "good condition".
№ 3 – 11	Scaffolds should be erected under the supervision of a "competent and responsible person" with qualified and trained workers. Materials used in scaffolds should be of a "good kind" and "have a sufficient hardiness to bear load", so are the wooden pieces. Scaffolds should also have a minimum width of $1\ m$, surrounded by side barriers (minimum $90\ cm$ from scaffolds level) when the height is above $1.5\ m$ from ground level. Use of cast iron nails is forbidden, and mounting strong shields is necessary above passages to protect from falling objects. Finally, workers should be equipped with safety belts, and a "competent person" should maintain and inspect the scaffolds.
№ 12 – 16	Digging trenches or holes should start from the top to the bottom provided the sides "have sufficient inclination" and are pillared if the nature of the land warrants it. Earth should also be removed from the sides of the holes, which in turn should be protected from water leakage. As for demolition works, they should happen under the supervision of an engineer, starting from the upper floor. Walls and the parts in relief of the building must be underpinned" and the surrounding environment should be protected from dust. Finally, debris should not be thrown from the top of the building, and heavy loads should be manually elevated. Barrier should also be placed around digging locations and places where debris is accumulated.
№ 17 – 19	People are forbidden to work on roof inclinations that could make them slip, unless precaution is taken. Workers on the roof should be provided with safety belts or tied to the rood with "sufficient ropes". They should also have long years of experience and the "required mental and physical qualifications". Roofs should also be equipped with barriers of suitable heights, strong ladders or panels, and a pallet with at least $40\ cm$ in width suitable for work.
№ 20	Elevator and tractor machines: machines must be of "strong and safe structure" and inspected weekly by knowledgeable personnel. Each machine should have the maximum load limit posted on it in a language common to workers. It is forbidden to use machines to "elevate, descend, or carry" any person unless in case of emergency under the supervision of a competent engineer, and all machines that transport workers must have doors that can be "tightly closed" during operation.
№ 21 – 25	Portable ladders must be "made of safe material" with "sufficient capacity" to carry loads. Ladders must be also equipped with anti-skidding bases, and the distance between consecutive steps should not exceed $40\ cm$.
№ 26	For gaps, wells, earthworks, fissures inside the earth and the tunnels, proper measures should be taken to protect workers from collapse or earth drift (through pillars) and protect anyone or anything from falling in the work zone, ensuring ventilation and safe exits.
№ 27	All exhaust barrages and rooms designed for underwater works should be of an "appropriate, safe, and high resistance materials" with devices that ensure safe exit of workers. Operations are not allowed without the supervision of a qualified person, and inspection is scheduled by the authority.
№ 28	Construction of frameworks and formworks should be performed under the supervision of a "qualified person", precautionary measures should be taken to protect workers from possible hazards, and materials should safely support potential loads.
№ 29	For work activities under compressed air, workers should be qualified by passing a medical exam and only work under supervision from "competent" personnel.
№ 30	Precautionary measures should be taken to work involved above water to prevent fall of workers and rescue in case of fall. Also, "sufficient and secure" transportation should be available and necessary rescue means should be given to workers.
№ 31	States that arrangements, machines, equipment, and materials should be of "good design and production" and properly used.
№ 32	Employer is responsible to ensure protection from fire hazards, establish a fast and efficient firefighting process, provide "sufficient and appropriate" places to store flammable materials, and supply a "sufficient quantity" of accessible fire extinguishers.
№ 33	Explosives should be "stored, transported, handled or used" as specified by the law with the presence of a "qualified person".
№ 34	Workers should be "informed about the potential risks of security and health" and provided with enough directions and training to prevent the risks.
№ 35 – 52	Contents are labeled as general provisions. Main highlights include that site should be illuminated properly with red lamps in dangerous places, drain holes and opening must be surrounded by barriers of athletes $90\ cm$ in height, employees can stop working if they feel safety or health threats, and owners should provide potable water, sanitary facilities, and suitable places to wash, change clothes, and eat. Owners should also provide suitable safety training, first aids kits, and "glasses, gloves, hats, belts, shoes and other protective clothes" to protect workers from falling, tripping, getting struck by objects, and electrocution.

When it comes to construction sites, there are engineering inspectors who perform visits with the help of assistant inspectors. If the inspectors notice any safety and/or health violation while on-site, they issue a warning letter to the enterprise to remove the violation within a notice period, else the enterprise would be fined a penalty (e.g., $167 within the first 15 days and $1667 thereafter, assuming $1=$1,500LL) [15].

4. Discussions

4.1. Weaknesses of the Lebanese Construction Safety and Health Laws

The examination of the current construction safety laws has further highlighted the gravity of the safety situation in Lebanon. The decree is short, brief, and written in a broad manner. The entire decree has barely five specifications shown in articles 6 (width of scaffold), 7 (heights for barriers), 19 (width of roof paddle), 24 (steps distance in ladders), and 40 (height of lateral barriers). Most of the used terminology is “good quality” to describe materials, “qualified and competent” to describe engineers and/or inspectors, and “sufficient and strong” for machines and equipment. To further attest to that, RStudio ® was used to generate word-clouds with the most frequent words and bigrams mentioned in the decree (Figure 1). It turned out that the most frequent words were “work” (21 occurrences), followed by “building” and “materials” (20 occurrences), then workers (19 occurrences) and “necessary” (23 occurrences). As for the most frequent bigrams, they were “building site” (9 occurrences), “precautionary measures” (8 occurrences) and “qualified person” (6 occurrences). All the terms shown are not well-defined and properly explained when used in the articles.

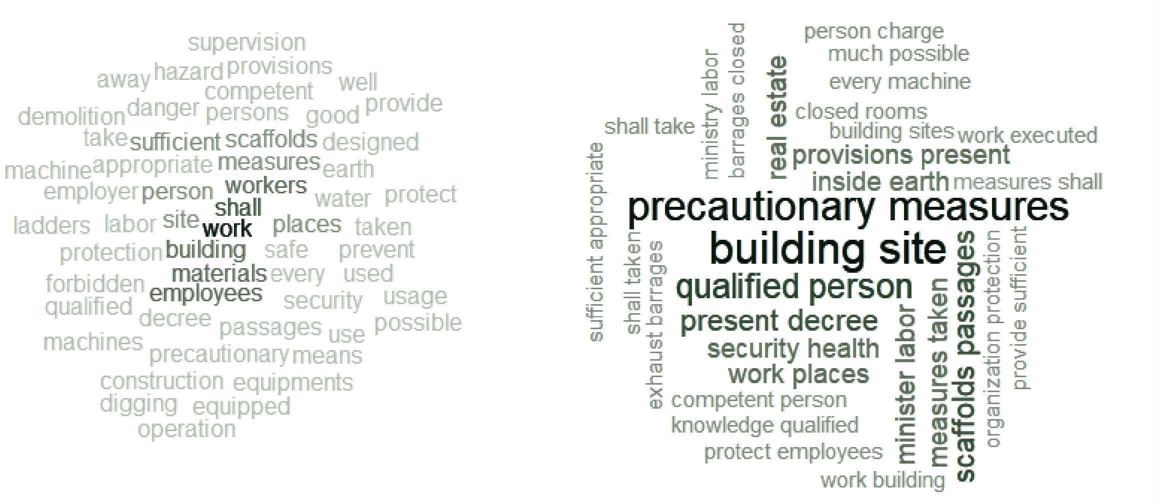

Figure 1. Word-Clouds with the most frequent words (left) and bigrams (right) in the decree (generated using RStudio)

The decree lacks even more when compared to foreign OSH laws like OSHA. Two major differences are highlighted in [6]. The first is related to the design of scaffolds. While OSHA offers extensive scaffold design guidelines with major specifics (i.e., each scaffold component should support its own load and four times the load it is intended to carry), the Lebanese law states that scaffolds should be designed with “good quality” and should be “sufficient to carry the applied loads”. The second example is related to excavation. While OSHA specifies that excavation should be sloped at an angle not steeper than 1. 5H:1V and excavated soil stored at least 0.6 m away from excavation, the Lebanese law does not provide any single specification and does not require protective systems.

Other differences not mentioned by [6] exist. For instance, the Lebanese construction law does not mention the use of cranes. Upon looking into other OSH decrees, it was found that the topic of cranes is covered in *Decree No. 11802 of 2004*, alongside other construction relevant topics like the use of chemicals, noise releases, and fixture of hedges. However, just like the construction *Decree No. 11958 of 2004*, it uses a very broad terminology. In fact, the cranes section is limited to having a licensed crane operator who is “medically fit”. OSHA, on the other hand, dives into details such as operation, assembly, disassembly, power line safety, and ropes inspection.

Another topic worth of comparison is safety training. Unlike the Lebanese laws which only specify "qualified personnel" to do hazardous tasks, and "sufficient and suitable training" to be provided for workers, OSHA's safety training standards are detailed, extensive, and specific to different tasks. OSHA has a general safety training and education section targeted at training for hazardous waste operations, scaffolds, steel erection, falls, ladders, and cranes [16].

Other notable missing information is in the area of safety communication. The decree does not provide provisions related to conducting and communicating safety audits within construction companies, site-specific safety orientations, recommended on-site safety meetings, leadership and disciplinary programs, safety analysis during constructability reviews and scheduling projects, project health and wellness reviews, evaluations of safety performance for on-site personnel, tracking and investigating near misses, rewards and incentives, and engaging employees in decision-making especially for hazard assessment and safety planning. Incorporating such provisions in the decree can encourage construction companies to further implement safety practices and highlight the importance of communication and training [17].

In addition to that, there is a lack of proper safety inspection in Lebanon. OSHA reports in its Commonly Used Statistics [18] that there is a total of 2,100 safety and health inspectors across the country for around 130 million workers. This averages to 1 inspector for every 59,000 workers. In Lebanon, there is 1 inspector for every 8,500 employees[19]. Nonetheless, inspectors in Lebanon face different burdens that complicate their jobs [15]. First, when recruited, new inspectors do not undergo any official training or program but rather perform site visits with senior inspectors. Second, assistant inspectors are not required to hold any bachelor's degree or OSH training diploma, thereby rendering them inexperienced for the role. Salaries of assistant inspectors are rather low, estimated at $707 while those of seniors can go up to $967 [15]. The low salaries are not even backed up with any sort of benefits which lead inspectors to search for other sources of income and work in other places. The rotations that happen every six months are done randomly, causing some inspectors to land in the same areas several times. This, in turn, becomes a burden for some who end up working far away from their places and incurring higher costs, a serious situation especially with the absence of monetary benefits. Moreover, when conducting an inspection, inspectors use a mere one-page inspection checklist. Unlike the OSHA inspection papers – which have a very detailed layout with checklists extending on multiple pages and including details such as scaffolds, personal protective equipment, cranes, forklifts, etc. – the Lebanese checklist is mainly made up of 4 sections namely: general information about the enterprise, services and benefits provided to workers, findings of the inspector, and outcome of visit. This pushes the inspectors to rely on their memory and experience in-lieu of the actual laws, thereby increasing the chances to overlook hazards and safety violations [15].

4.2. *Input from Insurance Companies*

In addition to described weaknesses, it was reported that insurance companies do not recognize whether contractors emphasize safety standards or adopt safety manuals [6]. Moreover, issuing or renewing premiums depends on the contractor's history of accidents [6]. Thus, another area warranting discussion is the perspective of insurance companies on construction safety and contractor premiums.

Thirty-minute semi-structured interviews were conducted with four professionals from two insurance companies to further understand premiums and laws. According to them, issuing premium rates depends on the size of the project and the time it takes for completion. Other factors such as the contractor's payroll and the number of laborers working on site are considered. However, these inputs cannot be validated. As a matter of fact, contractors can hide the correct number of laborers assigned on site to decrease the premium rate. After completion of the first year, premium rates increase or decrease based on a loss ratio. This loss ratio can be summarized as the ratio of cost incurred by the contractor during the year to the net premium paid by the contractor. This total includes the direct and indirect costs for non-fatal injuries, lost wages due to injuries ($30/working day for skilled labor and $25/day for unskilled labor), fatal injuries and related compensation, etc. For example, a contractor paid a total premium of $100,000 for a project. The net premium is calculated by subtracting the indirect costs (such as paperwork, governmental fees, etc.) from the total premium. Assuming the indirect costs in this example are $15,000, the net premium would be estimated as $85,000. At the end of the first year, the contractor incurred claims at a total cost of $25,000. The loss ratio would therefore be around 29.5% (i.e., 25,000/85,000=0.294). According to interviewees, if this loss ratio remains below 75% (as opposed to 50% in other countries such as the United Arab Emirates according to one of the interviewees who worked in Dubai), contractors would not be charged higher premiums. Moreover, the considered incurred costs are usually those of frequent claims. In other words, if one or two severe costly incidents were reported during a year, they would not be considered when calculating the loss ratio. However, if a contractor incurred frequent claims, then the entire total needs to be considered.

Different problems were discussed with interviewees concerning the safety and health laws. To begin with, *Decree No. 136 of 1983* stipulates the employers' responsibilities in cases of occupational injuries and corresponding compensation and workers' entitlements. It also stipulates the sanctions in case of violations. This decree hasn't been updated since 1983. The compensation for lost wages depends on this decree, so is the compensation for any death. Families of foreign labor who dies on construction sites get paid very low amounts (ranging between $5,000 to $8,000), which is cheaper compared to money compensation in case of major or severe injuries. This decree was then followed by *Decree No. 11802 of 2004* (Regulation of OSH in the Enterprises which includes the OSH requirements and precautions that employers should implement in their workplaces*), Decree No. 11958 of 2004* (Safety and Protection in Construction), and *Decree No. 14229 of 2005* (Occupational Diseases' Table). However, these decrees were not fully implemented at the beginning due to the dire political situation in Lebanon back in 2005.

The current premium injury exclusions and construction safety regulations are set by insurance companies based on *Decree No. 11958*. For example, insurance companies recommend using safety boots on sites and exclude stepping on a nail from the covered injuries. However, when this injury happens, contractors tend to always justify such mishaps by pinning it on workers' actions (e.g. the boot was not properly worn or loose, or even completely removed for religious reasons). Unless the cost of the claim is high, insurance companies do not typically investigate the reasons of the injury to avoid legal costs. It is worth noting that the competition among insurance companies is also a significant factor that affects premiums. For instance, one of the respondents noted their company decided to stop covering eye injuries from welding and discharged particles if workers on-site were not wearing safety glasses. However, the company revoked its decision when contractors threatened to head to other companies that provide unconditional coverage. This sheds a light on another major problem: when contractors move from one insurance company to another, there are no existing multipliers like the Experience Modification Rate (EMR) that are computed to reflect on the contractors' history with injuries that would ruin their reputation.

Additional problems faced by insurance companies include the abuse of the insurance premiums. As aforementioned, the insurance companies are not aware of the on-site workers' names and do not typically investigate accidents. This a loophole whereby some workers, not properly monitored by inspectors or engineers, make use of their medical insurance to medicate instead their family members or friends whenever injured.

All the above very much illustrates the safety status of the Lebanese construction industry whereby contractors can cheat the system instead of enforcing on-site safe practices to limit accidents and injuries, and workers abuse their insurance plans to benefit their family members and friends.

5. Conclusion, recommendations, and future work

The paper reviewed the Lebanese safety and health decrees affecting the construction industry. The decrees are written in a generic, broad, and vague form which may not force contractors to abide by safety protocols, especially in the absence of a proper labour inspection system. It was found as well that the decree misses on several areas including safety communication, training, engaging workers in decisions, and investigating near misses. Accordingly, it is recommended that the government take bold actions to update the safety and health laws and empower the inspection system on construction sites. Moreover, it is advised that Article 41 of Decree 11958 of 2004 be immediately enforced to push construction companies in reporting injuries. Such continuous reporting can help build a better national database in the Ministry of

Labour that keeps track of the annual injuries incurred by the construction industry. This can thereby allow researchers and practitioners to regularly investigate the nature of the injuries and understand the state of safety in the industry. In addition to that, insurance companies should implement a multiplier like EMR that is adopted in the United States. This can help expose construction companies that do not abide by the safety regulations and standards and restrict them from undergoing major projects.

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Best Practices for Essential Infrastructure Workers during Contagious Illness Outbreaks

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Abstract

The transportation system plays an important role in society and communities, enabling personal mobility, as well as freight movement, which is required to maintain the supply chain, ensure store shelves are stocked, and ensure the movement of medical supplies and other goods required for essential workers. In the U.S., much of the roadway transportation system is maintained by local agencies; many of these local agencies also provide essential services such as trash collection and water services for the community. In the U.S., workers that support critical infrastructure are considered essential workers and, in most cases, their work did not stop even when stay-at-home orders were issued during the recent Covid-19 pandemic. As true for most organizations, these agencies did not have detailed plans, hazard assessment or safety protocols for contagious illness outbreaks and as a result many agencies were not well prepared to properly protect worker health and safety. This paper discusses the role and classification of essential workers in the U.S.; this is important since it has an impact on which workers continued to work during the pandemic and which workers ceased to work during stay-at-home orders. This paper also documents how local agencies managed their on-going work during the pandemic, including results from a survey of local agencies during the height of the pandemic and four case studies describing innovative practices and challenges, as well as the information and materials needed to work effectively during the pandemic. This paper also provides a discussion of activities that can be undertaken to prepare for any future contagious illness outbreak.

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Keywords: Covid, Contagious Illness, Infrastructure Workers, Essential Services, Pandemic, Essential Workers

1. Introduction

Local highway and street departments play an important role in the daily lives of all citizens, ensuring the transportation infrastructure is available to ensure personal mobility, as well as freight movement, which is required to keep store shelves stocked and ensure the availability of medical and other critical supplies. Many local street and highway departments also provide essential services such as trash and recycling services, which are vital for all citizens and for the community. Workers that support critical infrastructure were considered essential workers during the Covid-19 pandemic and in most cases the work of the local transportation agencies did not stop, even when stay-at-home orders were issued.

Covid-19 has had a dramatic impact that has touched virtually every industry sector. The impact includes individual health and practices, community health, workplace practices, education, business, travel, supply chains, and local, regional, national and global economies. This paper documents survey results and practices employed by local agencies. The survey results were used to determine what information the local agencies needed and to provide support during the height of the pandemic. The best practices are illustrated through case studies and lessons learned.

The survey reflects responses from local highway and street departments (a.k.a. local agencies) in the State of Indiana in the U.S. The survey was implemented during the height of the pandemic to determine the local agencies' greatest needs including how best to protect workers and continue operations. The pandemic was unprecedented and differed significantly from other emergencies in terms of the duration, hazards and preparation; local agencies were asked if they had developed a plan for operations, had identified essential tasks, and had developed procedures to identify at-risk employees. Case studies of effective local responses to Covid-19 operations during stay-at-home orders were completed via virtual meetings with four local agencies. These case studies resulted in useful information regarding how local agencies had adjusted their operating procedures to safely complete essential tasks. The information from the survey, case studies, and findings from additional research regarding work procedures as published by health organizations and construction associations were quickly distilled into a set of best practices for operations and shared with local agencies to support operations.

2. Essential Infrastructure Workers

Transportation workers can be considered essential critical infrastructure workers as defined by the U.S. Department of Homeland Security [1]. Table 1 provides a summary of essential worker job responsibilities that are common for local agencies in the U.S. Operations and services include maintaining and repairing critical infrastructure, working construction, and supporting critical supply chains and critical infrastructure. In addition to transportation and logistics, some local agencies have responsibilities for water and wastewater and public works, which are also essential activities.

Table 1. Summary of Essential Work Responsibilities

System	Essential Work Responsibilities
Public Works and Infrastructure Support	Workers who support the construction, maintenance, or rehabilitation of critical infrastructure
	Workers who support the operation, inspection, and maintenance of essential public works facilities and operations
	Workers personnel, who support operations that ensure, the availability of and access to needed facilities, transportation, energy, and communications through activities such as road and line clearing
	Workers who support the effective removal, storage, and disposal of residential, industrial, and commercial solid waste and hazardous waste, including at landfill operations
Transportation and Logistics	Workers supporting or enabling transportation and logistics functions
	Workers supporting operation of essential highway infrastructure, including roads, bridges, and tunnels
	Mass transit workers providing critical transit services and performing critical or routine maintenance to mass transit infrastructure or equipment.
Water and Wastewater	Operations at Water and Wastewater Treatment Facilities
	Repair of Water and Wastewater Conveyances
	Performing required sampling or monitoring
	Operational staff for water distribution and testing
	Operational staff at wastewater collection facilities

3. Survey Results

A survey of local agencies was initiated soon after stay-at-home orders were issued in the U.S. In the State of Indiana, most local agency tasks were considered essential work, although local agencies in some counties and cities ceased work during the shutdown, per the decisions of local officials.

Survey results are based on 50 responses from local agency supervisors. Results indicate the most important Covid-19 topics are as follows (additional information shown in Figure 1). These are the topics that agency personnel said they would like additional information on.

(1) Response to positive employee Covid test.

(2) Interaction with the public.

(3) Communication with employees.

(4) Essential vs. non-essential work tasks.

Local agencies also provided information regarding where they were getting resources to support workers during the pandemic. The following resources were most often used by local agencies:

(1) The city or county. In most cases, the local agency resides within the city or county. Use of city or county resources ensures consistency with local policies. During the pandemic, local policies sometimes varied significantly depending on the jurisdiction.

(2) The U.S. Centers for Disease Control and Prevention.

(3) The Indiana Local Technical Assistance Program (LTAP). LTAP is an extension service for the State of Indiana to assist local agencies with resources for managing infrastructure. Every state in the US has a Technical Assistance Program, but the size of the program and the reliance on the program varies significantly from state to state.

The majority of local agencies (37 out of 50 representing 74%) were operating with a Covid pandemic plan; this plan was either based on the plan for the city or county, or was based on the activities within the street and highway department. It is notable that almost twenty percent of local agencies (9 agencies representing 18% of respondents) did not have a plan and thought it would be useful to have a plan to guide their activities.

There were a variety of concerns that arose while continuing to work during the pandemic shutdown. The top concerns included the following (all responses are shown in Figure 2):

(1) Managing employee work shifts and work crew modifications. It was important to try and reduce interaction between employees to reduce exposure, but maintain functional capabilities. Reducing exposure was important to reduce exposure for individual employees, especially employees with secondary health issues or family members with secondary health issues. Reducing exposure was also important to ensure entire workplace competencies would not be compromised. For example, if all mechanics work in the same garage and are exposed to the virus, the agency may lose all the mechanics at once.

(2) Human resource and legal issues. Requiring essential workers to report to work when the rest of the county is shut down during stay-at-home orders presented potential challenges to supervisors and affected workers. These considerations were amplified by daycare and school closings, as well as ambiguous and changing protocol regarding quarantine rules.

(3) Safety of the workplace. Workplace safety is a top priority for all local agencies, and expansion of safety considerations to include health considerations presented additional challenges. This was especially true during the height of the pandemic when there was significant uncertainty regarding transmission and preventative strategies such as masks. Program guidance for safety was exacerbated by changing mandates for mask use and related recommendations.

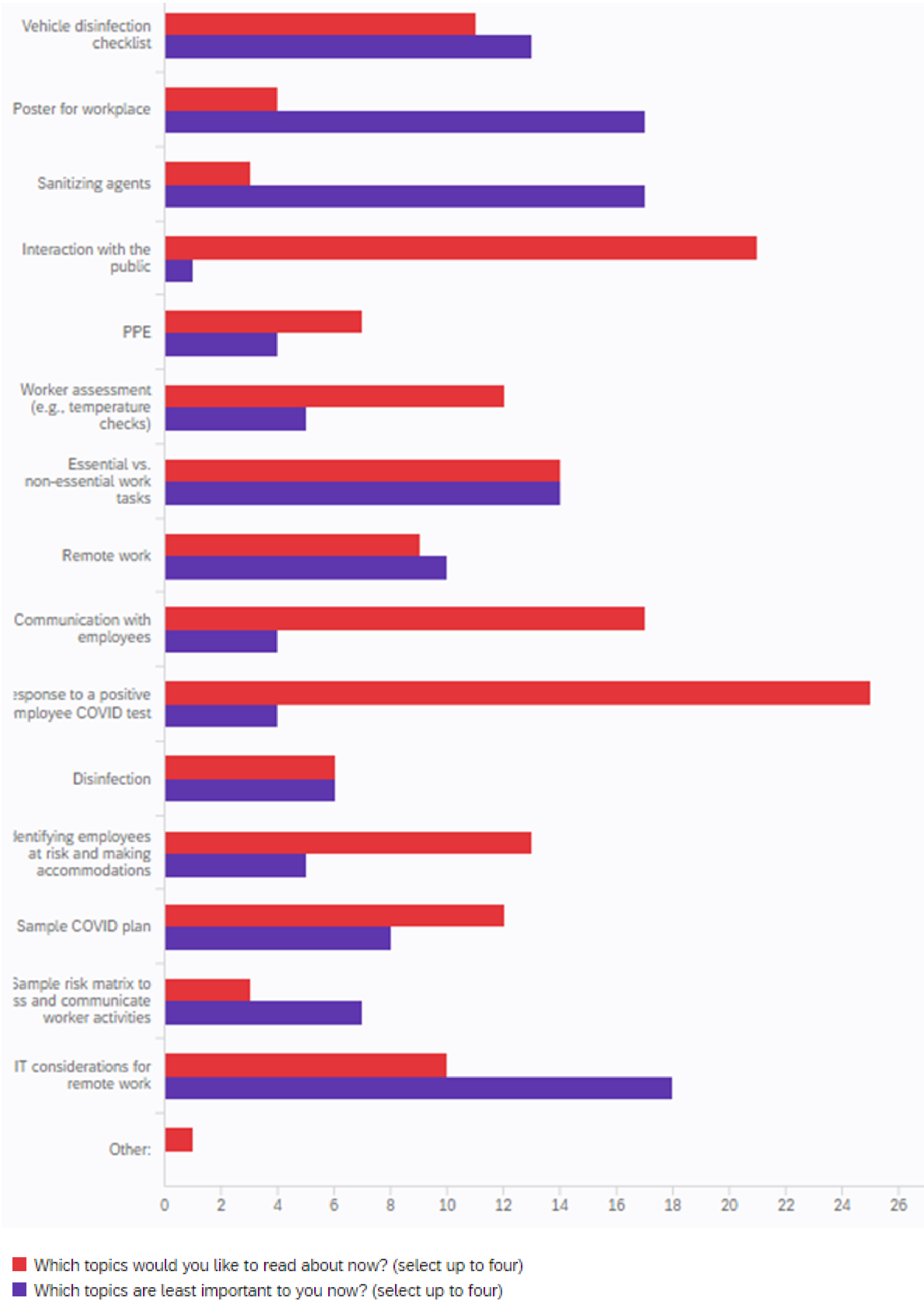

Fig. 1. Most Important Topics Related to Contagious Illness Outbreak

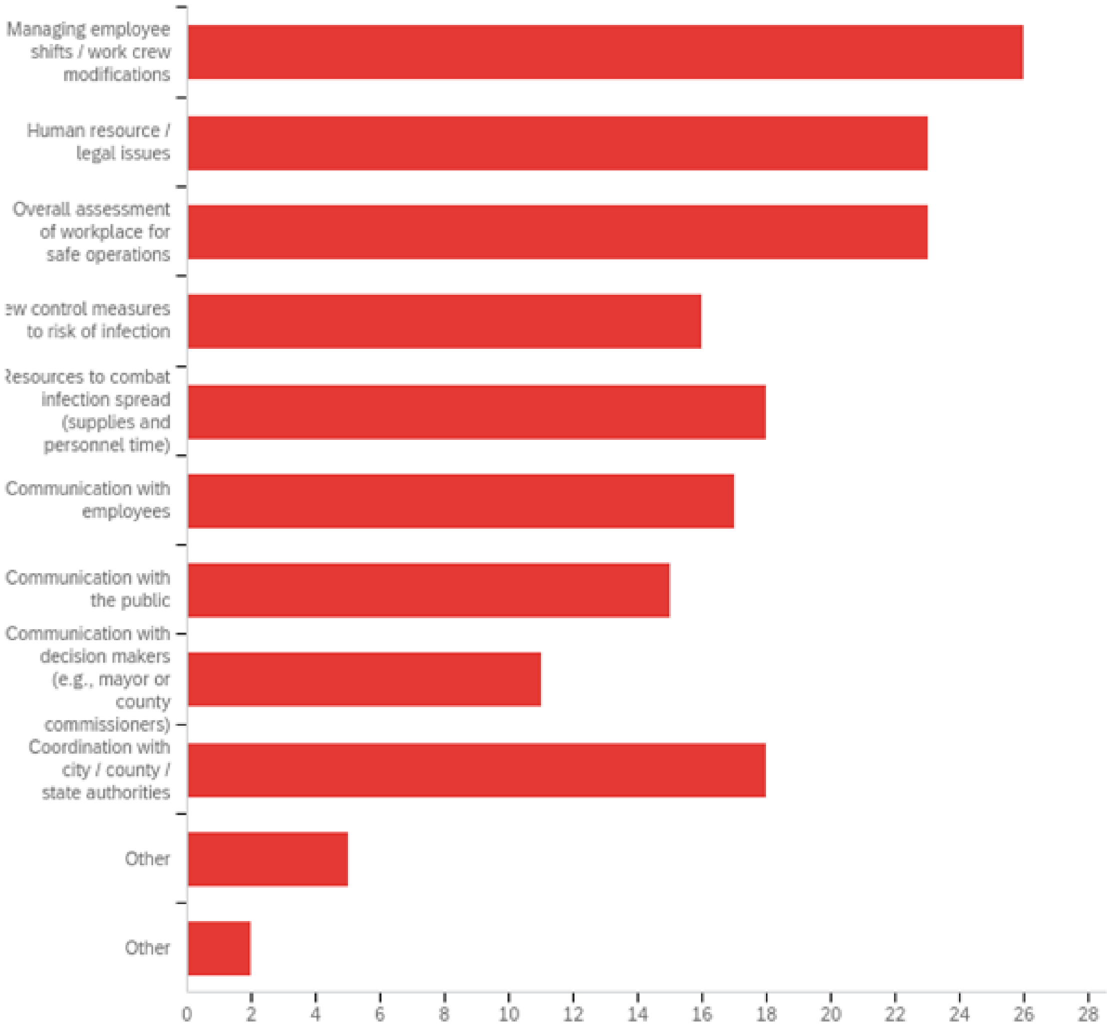

Fig. 2. Greatest concerns related to working under Covid restrictions

Local agencies were asked about procedures to identify employees who were at higher risk due to Covid. The majority of agencies had a framework to identify at-risk employees; the agencies had either developed these at the agency level or they relied on the city or county system to support these efforts.

4. Case Studies

Interviews with four local agency supervisors were conducted to get more information about how local agencies responded to the pandemic and supported worker health while maintaining operations. From these interviews, short case studies were developed to highlight effective work procedures that could be shared with other local agencies. Some of the key findings are noted below.

4.1. Limit worker exposure by reducing shift size

Work crew modifications were implemented to reduce potential exposure. At one agency, the agency transitioned from one shift each week (pre-pandemic) to two shifts that alternated each week. This work crew modification reduced the number of people each person was exposed to, which increased safety. This change also increased the likelihood that workers would be available to carry out essential functions. Splitting the work crews into smaller shifts and reducing overlap between shifts reduced the possibility that all workers would get sick at the same time, which would disrupt the agency's ability to carry out essential functions. When working with split shifts, capabilities of each worker were considered, so that each shift group had someone that could safely operate all necessary equipment during the week.

4.2. Adapting Work Duties and Schedules to Accommodate Employee Constraints

There were a variety of considerations that affect shift assignments and on-going scheduling. In addition to considerat0ion of workplace needs such as capabilities of each employees, it was necessary to consider the needs of individual employees, including scheduling and health considerations. In some cases, employee shift assignments reflected requirements for childcare drop-off and pickup. Since there was no in-person school during stay-at-home orders, some schedules needed to be modified to accommodate home schooling. In other cases, employee health considerations affected assignments. Employees who were more vulnerable due to age or health conditions were assigned to duties that could be done alone and did not require close interaction with other employees. All employees, particularly those who were more vulnerable, may choose to take breaks and eat lunch outside rather than in the break room, which also reduces exposure.

4.3. Electronic Bidding Eliminate Face-to-Face Bid Openings

Many local agencies have traditionally had a requirement that construction and other bids be opened in person, which resulted in numerous people coming to the bid opening. Electronic bidding moves all of the bid submissions and bid activities online, which significantly reduces face-to-face interaction. In most cases, the transition to electronic bidding was implemented at no direct cost to the city, since the vendor providing the electronic bid capability recovers their costs by charging for downloads and for bid submittals.

4.4. Smartphone Clock-In Improves Productivity and Reduces Congestion near Time Clock

Many agencies traditionally required workers to clock in using a standard time clock. This results in congestion at the time clock since workers must clock in and out every day. To minimize congestion for clocking in, one local agency worked with their information technology department to allow remote clock-in via smartphones. Workers were able to clock in from the site of their first assignment rather than the agency time clock. For example, workers who were mowing a park or a school first thing in the morning would report directly to that park or school, and clock in from that location. This also improved productivity since the workers clocked in at the job location rather than coming into the main office first.

5. Best practices

To support the local agencies, a series of best practices were developed based on the local agency needs as determined by the local agency survey. The best practices utilized information from health organizations and construction associations. The construction focused best practices are provided below. In some cases, these national best practices align closely with the case studies describing tactics that local agencies have taken.

5.1. Field work considerations

A common issue amongst local agencies was recording employee time worked for the purpose of calculating weekly earnings. Rather than have workers clock in directly at the agency local headquarters, it was useful for workers to report directly to their first field location. This reduces congestion at the central location (and reduces interaction amongst employees) and increases efficiency by reducing travel time. While some local agencies use electronic methods for clock-in (such as a smart phone app that allows remote clock-in from any location with GPS), other local agencies confirm attendance throughout the day by having supervisors visit the work sites.

In some cases, the public would approach workers doing field work, distracting them from their work and exposing them to the public. Some agencies also found it helpful to remind the public that workers in the field have a job to do, and questions about service should be handled via the phone or the internet, rather than via conversations with employees working in the field. These reminders for the public can be shared via the internet, newsletters (including e-newsletters), and other channels.

5.2. Limit worker exposure

Limiting worker exposure to others is an important way to reduce the spread of a contagious illness and there are a variety of ways to help reduce worker exposure. Worker exposure can be limited by modifying work schedules, compartmentalizing work crews, reducing multi-person jobs (when possible), and modifying work space to ensure each person can keep an adequate distance from others. Modifying employee arrival times, break times, and departure times can reduce close contact and interactions between employees, and thus limit employee exposure to contagious illness. Modifying arrival times may also accommodate the extra time required for employee health screenings, such as a temperature check and brief questionnaire regarding symptoms. Having employees arrive in a staggered approach limits the number of people waiting in one area at any given time [2]. Shift changes may also be appropriate, including the composition of each shift, the timing of the shift, and increasing the number of locations where workers report for their shift to reduce congestion.

Many local agencies implemented shift changes. There are multiple ways to split up shifts and utilize new locations for employee arrival. For example, workers could rotate on a weekly basis with two full-time shifts of workers. Each crew reports to work on alternate weeks, cutting in half the number of people at work on any given day. This strategy may be especially useful if work is focused on the most essential tasks, and other duties are postponed. Another option for high exposure jobs is to implement 4-day work weeks to reduce the number of days that have everyone at work (AIHA, 2020).

With any new schedule changes or other changes to accommodate social distancing and crew separation, it is important to notify all employees of their new schedule. It may be helpful to provide workers with graphics to illustrate the changes; visuals may be easier to reference and may help all workers understand the new system. It is also helpful to provide the reasoning behind the schedule change, and emphasize that it is intended to support their safety, which is most important. Changes in schedule can be confusing, and may present other challenges such as childcare arrangements.

5.3. Reduce crew size

Another precautionary measure to limit worker exposure is to divide employees into smaller work crews. The purpose of these smaller crews is to limit the number of people each worker is exposed to and to ensure that work can continue if an outbreak does occur within the agency. The interaction of each employee is limited to other members of their crew; everyone still practices appropriate physical distancing and avoids having any contact with members of other crews. When dividing the workforce into crews, ideally, each crew would have a breadth of skill sets, and range of experience levels. Distributing people with specific skills to all crews helps ensure that if there is an outbreak in one crew, other crews will not be affected and operations can continue. It is best to keep crew sizes small to limit the exposure of all employees.

It may also be helpful to consider whether there are any employees who are at a higher risk due to medical conditions or personal circumstances. It may be appropriate to have vulnerable employees perform individual tasks, rather than work with a crew (even if the crew is small). Agencies can have employees provide the results of a self-assessment in which case they self-identify as being at higher risk without disclosing why their risk is elevated.

5.4. Limit Workers in Small Areas

Another important way to prevent illness spread is to limit the number of workers in a small work areas, including breakrooms, vehicles, and small offices. For construction work, there are often needs to transport employees via vehicle to and from the jobsite. Limiting vehicle sharing will help to reduce worker exposure. If possible, it is preferable to have only one person per vehicle, and avoid ride sharing. If ride sharing is necessary, separate passengers as much as possible, and make sure all passengers wear face coverings and open the windows to increase ventilation [3].

5.5. Cross-train teams

Cross-training workers for additional job functions will support essential operations with a reduced work force. After identifying the essential tasks, assess the capabilities of employees and each work crew to identify the skills needed (and missing) in each work crew, as well as employees with the required skill who can provide cross-training. Employees should consider this an opportunity (rather than an obligation) and it should be presented as such. Benefits to cross training extend beyond the continuation of work if an outbreak occurs; cross-training provides lasting benefits and enable employees to learn new skills, and be more productive. Cross training also allows workers to conduct a variety of tasks which reduces physical and mental fatigue associated with doing the same repetitive work [4].

5.6. Job Hazard Analysis

Job hazard analysis is an important activity to identify activities that present the greatest risk. The results of job hazard analysis ensure resources and appropriate modifications can be focused on activities that present the greatest risk. It is important to involve employees during the job hazard analysis process. Involving employees is important since employees have direct knowledge as front-line workers; it is also important because employees are more likely to support and implement result changes that result from the process if they were involved. In this case, the job hazard analysis focuses on the risks associated with the spread of a contagious illness [5].

6. Conclusion

The Covid-19 pandemic presented a variety of challenges for local agencies tasked with maintaining local infrastructure and other essential duties. This paper documents the challenges that local agencies faced, provides insight into the issues through survey results, and identifies innovative solutions through case studies and best practices. Documenting the issues of the pandemic is useful for historic purposes, as well as to provide a resources in the future when agencies must deal with working through a contagious illness. Some agencies have been very innovative and changed their approach to employee health and the workplace. For example, the Indiana LTAP has taken the initiative to include training on contagious illnesses as part of their annual snow plow training since the flu season overlaps with snow season.

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Effects of Virtual Reality Safety Training on Critical Construction Accidents

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Abstract

Lack of safety training in construction sites is one of the main causes of construction accidents. This article provides a comprehensive and critical overview of the literature on the impact of virtual reality safety training on reducing the risk of construction accidents. First, previous research literature was reviewed, and the most dangerous and frequent construction accidents were extracted. Then the impact of safety training through virtual reality and traditional training in these accidents through questionnaires and interviews with experts were compared. The purpose of this article is to determine whether virtual reality education can play a more effective role in the safety of high-risk accidents such as falls, fires, slips, electric shocks, etc. This study shows that virtual reality in safety training for workers in some construction accidents can be more effective than traditional training and help increase the safety of projects and reduce the risk of accidents.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2022.

Keywords: Virtual Reality, Safety Management, Construction Projects, Training, Safety.

1. Background

1.1 Construction Safety

Today, the project environment is variable, and there is a lot of uncertainty in them, which leads to the occurrence of many safety risks in different stages of project implementation (Occupational Safety and Health Management System, 2021). Extensive research in this field has shown that the complex and dynamic nature of the construction industry is one of the main reasons for the high number of losses in projects. Because each construction project is unique, identifying all possible risks in one project and managing them will not be a reason for the prevention of other accidents in other projects (Ajar, 2017). As one of the accident-prone industries, construction is always associated with these risks and dangers (Panahi and Khanzadi, 1397). Risks related to the HSE field in the project construction process are among the safety risks that are mainly overlooked in the construction and implementation stages of construction projects and may lead to numerous damages, both in terms of time and cost (Segora et al., 2007). With the implementation and establishment of a safety management system in construction projects, many risks and accidents in project implementation operations have been identified. Based on this, it will be possible to provide appropriate solutions to reduce risks before potential hazards occur (Zhao and Lucas, 2018). The establishment of a safety management system in job site spaces of various industries, especially construction industry projects, has become one of the most basic needs of projects today. Providing preventive solutions simultaneously to health, safety, and environmental issues on the job site and eliminating similar activities due to technical and economic balance facilitates the increase of human resource productivity (Pham et al., 2018). Despite the benefits of implementing safety management in construction projects, the lack of knowledge of designers about the requirements, lack of considerations for creating a safety management system, and the lack of new tools and technologies in the design phase of construction projects can exacerbate the safety status (Zia Shams and Majrouhi Sardrood, 2017). Identifying, controlling, and managing various safety risks and hazards in the architecture, engineering, and construction industry is a global issue that has been considered by many researchers in the construction industry today. Failure to comply with the rules and standards and proper control of safety risks not only may lead to many problems in projects to achieve their goals but also will affect land use planning and design of useful construction spaces in the future growth of cities. In recent years, various construction technologies have been developed to provide new ways to increase safety management throughout the project life cycle, the primary purpose of which is management-based safety (Ahan et al., 2020). These technologies help identify human errors at every stage of the project life cycle and suggest preventive measures to prevent them from occurring during construction accidents. Since 1991, various studies have shown that the possibility of linking design systems such as CAD and the process of planning and safety management in construction projects is possible (Wang et al., 2018).

1.2 Virtual Reality and Safety

Due to the rapid development and adoption of the virtual reality system, the use of these technologies for safety risk management has become a growing research process. It has attracted the attention of many researchers to use virtual reality applications in the safety management of the manufacturing industry. This issue increases the demand for reviewing and analyzing published articles and resources in this field to identify and evaluate past research and develop strategies for conducting improved research on virtual reality-based safety management. Therefore, after reviewing the literature on the subject, this study tried to review and identify the research conducted in virtual reality-based safety risk management in construction.

In their research, Pham et al. (2018) designed a building safety tool based on a virtual reality visualization system that could efficiently consider the safety of designers and builders in different phases of the project. In the proposed model, all potential hazards and risks in the project construction process were identified and collected. Then a complete dictionary and a constraint model to avoid high-risk tasks were stored as a design platform. Afterward, monitoring employees' safety closely by using the software package and reviewing the proposed model in the project's construction phase was possible. The tool also allowed architects to provide optimized plans to minimize safety hazards and risks during project construction. At the same time, builders could take protective measures to eliminate construction hazards from the start of the project. Therefore, in both the design and construction stages, using this tool for safety management would significantly improve the safety of the builder (Pham et al., 2018). Tavaneli et al. (2015) examined the development and application of automated safety management rules and frameworks using the virtual reality approach. A construction information model was developed to automatically detect hazards and safety risks and propose preventive measures for users in the face of falling hazards in the project. As a result, the development of an automated safety platform informed building engineers and managers by reporting location, time, and safety precautions to prevent falls from a height in the project before construction (Tavanli et al., 2015). In their research, Zhao and Lucas (2015) examined the use of virtual reality in the construction industry by focusing on the relationship between this technology and health and safety management in the project. In this study, in addition to a comprehensive review of the research literature, using a questionnaire, information was collected about changing health and safety planning in relation to the virtual reality environment for site professionals. The results of the questionnaire response analysis in this study showed that virtual reality was able to improve organized planning for health and safety management for different project personnel. The results of this study also showed that to create a safe environment in construction projects, virtual reality should be integrated with health and safety management systems and used on construction sites (Zhao and Lucas, 2015).

Studies conducted by Ahan et al. (2020) on safety studies showed that understanding the properties of virtual reality as a useful and unique tool for safety management has not received much attention. The results of this study also indicated that there are only 21 types of innovative applied technologies and six documents related to the use of virtual reality in security management (Ahn et al., 2020). In another article, Sackes et al. (2013) examined the risks and potential risks of falling from heights in construction projects and evaluated how to identify and eliminate these risks in the early stages of construction project planning using the virtual reality approach. They developed a framework that included automated safety control algorithms through virtual reality. The prototype developed in this project was tested in a residential project. The first case study showed a comparison of the model of achieving an automated safety system through protection systems. In this study, the details of the design and construction of safety devices were also investigated. The second case study showed the results of using the project schedule framework. In particular, this study simulated the project's detection and prevention of falls from a height. The contribution was an automated legal control framework that linked safety to the impact and role of virtual reality and introduced professionals to a way to identify and prevent hazards associated with falls in projects. This article also discussed the commercialization of the prototype and the considerations of the developed framework, the understanding of which could have a significant impact on solving safety issues and the development of traditional safety management practices (Sackes et al., 2013). The problem addressed in the research of Abdul Aziz et al. (2014) was that the root of some of the incidents was related to temporary and scaffolding structures, the first of which was the interference of groups with the location of scaffolding and should be planned by virtual reality. To prevent interference, the next case was the fall of objects from the scaffolding, which was managed by planning the movement of groups from close distances to the scaffold, and the third case was the falling of objects from a higher height on the scaffolding, all of which were considered by virtual reality (Abdul Aziz et al., 2014).

Congestion and work interference in one place was one of the causes of accidents that were investigated by Nirim et al. (2018). This study intended to prevent such accidents with the help of virtual reality and proper planning. One of the issues this study dealt with was the planning between the work of the concreting workers and other workers, as well as the materials that were moved around the environment by the tower crane. By connecting the positioning system to the hat of 3 workers and examining the model and pattern of displacement of these people when concreting the columns and also the pattern of displacement of objects by the tower crane, the movement network of these two cases was obtained. Then, by planning, the state in which these two patterns would have the least interference was obtained (Nirim et al., 2018). Xu and Zheng (2020) based on their study of the percentage of published works in the field of virtual reality from the perspective of project management, concluded that 17% of existing studies in the field of program management and only 7% of studies related to safety management were about virtual reality. The results of this study also showed that the discussion of existing articles up to that time was more about virtual reality planning, innovative technologies for security management, and collaboration and communication of projects through virtual reality. In other words, the role of virtual reality in safety management has received less attention in previous articles (Xu and Zheng, 2020).

In another study, Afzal and Shafiq (2021) discussed the proposed theoretical framework of the virtual reality system for determining the safety index in construction projects. In this research, the current situation of occupational safety and health in the construction industry and improving methods for virtual reality in safety performance in the construction industry were investigated using a questionnaire. The results of the surveys in this study showed that most manufacturing companies implemented the necessary policies, programs, and procedures regarding occupational safety and health practices. However, the virtual reality system was not widely used in these methods, and based on this, an intelligent production and safety system including the concept of structural design, risk detection, prevention, and control theory, and building safety audit scoring system was presented. This system allowed users to analyze and monitor key aspects of project safety performance before starting and advancing the project (Afzal and Shafiq, 2021).

Moore and Qaisari (2019) examined the issue of safety design and have stated that safety design is considered an effective approach to improve the safety performance of the building due to safety problems during design. In this research, an attempt was made to use a virtual reality system to provide a practical approach to safety design with the ability to automatically detect potential problems in the building. To this end, safety-related design rules were first identified in construction projects, and then, using a virtual reality system, an integrated method for automatic detection of safety problems was designed. As a result, risk factors in the design during the construction of the building were identified on-site and compared to traditional safety management methods. This method would reduce the cost of reprocessing to check the safety and improve building safety management performance. (Moore and Qaisari, 2019). In Another study, Azhar (2017) conducted three case studies on construction industry projects, examining the effectiveness of visualization technologies and visualizing potential risks in the design of construction projects and the communication and implementation of building safety plans. The results of case studies in this study showed that dynamic three- and four-dimensional tools were much more effective in the design and safety management of construction projects than two-dimensional tools. Because multidimensional tools were able to simulate the real conditions of the project implementation process, and in addition, visualization technologies would be very effective in teaching safety requirements in the construction industry in both formal and informal modes (Azhar, 2017).

In his paper, Riad (2015) discussed a four-dimensional virtual reality-based safety management model to identify potential safety hazards in construction projects. In this system, by combining the information of the site's experts as well as virtual reality, preventive measures were provided to prevent possible project accidents. The results of this study showed that if the proposed system was used, the number of deaths due to accidents and damages would be significantly reduced, and the practical application of this model allowed safety experts to identify hazards and appropriate strategies to eliminate them. Develop (Riad, 2015). Li et al. (2018) examined the methods of controlling safety risks in the Chinese subway construction industry using virtual reality. The researchers stated that the dangers and risks of subway construction in China due to the lack of safety risks in the field of construction have occurred on a large scale and have become one of the most challenging issues in this country. Safety risk control for China Metro construction mainly involved pre-construction risk identification and warning signs of risk and danger in the builder, which was known as a "black box" of safety risk management in projects. This study presented a safety risk identification system and early warning system for subway construction projects in China based on the virtual reality platform. Various approaches, including the modeling process, key methods, and technologies for the safety risk identification system and early warning system, were discussed in more detail. The construction of a risk identification database is a plan recovery matching algorithm and calculating the level of risk assurance (Li et al., 2018).

Asemi Esfahani et al. (2014) introduced and reviewed the current applications of virtual reality in the construction industry and then examined the efforts made to expand virtual reality in the fields of safety, energy, and supply chain management. The findings of this study aimed to pave the way for more familiarity and wider use of virtual reality (Asemi Esfahani et al., 2014). Hosseinzadeh and Eshtehardian (2015) in their article, initially stated the most important causes of construction accidents in the planning and training groups and discussed the shortcomings of traditional methods to solve these problems. They then categorized the research conducted in the last decade in the field of safety management by virtual reality, reviewed the research conducted in each category in detail, and discussed their advantages and limitations. After that, they described the potential of virtual reality to solve security problems in the project stages and finally presented suggestions for future research (Hosseinzadeh and Eshtehardian, 2015). Hassani et al. (2014) examined the constructability and safety planning as well as the relationship between constructability and safety. In this study, the identification of cases as well as areas in which the model can be developed was discussed. In order to obtain a comprehensive insight into the constructability of completed buildings and the specialties related to the construction industry, industry representatives were surveyed, and their opinions and suggestions on the most appropriate methods of using virtual reality in the field of safety and constructability were evaluated (Hassani Et al., 2014).

Zia Shams and Majroohi Sardrood (2017) identified VR applications in different phases of construction in the form of subsets that could quickly identify and express all the dimensions of this technology. Finally, they introduced new areas for users of this technology, such as the development of tools based on virtual reality, law and standards review, laser scanning technology, scheduling management, safety management, energy performance, and sustainable performance (Zia Shams and Majrouhi Sardrood, 1396). Panahi and Khanzadi (1398) studied the structure of the integration of virtual reality and augmented reality technologies based on cloud processing to increase productivity and reduce the wasted time for better access to information of virtual reality models. The researchers stated that the complexities of augmented reality applications include safety tips, the type of devices used in terms of weight and quality, access to information, and complete and real-time 3D models that can be used to make the most of these models (Panahi and Khanzadi, 1398).

2. Research Methodology

At the beginning of the research, the most common and most frequent construction accidents were identified, which initially numbered 14 accident types. These 14 accident types were scored through a questionnaire and also interviews with site supervisors, and among them, three important accidents with the highest score were selected.

In the next step, these important accidents were simulated and provided to 15 site supervisors familiar with traditional safety training so that they could experience virtual reality training to reduce the risk of construction accidents. Then, these site supervisors, who had both traditional and virtual training experience, were given a risk table. Through the comparison between traditional safety training and virtual safety training, site supervisors sored the probability and impact of accidents after virtual safety training and traditional training based on their knowledge and experience. Then the two methods were compared based on their point in each section.

3. Results and Discussions

3.1 The most frequent and risky construction accidents

In the table below, three important incidents are provided. These three items were extracted from 14 incidents through questionnaires and interviews with site supervisors.

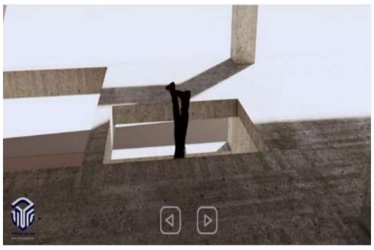
Table 1. construction accident types

	construction accidents	
1	Falling from height	Scaffold Windows Stairs floors
2	Falling objects (safety of pedestrians and neighbors of construction sites)	
3	Falling into holes and openings	Stairs Elevator

3.2 Simulation of 3 important building incidents

The following important construction accidents that were extracted in the first phase were simulated by krpano software, some of which are shown below:

Falling into the opening of the elevator during construction

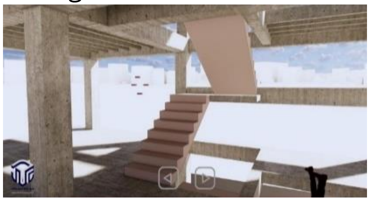


Without following the safety tips

Following the safety tips

Safety tips after clicking on the signs

Falling From The Stairs:



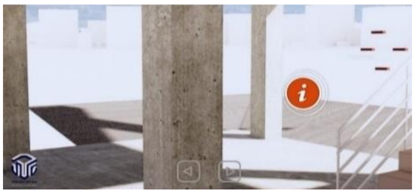
Without following the safety tips

Following the safety tips

Safety tips after clicking on the signs

Falling objects:

Without following the safety tips



Following the safety tips

Safety tips after clicking on the signs

Figure 1. Different scenarios with safety tips

As shown in the pictures above, in the first image of each accident, safety points are not observed, and in the second image of each accident, all safety points that must be observed during construction are shown, and in the third image, users can click on the symbols and see the safety tips of each part.

3.3 Risk table of construction accidents before and after safety training in traditional and virtual methods

After the site supervisors gained virtual reality safety training experience, they were given a risk table to complete the risk register table, as shown below:

Table 2. Scale for the probability and effect of construction accidents

Probability / Impact		**4**	**3**	**2**	**1**
		Daily Occurrence	**weekly occurrence**	**once in Six Months**	**once a Year**
4	**Fatality Catastrophic Property Damage Catastrophic Spillage Release**	**16**	**12**	**8**	**4**
3	**Permanent Disability Major Property Damage Major Spillage/ Release**	**12**	**9**	**6**	**3**
2	**Medical Treatment Damage Spillage/Release**	**8**	**6**	**4**	**2**
1	**minor/No Injury**	**4**	**3**	**2**	**1**

Fifteen workshop supervisors rated the likelihood and impact of construction accidents after virtual reality safety training and traditional safety training. And then, their average scores were placed in the table below, and the risk of each was calculated. The results can be seen in the table below:

Table 3. Risk of construction accidents

	virtual reality								Traditional										
Risk	Probability				impact				Risk	Probability				impact					
	4	3	2	1	4	3	2	1		4	3	2	1	4	3	2	1	Accident	
8	✓ 3.6						✓ 2.0		12	✓ 3.9					✓ 3.0			Scaffold	Falling from height
8	✓ 3.4						✓ 1.9		8	✓ 3.6						✓ 2.4		Windows	
4	✓ 3.4							✓ 1.2	8	✓ 3.6						✓ 2.0		Stairs	
8	✓ 3.6						✓ 2		12	✓ 3.9					✓ 3.0			floors	
1				✓ 1				✓ 1.0	6			✓ 2			✓ 3			Falling objects (safety of pedestrians and neighbors of construction sites)	
6		✓ 2.8					✓ 2		6		✓ 3					✓ 2.4		Elevator	Falling into holes and openings
6		✓ 2.7					✓ 2.0		9		✓ 2.9				✓ 2.9			Stairs	

As shown in Table3, it can be concluded that virtual reality training is more effective than traditional training in the following cases and reduces the risk significantly:

- Falling from a height - scaffolding
- Falling from a height - stairs
- Falling from a height - floors
- Falling objects (safety of pedestrians and neighbors of construction sites)
- Falling into the opening - the opening of the stairs

After using the glasses by the workshop supervisors, they were given questionnaires to evaluate the glasses, the results of which can be seen in the table below:

Table 4. Virtual reality glasses evaluation questionnaire results

	1	2	3	4	5
Focus level when using glasses	%0	%0	%20	%73	%6
Feeling dizzy when using glasses	%6	%6	%73	%6	%9
Ease of use	%0	%0	%6	%93	%1
Clarity of instructions	%0	%0	%73	%6	%21

4. Conclusion

In this study, VR-based safety training was proposed as an alternative to traditional safety training. At first, repetitive and high-risk construction accidents were identified, and then the most important ones were extracted: Falling from height, Falling objects (safety of pedestrians and neighbors of construction sites), and Falling into holes and openings. These construction incidents were then simulated by software, and site supervisors were invited to experience safety training through virtual reality. Then, these supervisors, who were both familiar with traditional safety training and experienced virtual reality safety training, rated the probability and effect of construction accidents after traditional safety training and virtual reality safety training, which were then compared. This study showed that in construction accidents such as falling from a height – scaffolding, falling from a height – stairs, falling from a height – floors, falling objects (safety of pedestrians and neighbors of construction sites), falling into the opening - the opening of the stairs, can be improved by VR by educating workers about safety reduces the likelihood of construction accidents. Also, after using the VR headsets by the site supervisors, they were given questionnaires to evaluate the VR sets. Based on the results, the concentration of users was high when using headsets, and users believed that the headsets were very easy to use.

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Explore Challenges and Benefits of Virtual Reality in Construction Projects

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Abstract

Today, the construction industry has undergone extensive changes, and with the introduction of new technologies, it has moved away from traditional project methods in different phases. One of these technologies is virtual reality technology (VR), which has more and more applications in different stages of the life cycle of construction projects, from design to delivery. One of the capabilities that this technology provides is that people can view the project's construction details virtually before completing the project, evaluate the project characteristics at the time of completion, and have a close-to-reality understanding of the final product. In this study, 57 experts in virtual reality were surveyed to examine the challenges and advantages of using virtual reality. The exploration was done through surveys and interviews. As a result, the most important challenges and benefits of using virtual reality in construction projects were identified and categorized.

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Keywords: Construction, Training, Emerging Technologies, Virtual Reality

1. Introduction

In recent years, the development of digital concepts and technologies has made professionals involved in the construction industry familiar with various technologies, including building information modeling. However, there is still a long way to go to fully understand and utilize this process and related technologies. One of the tangible benefits of building-information modeling that some employers have experienced is the observation of a three-dimensional design model using virtual reality technologies. This has caused the various stakeholders of the project to have a better understanding of what is to be built before implementing the design and to announce the necessary changes to the design and construction department if necessary (Hirani and Patel, 2020).

1.1 Application of virtual reality in the construction industry

In 1996, Bushlagm et al. addressed the use of virtual reality in the UK construction industry and showed that this technology could be useful in both design and construction. In the design section landscaping, fire risk assessment, lighting design, interior design, and space modeling were areas to use VR. The VR technology in construction can be used to evaluate construction scenarios, planning and monitoring, and site planning and equipment (Thabet et al., 2002). Studies have shown that in the manufacturing industry, engineers tend to use virtual reality more to identify and understand engineering problems in large and complex projects and review the design (Goulding et al., 2014). In recent years, virtual and augmented reality technologies have taken their place in various industries such as computer games, education, medicine, and tourism. Rapid advances, especially in smartphones, have made these technologies cheaper, more pervasive, and usable in other industries (Hirani and Patel, 2020). The medical community strives to improve the health and protection of human lives. It has gained significant success in using this technology to train novice physicians in high-risk situations (Dawood, 2009). Virtual reality and related technologies have also been used in other industries to assist in designing, developing, and evaluating before the construction of costly physical samples (Thabet et al., 2002). In the construction industry, VR tools were first used in the design department (Kalhoub and Ayre, 2018). Wang et al., For example, believed that virtual environments enable designers to more easily articulate and evaluate what they have in mind. These technologies also increased interaction between the design team (Wang et al., 2018). Chen and Schneibel addressed the issue of "lost spaces" and showed that there were spaces in design as hidden spaces that allow virtual reality to explore, and thus architects can use those spaces better in their design (Chen and Schneibel, 2009). Recently, research has been conducted on the design of prototypes and architectural models in the virtual reality environment. Cassis et al. developed a floating environment for conceptual design modeling in which designers were able to edit three-dimensional models in a stereoscopic environment using body movements. In this environment, there were two communication spaces, one on a multi-touch screen and the other at the top, where users could select various tools and modeling techniques in this environment and use it to edit the model (De Araujo et al., 2013). In a study, Jackson and Keefe used a lift-off interface that allowed the user to create their own 3D models in a controlled, hand-crafted style over reference images. In this model, after the initial design, it was entered as images in the virtual reality environment, and then two-dimensional curves were extracted from images with image processing algorithms (Jackson and Kiev, 2016). In interaction with the virtual reality environment, the user could select these curves in space and give them a third dimension to create a three-dimensional curved network whose surfaces were designed to build a three-dimensional model. This interface is due to the use of the CAVE environment (a floating virtual reality environment in which projectors were placed between three to six cubic walls the size of a room) (Cruz-Neira et al., 1992). With four walls, it placed limitations on designers compared to the virtual reality open environment that used head-mounted devices (HDM). Clerk et al. also developed a virtual reality-based system for creating prototype architectures using the Minecraft idea to create digital environments. The system made designers tired for a long time (Clerk et al., 2019).

Comparing traditional non-floating and fully floating virtual reality architectural design platforms, Piez et al. presented research with quantitative criteria and statistical analysis based on participants' performance. This study showed that the use of a floating environment caused the user to provide a better understanding of space. Also, the floating environment increased the accuracy of estimating distances in users. But a better understanding of the spatial arrangement in the floating virtual model had no effect on improving the understanding of architectural design and its optimal design. This study also showed that a better understanding of the spatial arrangement of the virtual reality environment is directly related to age and education (Paes et al., 2017). Virtual reality and augmented reality are used in various areas of safety management, including safety planning, safety training, and safety inspection (Du et al., 2018).

Recently, most studies on the applications of augmented reality and virtual reality in construction safety have been conducted in the areas of hazard identification, safety training and practice, and safety inspection (Syamimi et al., 2020). The purpose of identifying risks is to analyze and extract potential hazards during construction (Du et al., 2018). Traditional desktop-focused risk identification methods and common sources in maps, accident cases, and exploratory knowledge are used to provide prevention of potential safety hazards through project meetings (Rankohi and Vogue, 2012). Using this approach to understand the danger for people involved in the construction process is difficult in the real-world situations. Modeling and visualizing in virtual reality environments enhance people's experiences and predict how they interact in real-world situations. To this end, various studies are conducted on the development of risk identification systems based on three-dimensional visualization and virtual and augmented reality systems. These inlcude design systems for safety processes (Hadicosumo and Rawlinson, 2002), augmented virtual systems (Ge, L., & Kuester, 2014), peripheral systems virtual automatic caves (Perlman et al., 2014), and display-based safety management systems (Park and Kim, 2013) (Li et al., 2018). The results of these studies show that most users in the virtual environment have assessed a higher level of risk and identified more risks than those who see photos and read documents. In addition, virtual reality systems can receive rapid feedback to understand the performance of individuals in risk identification (Liu et al., 2020). In the field of safety education, virtual reality and augmented reality provide new opportunities for effective training and practice for individuals and students with a higher level of knowledge and less risk (Liu et al., 2020). The use of these technologies as a complement to digital modeling can lead to better communication in the training of construction safety training professionals and increase student safety awareness (Liu et al., 2020). Lee et al. Showed that VR and AR increase students' interest in learning, improve their level of safety knowledge, and help develop realistic behaviors in safety training games.

Another application of virtual reality is safety inspection and building safety assessment (Li et al., 2018). Kamat and Al-Tawil discussed the identification of earthquake damage and the differences that occurred after the earthquake by adding previously-stored building information to the actual structure by augmented reality. For building fires, the time spent evacuating is a determining factor in rescuing people. Virtual reality-based emergency evacuation simulation and a navigation method can be a convenient approach to construction safety guidelines to shorten emergency evacuation time (Salem et al., 2020).

Another application of virtual reality technology in the manufacturing industry is project control and defect management. Many existing fault management systems, such as PDAs, RFIDs, and laser scanners, have responsive performance, meaning that they operate after the appearance of defects. The use of building information modeling technologies can lead to the development of dynamic, automated pre-fault inspection systems. Faults and errors inevitably and frequently occur in the construction process, increasing construction time and project costs. On the other hand, the responsiveness of many existing systems has made the project control and inspection process time-consuming, so project managers have to spend a lot of time controlling, and monitoring. The loss of shop plan information is another part of the problem. Re-entering this information into the systems is a process that requires a lot of time and effort. Thus, due to the existing problems, an automated system using building information model and augmented reality technologies and virtual reality along with image-matching technology can be effective in speeding up the process of identifying defects (Rakhsari-Talmi et al., 2020). Studies on some of these systems have shown that the proposed systems can be very useful in saving time and also reduce the cost of reprocessing (George et al., 2017).

Virtual reality and augmented reality applications are not limited to the construction sector. Other studies on augmented reality applications in the manufacturing industry include research by Zhou et al. In this study, Zhou et al. used augmented reality to quickly inspect the displacement of segments in tunnel construction. This technology enabled construction site quality inspectors to retrieve the basic model of virtual quality control built to quality standards and to adapt this model to actual displacements. Therefore, the safety of the structure could be assessed automatically by measuring the difference between the base model and what was built. The results showed that the augmented reality system responded to the accuracy required to inspect the displacement of segments and was suitable for further development in this field. However, this system needed improvements, such as increasing the scope of the tracking system and improving the calibration system. Since the size of the segments varied in different tunnels, an automated method for generating VRML files from building information model objects needed to be designed (Du et al., 2018).

In addition, virtual reality and augmented reality technology have rapidly found their ways into the training industry. The advantage of using these technologies in education is that people can react and react to the three-dimensional environment, and the virtual environment helps them to learn and understand visually. Individuals' minds become located (Haggard, 2017).

Virtual reality-related technologies in training in the manufacturing industry can be divided into five main types. Desktop-based virtual reality, floating virtual reality, 3D reality based on 3D games, virtual reality-based on building information models, and augmented reality. This division is based on both media presentation and platform. Desktop-based virtual reality is the most common type of technology in manufacturing education. In this type of technology, only one monitor without any tracking equipment is used to communicate with the virtual 3D environment. Some of the most popular of these types of training systems in the manufacturing industry are V-REALISM for engineering maintenance training and the Interactive Construction Management Learning System (ICMLS) developed by Sunny et al. (Wang et al., 2018). Sax et al. used a Powerwall (a large, high-resolution screen made from a matrix of other displays) to create a floating three-dimensional virtual reality environment for safety training purposes. The Powerwall consisted of three projector screens at the rear, an open configuration of a three-way CAVE that uses stereo 3D imaging with a pair of glasses. The trainees used an XBOX head tracking and control system that used eight cameras mounted on the screens. The results showed that VR-based training was effective in improving participants' concentration and perception of measuring environmental control. In this study, sixty-six people participated in construction safety training. Participants' safety knowledge and skills were evaluated before the test, immediately after the test, and one month after the test. Half of the participants were traditionally trained in the classroom with photos and videos, and the other half were mentioned in the floating virtual reality environment. Measuring general safety knowledge did not show significant difference (Hirani and Patel, 2020).

2. Research Approach

First, by studying and interviewing virtual reality experts, a list of advantages and challenges of using virtual reality in construction projects was prepared. Challenges were categorized into five categories and advantages into four categories. Then, this list was placed in the form of a questionnaire and was given to 57 experts in this field. They scored the challenges and advantages and based on the scores, the most important ones in each section were identified .

3. Results and Discussions

3.1 Challenges

Initially, 21 challenges were identified for the application of virtual reality in construction projects, which were divided into the following five categories. Table 1 shows the challenges associated with each category:

Table 1. Challenges of Virtual Reality Application in Construction Projects

	Categories	Challenges
1	Financing and costs	Support costs (network, data management, etc.) Software and hardware costs High cost for evaluation and implementation (Upgrading software-hardware - account preparation) Costs of learning and training to employees Initial costs, financing, and investment in this field Cost for consumers, companies, and organizations High cost of compensation in the event of a technology failure
2	Hardware	Hardware dependency Easier and more intuitive experiences provided by other software
3	Organizational Culture	Lack of trust and resistance to change High competition of startups Consumers and businesses are reluctant to use new technology such as VR
4	Rules and Regulations	Failure to disclose information and strengthen data security measures to reduce the risk of breach or hacking Legal rules and privileges
5	Knowledge and expertise	User experience (in terms of hardware and software) Insufficient knowledge and information in the field of virtual reality Lack of sufficient experts in this field

These challenges were then scored in terms of importance by 57 experts in the field of virtual reality, the average of which factor is provided in Figure 1.

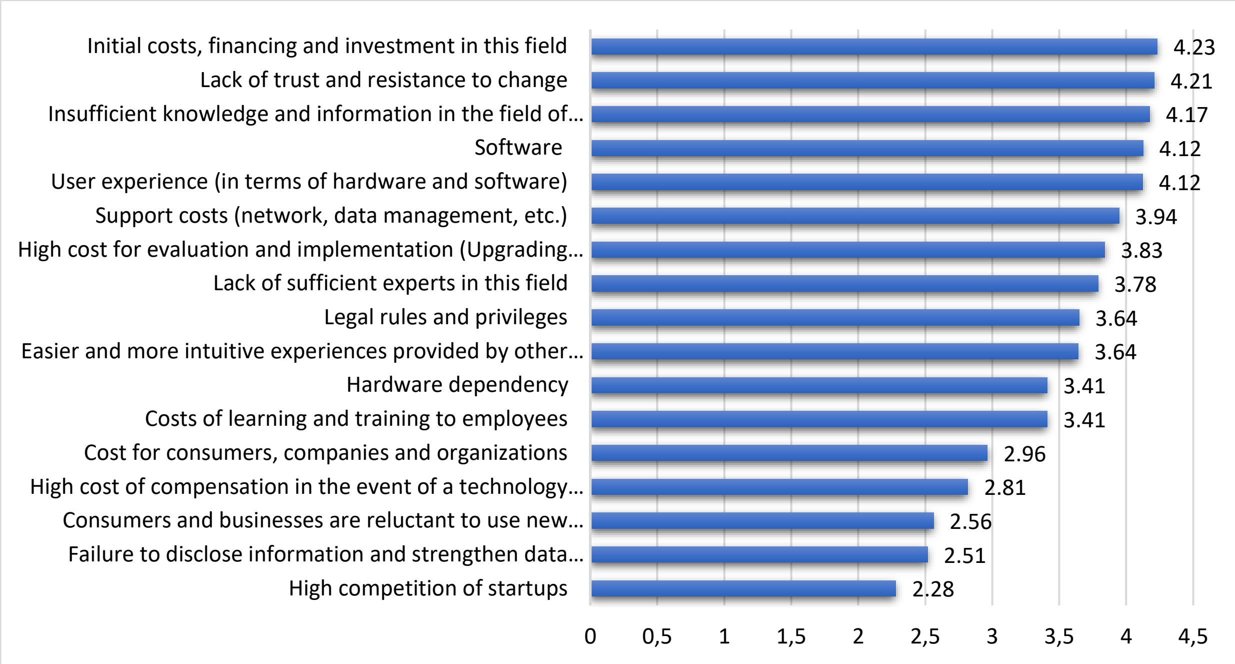

Fig. 1. Average Scores of Virtual Reality Application Challenges in Construction Projects

Also, according to the results, the most important challenges in each category are provided in Figure 2.

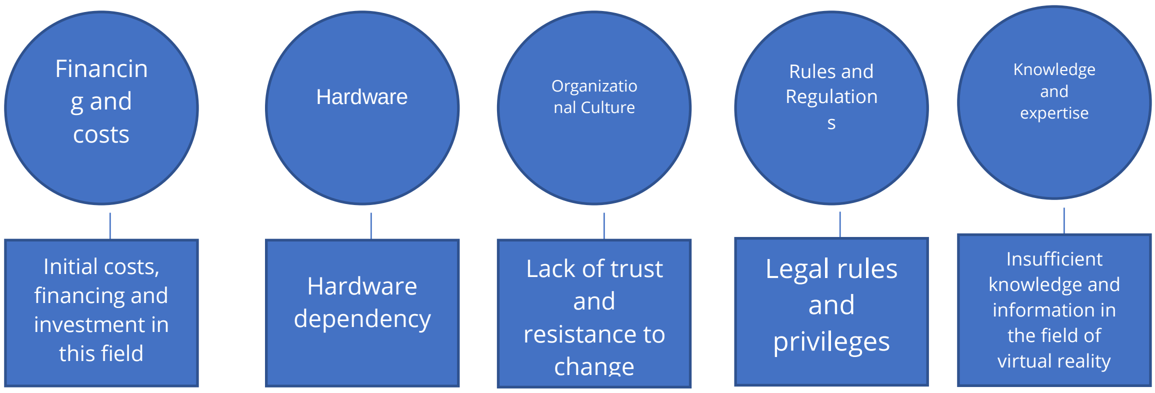

Fig. 2. The most important challenges of using virtual reality in construction projects in each category

3.2 Benefits

Initially, 23 advantages were identified for the use of virtual reality in construction projects, which were divided into the following four categories. Table 2 shows the advantages associated with each category:

Table 2. Benefits of using virtual reality in construction projects categorization

	Categories	Benefits
1	Project quality	Reduce rework Increase build safety Reduce project construction time Improving the final quality of the project Reduce construction and operating costs Ability to integrate systems Easy access to the model Ability to create more appropriate planning before starting work Increase the quality of decision making
2	Technology	Improved 3D design The flexibility of the visualization system Increase the level of confidence about the future of new technologies Increase the effectiveness of systems in the construction industry
3	Organizational Culture	Information sharing Improve information management Participate in achieving goals in the software environment Increase communication and development of information Improve the quality of information retention Possibility to create telecommuting (values participation and distance learning) Reduce the need to refer to paper manuals Increase coordination between employees while doing work
4	Knowledge and expertise	Increase the level of education and knowledge in the field of AR / VR Increasing experience and expertise in this field (gaining experience in related programs and software)

These advantages were then scored in terms of importance by experts in the field of virtual reality, and the average of each factor is shown in Figure 3.

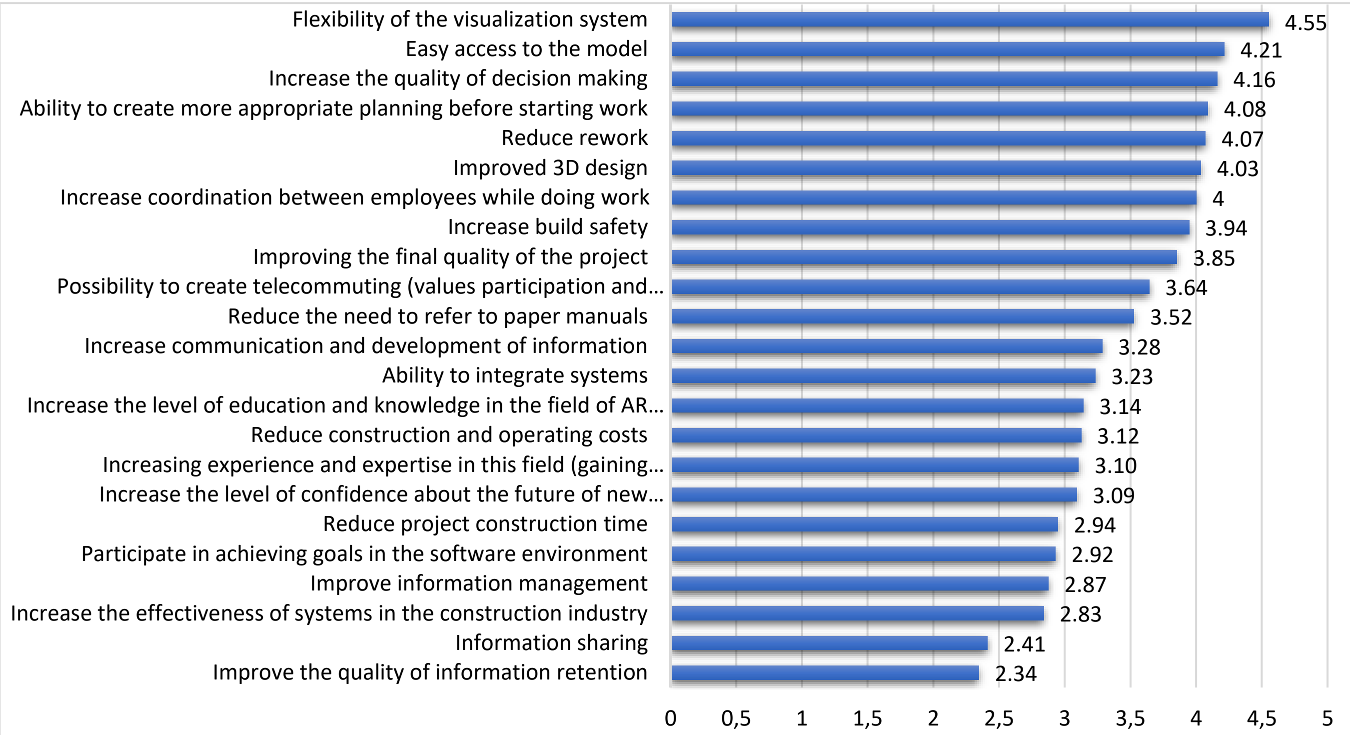

Fig. 3. Average Scores of Virtual Reality Application benefits in Construction Projects

Also, according to the results, the most important advantages are depicted in Figure 4.

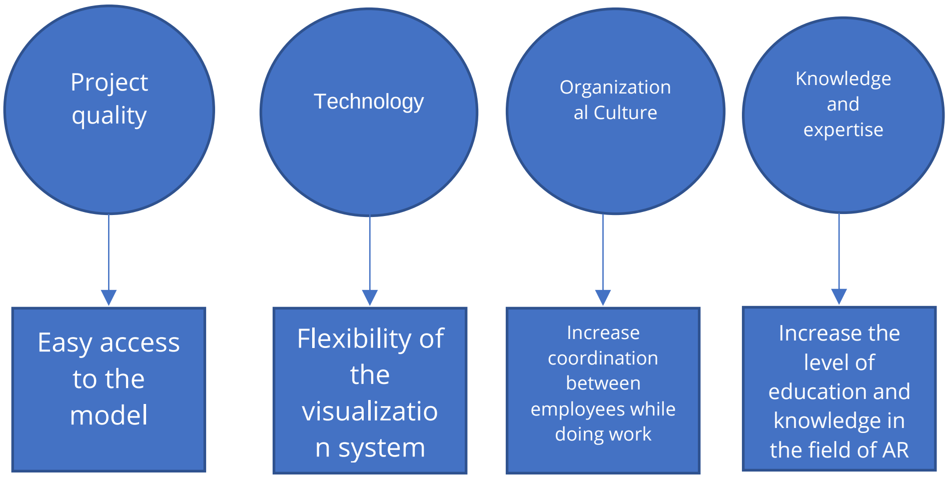

Fig. 4. The most important benefits of using virtual reality in construction projects in each category

4. Conclusion

In this study, the challenges and benefits of using virtual reality in construction projects were examined. Initially, 21 challenges and 23 advantages were identified through study and interviews with virtual reality experts.

Challenges were divided into the following five categories:

- Financing and costs
- Hardware
- Organizational culture
- Rules and regulations
- Knowledge and expertise

Advantages were also categorized into the following five categories:

- Project quality
- Technology
- Organizational culture
- Increase the level of education and knowledge in the field of AR / VR

These challenges and benefits were then placed in the form of a questionnaire and given to virtual reality experts so that they could score on these challenges and benefits. In this way, the most important advantages and the challenges were identified based on the order of the average points they gained. The most important challenges in the application of virtual reality in construction projects included initial costs, financing, and investment in this field, lack of trust and resistance to change, and insufficient knowledge and information in the field of virtual reality. Also, the most important benefits of using virtual reality in construction projects included the flexibility of the visualization system, easy access to the model, and an increase in the quality of decision making

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Exploring 3D Printing Potentials for Sustainable, Resilient, and Affordable Housing

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Abstract

The construction industry showed remarkable resiliency during the global pandemic, and it is a worldwide engine for economic growth. However, many construction companies are predominantly building with traditional techniques and have not adapted to utilize available technological advancements. Therefore, industry is behind the curve to address global issues such as combating climate change and providing more affordable housing. Thus, it is necessary to continue the exploration of options to utilize available technologies that offer innovative solutions to today's global challenges and pivot toward a more sustainable and inclusive future. Nowadays, 3D printing is one of the fastest-growing technologies in construction. This building method could provide answers to the above-mentioned issues and open new and exciting opportunities for the construction industry. This paper will examine how 3D printing can contribute to solving the needs for more sustainable, resilient, and affordable housing. The technology of 3D printing is explained, focusing on the use of 3D printing of structures for housing construction. Once the technology behind 3D printed houses is conveyed, the sustainability and cost benefit analysis of this construction method are explored and compared with traditional construction techniques. The sustainability aspect is explored through analyzing and comparing other similar sized traditionally built homes. Similarly, the affordability of this construction method is compared with current techniques to determine the benefits of this type of construction. Upon the conclusion of the work, a clear pathway is provided on how to utilize 3D printing in constructing more sustainable, resilient, and affordable housing for the future.

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Keywords: Construction, 3D printed houses, sustainability, resiliency, affordability.

1. Introduction

1.1. 3D printing technology

Additive fabrication or 3D printing is a technology that is reshaping the manufacturing and building industries. This construction method can be defined as the automated process of adding materials to build objects or structures using digital data made by Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM). The construction process consists of developing a digital model that will be divided into a series of layers. After that, a 3D printing machine will deposit material layer by layer, as each successive layer bonds with the previous one until the object or structure is complete. 3D printing process is depicted in Fig. 1.

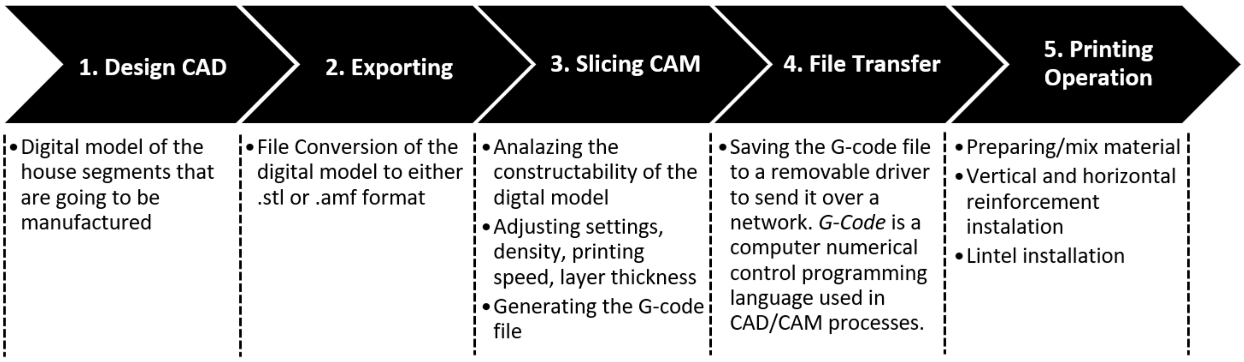

Fig 1. An illustration of 3D printing process

1.2. 3D printing in the construction industry

Since the moment of its invention, 3D printing has targeted the manufacturing sector. This technology has been used to develop prototypes with low manufacturing volumes, objects with small dimensions, and products with complex designs [1]. However, over the years, this technology has been expanded for use in projects related to the architectural, engineering, and construction (AEC) industry. The following three areas have used 3D printing in projects related to the AEC industry: (1) the development of small-scale products that are installed in structures, (2) the manufacturing of architectural scale models, and (3) the construction of building elements.

The first way to use 3D printing technology in the manufacturing sector is to produce objects that are part of a given building. For example, [2] explored the practical adoption of 3D printing for creating an electronic switch knob from a digital model. Later in 2016, Wu et al. [1] described how 3D printers could employ materials such as plastic and nylon. These materials are commonly used to produce small building devices, including plug fixtures, window frame fittings, and plumbing fittings. Recently, Branch Technology [3], focused on the manufacturing of panels and facade systems that are stronger and lighter with a variety of designs. Thus, the AEC industry has the potential of utilizing 3D printing to make small and medium-scale products for the construction process.

The second way to use 3D printing is in projects related to manufacturing architectural scale models. Model makers have been vital to exploring and testing architectural and infrastructure projects before starting construction. While technical tools and manufacturing methods have evolved, the fundamental role of a physical model, to explore and analyse ideas in three-dimensional form, has endured [4]. In the initial stages of the design process, scale models are built to conduct volumetric, energy, and strength analyses. One of the advantages that technology offers is the reproduction scale of both complicated and straightforward geometric shapes within hours. Therefore, the AEC industry has embraced this technology to create scale models since the early 2000s [1].

Finally, the third use of this technology is connected to the automated manufacturing of large-scale building elements. One of the innovations in 3D printing is the Contour Crafting (CC) layer manufacturing process, developed in 1998 by Dr. Behrokh Khoshnevis, professor at the University of Southern California (USC) and researcher in robotics. CC is a 3D printing technology that uses CAD and CAM to create various surface shapes, using fewer trowelling tools than traditional plaster handwork and sculpting [5]. This printing methodology is used to manufacture building components such as internal and external walls or structural elements, including columns and beams. Buildings that have been benefiting from this technology have typically focused on the automated manufacturing of exterior and interior walls which mimics the concrete masonry unit (CMU) construction process. Fig. 2 provides a comparison between traditional CMU and 3D concrete printed walls.

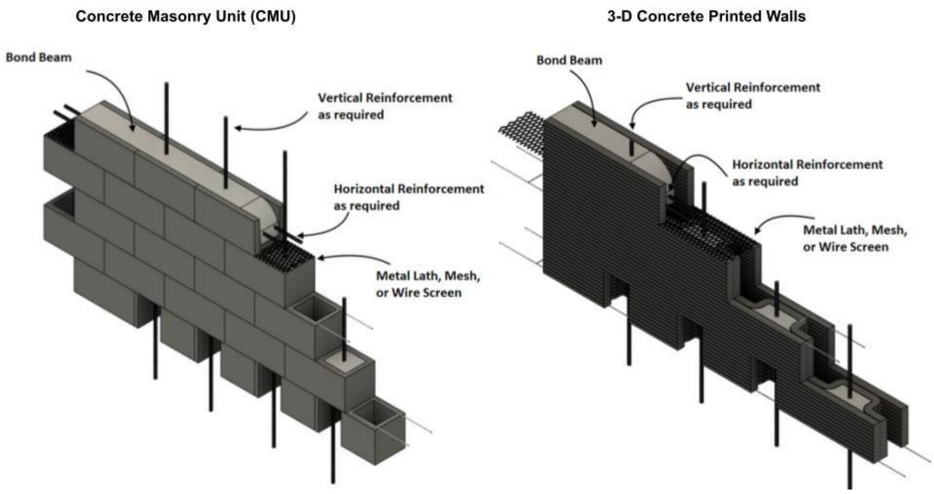

Fig. 2. Comparison between traditional CMU and 3D concrete printed walls [6]

Since the printed material acts as a mold, one of the advantages of CC technology is the elimination of formwork for cast-in-place concrete. Local casting has been used inside 3D printed walls around manually installed steel reinforcement bars by Apis Cor [6]. Thus, it is possible to add vertical and horizontal reinforcements during the printing process. Additionally, walls built using this technology can have different finishes and insulation between layers. Fig. 3 shows the details of a 3D printed wall.

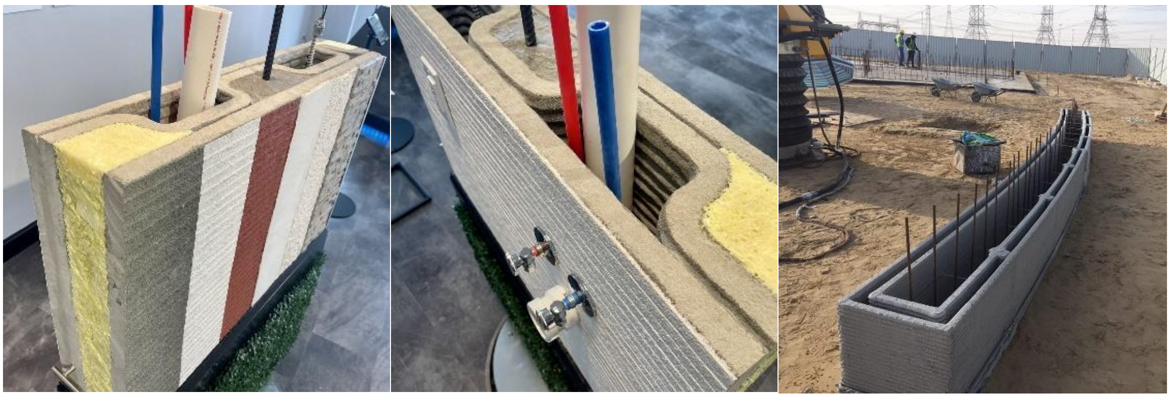

Fig. 3. Details of a 3D printed wall by Apis Cor [6]

1.3. Construction 3D printer machine types

There are different 3D printing machines focused on manufacturing of building elements. Companies and universities worldwide have developed various devices, including (1) the Robotic Arm, (2) the Telescopic Arm, (3) the Gantry System, and (4) the Modular Crane, just to name a few. Each machine has advantages and disadvantages, such as the printable area, the weight of the equipment, and its transportation and assembly processes. For example, as COBOD [7] states, the advantages of robotic printers are their easy transportation and versatility to print individual elements with high complexity. That is due to the 6-axis movement of these machines. However, one of the disadvantages of robotic printers is the limited printable area. Users of robot printers are virtually forced to print components rather than whole structures or buildings. The robot is large, the arm is short, with a maximum reach of three meters, which is typical of robot printers, and it requires a lot of free space [8]. This feature can limit the printable area considerably. Thus, this machine is not ideal for printing the entire building elements or large structures.

On the other hand, gantry printers can do larger-scale prints continuously. Additionally, this type of machine is easy to control and does not require highly skilled programmers [8]. One of the disadvantages of gantry printers is their low flexibility for printing complex and detailed geometries. That is due to the 3-axis movement of this machine. Nowadays, companies typically develop their own software for importing 3D models, performing the slicing process, and converting the 3D geometry to G-Code. Table 1 shows devices developed for 3D printing in construction with advantages and disadvantages of each.

Table 1. Construction 3D printer machine types

Machine Type	Advantages	Disadvantages
Robotic Arm	Transportability and versatility in printing individual elements of high geometry complexity.	This machine has a limited printable area. The robot cannot print large structures. Additionally, the machine requires highly skilled programmers.
Telescopic Arm	This type of machine can manufacture larger-scale walls continuously. Furthermore, due to its light weight, it can be easily transported and placed in different site work areas.	Medium-low precision in printing elements with high geometry complexity.
Gantry System	This type of machine is easy to control and does not require highly skilled programmers. Printing with a gantry printer lets operators control the material flow. Moreover, the gantry system can manufacture small and large-scale walls continuously.	Medium-low precision in printing elements with high geometry complexity. The transportation and assembly processes could take more time and be more complex. For example, the transportation and assembly of the COBOD machine could take approximately two days.
Modular Crane	Due to its modular design, this type of machine can manufacture larger size walls continuously.	Medium-low precision in printing elements with high geometry complexity. The transportation and assembly processes could be more complex and take more time than the Robotic and Telescopic Arm.

1.4. 3D printing process in construction

The building process using 3D printing technology can be divided into three main stages: (1) Computer-Aided Design; (2) Computer-Aided Manufacture; and (3) installation of utilities and finishes. Even though the first two stages are entirely connected to CAD and CAM, it is necessary to continue and finish the building process by conventional construction activities in the final phase. The stages are as follows [9]:

1. Computer Aided Design – CAD (3D model of what will be built)
   - 1.1. Architectural Design
   - 1.2. Structural Design
   - 1.3. MEP Design
2. Computer Aided Manufacture – CAM
   - 2.1. Model Analysis: Analysis of the project's constructability using 3D printer technology
   - 2.2. Exporting: generation of a file in a specific format, e.g., stereolithography file (STL) or additive manufacturing file (AMF), with all the geometric information to build the project
   - 2.3. Importing and slicing: conversion of the digital model into a list of commands (G-code) that the 3D printer can understand and carry out
   - 2.4. Printing: transportation and preparation of the machine, transportation of building material, beginning of the printing process, vertical and horizontal reinforcement installation, and lintel installation
   - 2.5. Post-processing: after the material is printed, a curing period is necessary to increase the strength of the walls
3. Utilities and Finishes: the final stage employs traditional construction methods, including the installation of roofs, doors, windows, utilities, and surface finishing of exterior and interior walls.

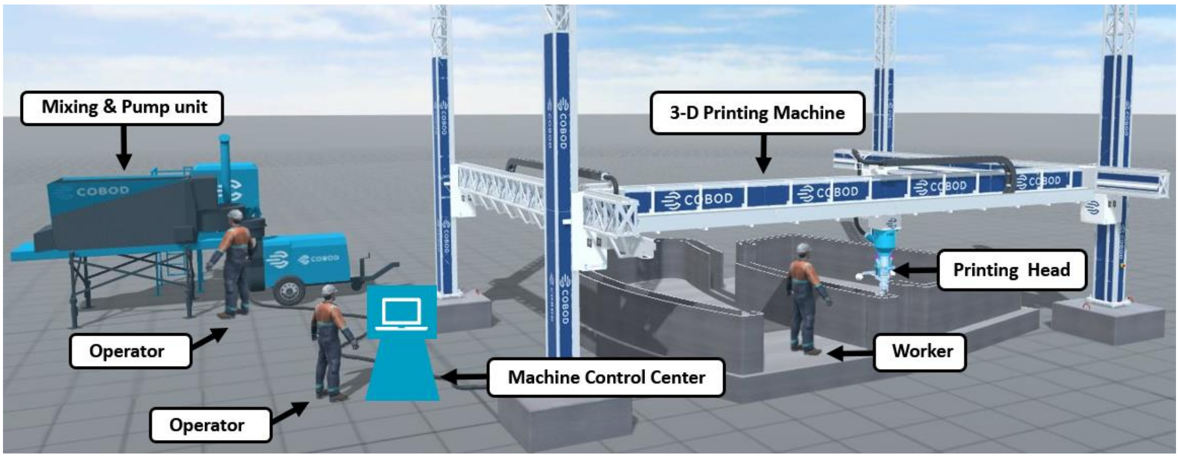

Fig. 4. Components of 3D printing machine, Gantry System [7]

1.5. Materials for 3D printing in construction

New construction methods require materials with up-to-date characteristics and specifications. For 3D printing of a house elements, new materials have been introduced to respond to the technology's requirements. According to Kashani and Nago [10], materials suitable for 3D printing need to have three main properties: (1) high workability for extrusion, (2) short curing time, and (3) strengthened resistance to support successive layers of material. As a result, a mixed material that can fulfill these conditions is required for a successful 3D printed construction project.

Concrete is one of the most used materials in the construction industry. However, this material cannot be extruded due to its aggregates' size. Thus, mortar has been used successfully with 3D printing technology [11]. Additionally, researchers also experimented with earth-based materials such as soil and thermoplastic polymer materials that appeared to be effective. The use of these three materials is explained below.

Mortar is a workable material based on a mixture of sand, water, and cement [12]. Typically, mortar is used to join building elements such as bricks and blocks. Recently, that material has been used as the main element in manufacturing walls using 3D printing. In 2022, ICON, an American company, built the House Zero project in Austin, Texas [13]. The walls were built using their own mortar called Lavacrete. It is a cementitious-based mix that offers high strength and can resist severe weather. Lavacrete has a compressive strength of 2,000 - 3,500 psi and can withstand extreme weather and significantly reduce the impact of natural disasters such as earthquakes while providing maximum efficiency. For example, ICON's homes in Nacajuca, Mexico, can endure severe conditions and have already resisted a 7.4 magnitude earthquake [14]. Furthermore, the ICON team [15] explains that Lavacrete reduces heat transfer by adding thermal mass to the home. In addition, thermal mass, increased insulation, and an airtight wall improves energy efficiency.

Soil is a natural body made up of solids (minerals and organic matter), liquids, and gases found on the Earth's surface [16]. This is one of the oldest construction materials used for building houses. In 2021, the Italian company WASP (World's Advanced Saving Project) built TECLA (Technology and Clay Project). This is a prototype of an eco-sustainable house printed using a mix of locally sourced subsoil, water, and binder. The project was a challenge in mixing one of the oldest building materials with the newest construction processing techniques.

Polymer is "a chemical substance consisting of large molecules made from smaller, simpler molecules" [17]. Polymeric materials are present in several construction elements, including walls, ceiling panels, and piping systems. Following the idea of manufacturing construction elements, the American company, Branch Technology, prefabricates panel systems using fibre-reinforced polymers and 3D printing. Its panels have an internal structure that decreases the weight and optimizes the use of materials.

1.6. Sustainable Buildings

As climate change mitigation efforts become widespread through regulations and social pressures, the AEC industry is focused on becoming more environmentally friendly. Sustainability as defined by the Environmental Protection Agency (EPA) is: "Everything that we need for our survival and well-being depends, either directly or indirectly, on our natural environment. To pursue sustainability is to create and maintain the conditions under which humans and nature can exist in productive harmony to support present and future generations" [18]. The goal of many modern designs is to create a sustainable structure to minimize the impact on the environment. An effect of this goal is reducing energy consumption, which in turn saves money in operation costs. The criteria for these modern designs have both public and private entities involved in pursuing the goals. On the public side, numerous states and cities have enacted building codes which push new construction to be more sustainable such as Boston and New York City. The various private organizations such as Passive House or Leadership in Energy and Environmental Design (LEED) set building certifications that modern building owners want. This can be seen through private building owners pursuing these certifications. Since the introduction of LEED in 2000, there has been over 110,000 projects that received different levels of LEED certification [19]. In addition to the private sector's acceptance of LEED, the public sector in many jurisdictions now require their own public buildings to be achieve LEED certification.

What makes a building sustainable is the combination of the materials used to construct it and the efficiency of the operation of that building. Just using sustainable materials or only ensuring a high-efficient building is one sided and does not provide a comprehensive solution. This is further broken down into the concept of embodied carbon. Embodied carbon is the total carbon dioxide (CO_2) associated with manufacturing of materials, transportation, and construction methods used during the whole lifecycle of a building. Once a building is built, operational carbon measures the energy consumed to operate the structure. This measures the heating and cooling loads, ventilation, lighting, power, lifts, automatic doors, and heating water. A true sustainable building should focus on both embodied and operational carbon.

1.7. Resilient Buildings

A part of creating a sustainable built environment is the longevity of the structures. The longer the lifespan, the more sustainable the building is, and this is where resiliency comes into play. Built environment resiliency is how well the structure can withstand the environment including the normal wear and tear of occupancy along with environmental forces such as storms and floods. As the world becomes more extreme in weather events, the need for resilient homes is paramount. A key area within the United States where resiliency should be the focus, in near future, are the Gulf Coast, Tornado Alley (Midwest), and the Rocky Mountain west which experience hurricanes, tornados, and devasting wildfires, respectively. These areas need housing and buildings that can be resilient to the natural forces they will unavoidably be exposed to. The consensus behind climate change is an increasing frequency of more powerful storms and larger swings between dry and wet seasons, all of these present a future that requires a departure from the current building methods to a more durable type of structure that can resist high winds, debris impact, flood, and fire. In any given year, homes are destroyed in America by tornadoes, hurricanes, wildfires, floods, and earthquakes highlighting that the current method of construction does not meet the current and future needs of a resilient structure, let alone the predicted intensified future events.

1.8. Affordable Housing

The need for affordable housing is a dire need in all locations across the world. Even within the United States, homelessness is an issue in all major cities. The cost of housing has been increasing at rates that far outpace wage increases. What makes housing affordable is if the cost of housing is less than 30% of the 0households' income [20]. The exact dollar figure ranges based on local demographics but the results of lack of affordable housing are well documented. A stable housing situation provides children and adults the stability to have better outcomes in their health, employment, and education [15]. Affordable housing does not only affect the lowest income earners. When using average income median (AMI), which is the average family income in a geographical location such as a metropolitan area, all ranges of income earners are affected. One the lowest end of income earners, there is only 32 affordable and available rental properties for every 100 renter households [21]. For households at the AMI, this number is 102 affordable and available homes per 100 renters, which is the only surplus of housing seen for all percentages of AMI at 100% AMI or lower [21]. Affordable housing is expanding into all levels of income and is becoming an increasing problem in areas that are experiencing rapid growth of population and limited housing growth.

2. 3D Printed Solutions

2.1. Sustainability with 3D printed homes

A key point to create more sustainable buildings is reducing the overall embodied carbon. 3D printed homes are currently made from a form of concrete which is a leading emitter of carbon dioxide (CO_2). This is related to the process of making concrete and its key ingredient Portland Cement [22]. There are currently numerous efforts to reduce the embodied carbon in concrete such as using alternative products in the mix such as fly ash, slag, crumbled recycled concrete, and other waste products [23]. This helps reduce the embodied carbon and takes pressure of landfills where this waste would normally end. The 3D printing materials allow for more flexibility in implementing recycled products, reducing the need for new products, and diverting less waste to landfills.

A large part of creating a sustainable construction industry is reducing the waste generated from the building process and reusing materials from demolitions to prevent the useful materials from going to waste and forcing new materials to be created to fill that void. 3D printing reduces the carbon footprint by limiting the number of materials required on site through the method of construction, or the elimination of major areas of traditional building. The reduction or elimination of wood framing, minimal interior finishing, and minimal labour provide savings on the emissions from numerous deliveries of multiple materials and the volume of workers traveling to the site. The average waste during a house construction is 2 tons of waste [24]. Prefabrication plays a huge part in reducing waste. Studies show that prefabrication can reduce waste on average by up to 50% [25]. From efficient designs that can print foundations and walls without forming or waste from cutting materials to size, printing and using the exact number of materials is a strength of printing homes. Many 3D printing companies use wooden trusses to complete the roof which come prefabricated. Prefabrication is used even more commonly as some 3D printed homes are 3D printed assemblies that are built in factories and then shipped to the site to be assembled into the final structure. This reduces all the waste as the 3D printed assemblies in the factory allow for precision material use with minimal waste.

2.2. Resiliency with 3D printed homes

The use of concrete to make structures that resist impacts from both natural and human forces is a customary practice. With the growing strength and frequency of extreme weather events, the current building methods are struggling to stay resilient. 3D printed homes are typically constructed from a cementitious material that in many models performs like concrete masonry units (CMUs). The building codes are not uniform, but buildings need to meet code standards and are considered an alternative means and method in the International Building Code and each project needs to show its conformance to the required aspects [26]. Regardless of building code status, the materials used in the printing process creates strong structures that can resist impacts from natural forces. The resiliency of a building plays a key role in the sustainability. The more resilient, the longer the life span, which in turn reduces the need for construction of new buildings to replace the current stock. This helps the structure be more sustainable as well.

The current life cycle analysis of 3D printed homes is still in its infancy, the longevity of the structures has yet to be seen but the hopes are high. As the current buildings begin to age, further research needs to be conducted to monitor the durability of these structures. Many companies have a few 3D homes printed as models as a proof of concept to sell their investment opportunity to investors and some have large scale communities planned and scheduled for ground-breaking in 2022. This year, 2022, has numerous projects starting up that have 3D printed homes at the centre of the project. A community is planned in Texas by ICON and the current projects being conducted by SQ4D in New York that sell at 40% cost of comparable traditionally built homes [27], [28]. This provides limited data for review and full assessment of actual performance and requires a review of the materials used. This is true regarding all structures, the type of materials used play an important role in the performance of the building. Cement can resist fire, but if the roof and windows use wood or other flammable materials, the building would not be resilient against fires. For 3D printed homes to be resilient, the products used alongside the cement need to be carefully examined and reviewed to ensure the entire system is resilient to the threats of specific location that they will be built. The current status of 3D printed houses looks promising and future research is needed to confirm the theory that this technology provides resilient houses in the future.

2.3 Affordability with 3D printed homes

Labour and time are large factors in the cost of construction. Current homes depending on their size and design, require multiple different contractors to mobilize and complete their work in sequence. In 2021, the United States average timeframe for a house to be built was 7 months [29] compared to the days that it takes for the exterior shell of the building using 3D printing [27]. The total time for finishing the interior of the building to an occupiable space can take 4 – 6 weeks, but in some cases just days. Time is money, the more man hours expended on a build, the higher the cost. The cost savings range greatly in the cost of the printed homes, but most companies state between a 30% to 40% reduction in cost [27]. Habitat for Humanity, which uses voluntary labour to construct their homes even saw a 15% reduction in cost to their average cost for a home [30]. This could be due to the reduction of waste which reduces the cost of require materials. The fast-paced 3D printing allows minimizing the amount of labour costs and maximizing production rate of buildings. This should in turn increase supply, decreasing demand, and lower the price based on economics. In addition to this, the trend of the housing market is such that the cost of building a new home, sets a benchmark for the existing housing stock. This premise works out to be that the higher a new construction house costs to produce, the existing housing stock value increases as the sole competitor which is new construction costs more. The past few years have seen unforeseeable disturbances to all markets and the housing market was no exception. With this acknowledged, prices of traditionally built homes were higher before the pandemic than the 3D printed homes of that period. Acknowledging the unprecedented past few years, the housing prices before the pandemic were lower but still above the cost of 3D printed homes.

3. Cost Comparison

Affordability is based on the cost of the building. Currently, housing prices can be blamed on a variety of reasons ranging from zoning regulations, interest rates, shortage of housing, and growing populations especially in urban areas. While 3D printed homes cannot address some of these issues that are causing shortage of affordability housing, 3D printed homes can be constructed quickly and cost effectively. When comparing the sale prices of 3D printed homes, the sale price in some locations can be half of the average of selling price of comparable traditionally built homes. For example, SQ4D has sold a small number of homes for around 40% of comparable homes [27]. Other printing companies also advertise the lower cost of their properties. One of the larger costs in all construction projects is the cost of labour. Labour cost can range from 20 to 40% of the total cost of a project. 3D printing reduces the amount of manhours spent on the project, which will reduce the overall cost of a project. In addition to reducing the number of hours spent working on the project, the turnaround time is faster. This means more projects can be completed in the same period of time. The speed to construct can help overcome the current shortage of housing in rapidly developing or expanding cities. Table 2 highlights certain facts about the costs of 3D printed homes in comparison with traditionally built homes.

Table 2. Studies on the cost comparison of traditional and 3D printed homes

Reference	Highlights
[31]	Homes can be printed within 24 hours and just for $4,000. These are post-disaster shelters, but this shows the versatility and affordability of 3D printed homes can bring.
[32]	Depending on the printing company cost savings range from 15% to 50%.
[33]	3D printing can reduce costs by 20-40%.
[34]	With the right printing material design, most of the printing compound can be locally sourced with little shipping requirement from a central stocking location.
[35]	Countries that depend heavily on migrant labour can save up to 50-80% on labour costs from 3D printing. A reduction of waste was reported between 30-60%.
[36]	The savings from 3D printing can be up to 35% in overall costs and a reduction of 91% in total man-hours.

4. Limitations

5.1. 4.1. Current limitations of 3D printing in construction

The application of 3D printing to the construction sector is in its initial stage since its practice only began around a decade ago. Although the AEC industry can learn from the 3D implementation in other industries, this process could be more complex in the building sector due to the scale of the projects, the diversity of materials, the variability of the environment, and the building codes, among other factors [1]. Therefore, there are multiple challenges that this technology needs to solve, such as construction codes, workforce reduction, and maintenance processes.

As it is often the case with implementing the latest technologies, the challenge is that laws and regulations sometimes cannot track innovation fast enough. As Kroes [37] explains, when 3D printing moved from the conceptual stage to the construction site, a gap emerged between the available technology and the construction industry standards such as building codes, permits, inspection authorities, and contractual provisions for new buildings. However, this code does not have any provisions or guidance related to 3D printing. Therefore, the International Code Council (ICC) Assessment Service developed an acceptance criteria document for three-dimensional concrete walls (AC509) under Section 104.11 of the IBC. The recently released AC509 focuses on wall construction using 3D printing, evaluating the material's structural strength, fire resistance, and durability. AC509 also details the specific product quality and sampling standards required to achieve code compliance [38].

Although one of the advantages offered by 3D printing technology is automation and cost reduction, it is crucial to understand the side impacts it can also generate. A widespread problem with the automation of manufacturing activities is the reduction of the workforce. Since construction is an essential source of employment in many countries, eliminating jobs may affect laborers significantly. For example, if activities such as masonry were totally automated, workers of this trade would have to move to other sectors or learn different skills. The construction industry will have to face this challenge since the workforce is an essential part of its growth.

The maintenance of buildings, known as all the activities that focus on preserving and restoring the functionality of a building, is of vital importance. Currently, a significant advantage is that mechanical, electrical, and plumbing systems can be integrated into the 3D printing process. However, questions arise regarding the maintenance and repair of these systems and the manufactured walls using this type of technology. For example, if there are leaks, humidity, or a need for pipe inspection, perforations on the walls may be necessary. Since 3D printed walls mimic the CMU building method, repatching perforations or cracks are similar to repairing a CMU wall. The process consists of (1) preparing the surface and cleaning the hole in the wall, (2) applying a bonding agent, (3) repatching/repairing/filling the hole in the wall using mortar or patching cement, and (4) finishing and painting the repair to match the surrounding. 3D printed walls can be cut and drilled as standard CMU or concrete walls. 3D printing technology merely shifts the way walls are constructed from manually to robotically. Therefore, processes such as repairs or maintenance are not affected [6].

5. Conclusion

As 3D printing becomes a more integral part of the construction industry, the above problems will be alleviated. Thus, establishing relationship between the different parties such as companies, government, and academia is necessary. In this way, new building processes and tools will be developed to eliminate the current limitations and provide more advantages for constructing sustainable, resilient, and affordable housing. Although 3D printing technology for the construction industry is an outstanding tool, it will not solely transform the AEC industry on its own. That technology must continue to evolve to meet current standards and construction practices. Training and developing new skills in construction professionals will be necessary to generate a new workforce that takes advantage of this technology.

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Investigating the Required Operational Changes in the Construction Industry to Comply with Circular Economy Concepts

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Abstract

Circular economy has been widely considered an efficient concept to reduce carbon emissions in the built environment. Many researchers have investigated frameworks, strategies, and technologies to drive the implementation of circular economy principles. However, the evidence remains inadequate to show industry partners and researchers what changes should be made to current construction practices so that stakeholders can successfully adopt circular economy principles to improve project performance. To fill this knowledge gap, this study carried out a questionnaire survey to collect data and analyze different scenarios of implementing changes in construction projects to realize circular economy targets – slowing, narrowing, and closing resource flows. The questionnaire was shared through email and social media platforms. In total, 59 responses were recorded as effective and were used to conduct a descriptive analysis. Results showed that modern methods of construction (MMC) was a better alternative to traditional construction. MMC reduces wastage on-site and allows stakeholders to reduce the requirement of raw materials in new projects. Based on these findings, recommendations are made to provide a direction for future research to help the construction industry transform toward UN's Net-zero Action and help stakeholders bring up certain fundamental changes required to comply with the concept in companies.

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Keywords: circular economy; survey; modern methods of construction (MMC); reuse and recycle; operational changes.

1. Introduction

One of the biggest concerns of the modern world, impacting all businesses, is climate change, and the construction industry is a major contributor to it [1]. Due to heavy energy and fossil fuel usage along its fragmented supply chain, the construction industry accounts for a high carbon footprint during the construction and operational stages [2]. It has been estimated that the construction industry emits 40% of global greenhouse gas (GHG) emissions, reflecting an urgent need to shift the focus towards a sustainable direction [3]. In a developed country like the UK, the demand for the electricity supply in the construction sector is projected to reach 180% by 2030 [4], and 80% is emitted by the building energy [5]. Thus, it is crucial to study new approaches to reducing the carbon footprint by reducing construction emissions.

Leading construction companies, together with local governments, have recently made great efforts to apply the concept of circular economy to minimize wastage and develop a sustainable ecosystem. There is a call for changes in the fundamentals of the construction practices by fitting the circular material flows into the construction project lifecycles. Alongside this goal, this study is conducted to understand the impact of the carbon footprint emitted by the construction industry and to review the concept of a circular economy to reduce emissions in the construction industry. To do that, a questionnaire survey was used to collect, analyze and interpret data from participants' opinions on circular economy in construction. The survey findings can help stakeholders understand the impact of the carbon footprint emitted by the construction industry on the environment and how the concept of circular economy relates to the construction industry.

This study includes two objectives: 1) to explore the circular economy concept and its integration with the construction industry through a literature review in sustainable development, and 2) to investigate the opinions of different stakeholders on the modern methods of construction (MMC) and its role in reducing the carbon footprint to achieve the circular economy.

The remainder of the paper is structured as follows. Section 2 provides a literature review of circular economy in construction, which identifies the impacts of the construction carbon footprint on the global environment and the integration of circular economy with MMC. Section 3 illustrates the data collection process. Section 4 describes the survey findings, followed by the conclusion and recommendations for future practices.

2. Literature review

2.1. Impacts of the construction carbon footprint on the global environment

Over the last four decades, the construction industry has been the highest consumer of natural resources and consumes around 40% of the total [6]. The construction industry is not only the highest consumer of resources, but one-third of solid waste worldwide is created by the construction industry [7]. In the traditional method of construction and demolition, waste is generated throughout the life cycle; however, waste management is not considered at the earlier stage of construction design and planning. Though the most impactful stage is the demolition, in which 50% of total material gets wasted [8]. The main reason behind the waste phenomena is the linear economic model used by the construction industry, which follows the process of "take-make-dispose of [9]. In contrast, the circular economy model is proving to be more efficient, and its basic principle is resource management [10]. According to the circular economy model, the building materials should be reused after the building life and used at the material bank for new construction [11]. Ellen MacArthur Foundation has proposed a very basic idea to adopt the concept in the construction industry; development in knowledge and adaptability is required. Implementing a circular economy in a built environment has multiple benefits considering the environmental benefits and economic advantages, according to the report by Roland Berger [12]. As the construction industry is a significant part of the economy and due to the complexity involved in the supply chain, a very well-planned implementation is required.

2.2. Integration of Circular economy with Modern Methods of Construction

The concept of MMC is mostly associated with off-site construction techniques, including modularization, in which all the major components of the building are manufactured in a factory and transported to the site where the assembling takes place [13][14]. The most common and known form of MMC is bathroom pods installed in many residential and commercial buildings. In the past few years, Asian countries such as China and Malaysia have increased MMC use beyond bathroom pods [15]. Many major components are pre-manufactured now and assembled on-site, which dramatically decreases material wastage and reduces the carbon footprints on site. Throughout several developed areas, MMC has developed at a quite impressive pace. In November 2019, for example, Home England invested £30m for the construction of the modular home [16].

There are numerous benefits of using MMC as it reduces waste and landfills. When the building components are manufactured in a factory environment, it saves energy compared to the construction in the open environment. According to the reported statistics, MMC reduces 90% of waste compared to the traditional method [17]. MMC completely fits into the circular economy concept as many components are manufactured using recycled materials from different projects. The principles of circular economy focus completely on functionality and how to reuse the individual building components [18]. Modularization implemented in the building sector can contribute to circularity by reducing the transport of materials and components, and the potential dismantling and relocating of building components after the lifecycle will eventually reduce the demands for raw materials and energy consumption [19]. Among the many ongoing research studies around circular economy in construction, this study uses a survey method to provide evidence-based ramifications on how the construction industry perceives the circular economy concepts and how MMC relates to the goal of carbon reduction.

3. Research methodology

3.1. Data collection

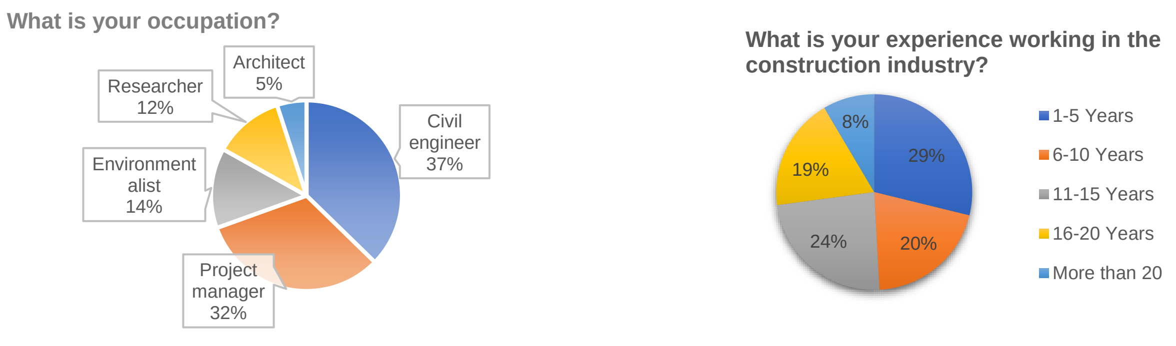
A questionnaire with a set of questions was created to gather information from the participants. The questionnaire allowed to obtain the maximum number of responses in a short period. A Google Form was used to manage the questionnaire over the internet, and the link was shared through Social Media groups, LinkedIn, emails, etc., to the targeted population in the industry and academia. The questions included in the questionnaire are provided in Table 1.

Table 1. Questionnaire overview

Question No.	Question
1.	What is your occupation?
2.	What is your experience working in the construction industry?
3.	How do you feel about the following statement? *"The construction industry is one of the main contributors to the carbon footprint impacting the environment globally."*
4.	How well do you understand the concept of circular economy?
5.	Do you think the implementation of circular economy in various industries has effectively reduced the carbon footprint?
6.	At which phase should resource management be implemented in construction projects?
7.	Which sustainable approaches should be adopted to efficiently manage the resources and reduce waste?
8.	What are the main factors affecting the implementation of circular economy in the construction industry?
9.	Do you know about the Modern Methods of Construction (MMC) (i.e., off-site/modular construction)?
10.	Does the concept of MMC comply with the principle of circular economy?
11.	What are the main advantages of implementing an MMC project?
12.	What is the main drawback of MMC projects?

3.2. Population and sample collection

The study targets professionals from different fields, such as civil engineers, project managers, researchers, environmentalists, and architects. The questionnaire for the research was published on google forms and was sent to the work colleagues through email, and more professionals were reached through the social media platform. In total, 59 responses were recorded to be effective, and the descriptive analysis was carried out based on the responses. The distribution of the respondents' occupations and experience is shown in Fig. 1.



(a) (b)

Fig. 1. Distribution of (a) respondents' occupation and (b) experience

Ethical consideration was given the utmost importance going forward with the research. The design was created considering the 10 points of ethics from Bryman and Bell's Business research methods [20]. Consent of the participants was taken at the beginning of the questionnaire, and it was carried out voluntarily. A brief knowledge of the research was given to the participants, and they were informed about the purpose of the survey. Participants' integrity, privacy, and confidentiality were given the topmost priority. The research study complies with the Northumbria university code of ethical conduct, the Data Protection act 1998, and the General Data Protection Regulation (GDPR) in all the aspects of research.

4. Findings and Discussion

The questionnaire survey yielded results based on only effective responses. The discussion is carried out for the descriptive analysis results of all the questions providing a logical argument on a specific question. It is important to record the responses and carry out a proper discussion to analyze all the options rationally. In order to understand the responses of the two objectives about the concept of circular economy and the knowledge of MMC, four main questions highlighting the key components of each section were selected and evaluated in this section.

4.1. Impacts of the construction industry on the environment

Survey Question No. 3 was designed to solicit participants' opinions regarding the impacts of the construction industry on the environment and carbon footprint emissions. As indicated in the Literature Review section, the construction industry is one of the major producers of carbon footprint.

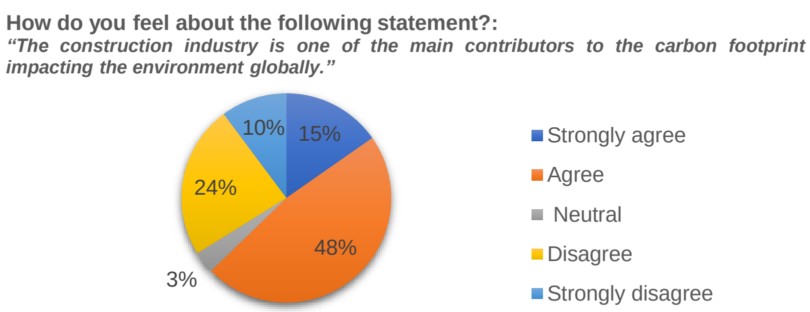


Fig. 2. Responses from the survey participants regarding Question No. 3

Specifically, the goal of Question No. 3 (Fig. 2) was to understand how the response from the participants aligns with the statement found in the literature about the construction industry being one of the major contributors to the carbon footprint. According to the survey results, 15.3% strongly agree with that statement. Almost half (47.5%) agree with it. Only 3.4% are neutral. 23.7% disagree, and 10.2% strongly disagree. The results indicate that although most participants (62.8%) agree, around 40% do not consider the construction industry as one of the main contributors; hence, the respondents do not have a consistent view that construction has heavier impacts on the carbon footprint.

4.2. Understanding and implementation of circular economy

Question No. 4 (Fig. 3) was designed to show participants' knowledge regarding the concept of the circular economy and the implementation of circular economy in the construction industry. According to the results, 30.5% regularly read about the circular economy and are updated about its developments, whereas 49.2% regularly read about it but are not updated on its implementation. 13.6% have heard the term 'circular economy' but have not learned much about it. 2.7% have only heard about the term 'circular economy' but do not know it. The results indicate that most respondents know about circular economy but are not very familiar with its implementation.

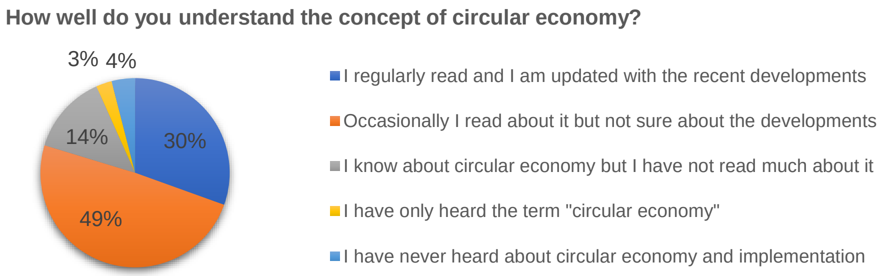


Fig. 3. Responses from the survey participants regarding Question No. 4

4.3. Sustainable approach and resource management in the construction industry

Question No. 7 (Fig. 4) was designed to reveal the participants' opinions considering the sustainable approach and resource management in the construction industry. Carbon footprint is one of the major concerns towards the environment globally, and the construction industry is arguably one of the major contributors to carbon footprint; therefore, it is essential to reduce its carbon footprint exposed to the environment. Fig. 4 shows the options through which carbon footprint could be reduced. More than half of the respondents (52.5%) voted to adopt the MMC and manufacture components in a factory environment, reflecting the agreement on using modular construction.

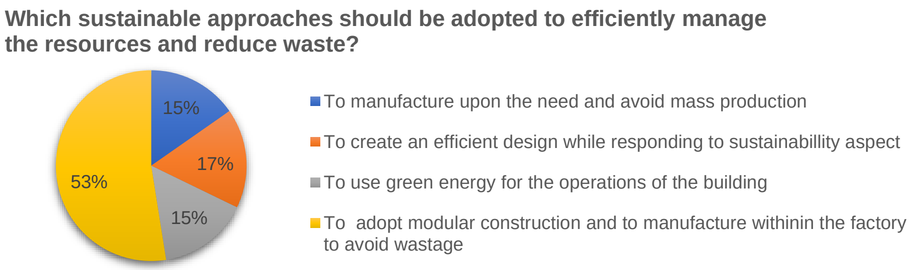


Fig. 4. Responses from the survey participants regarding Question No. 7

4.4. Advantages and limitations of MMC

Question No. 10 (Fig. 5) was designed to reflect respondents' direct opinions' on MMC's potential for a circular economy. The prefabricated or industrialized modular building systems have been suggested in the literature as a potential approach toward sustainable development and can be more beneficial when combined with the concept of circular economy. According to our survey results, 76.3% of participants believe that MMC complies with the concept of circular economy, while 20.3% do not believe so, and 3% are not sure about the relevance of this approach. The results indicate a strong consensus among the different participants to develop the idea of circular economy through expanding MMC processes.

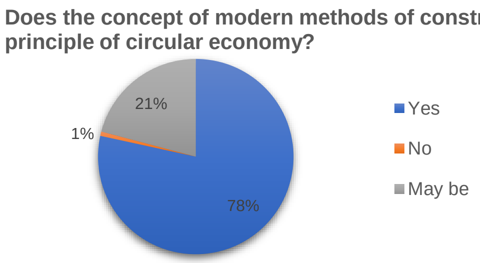


Fig. 5. Responses from the survey participants regarding Question No. 10

5. Conclusions and Recommendations

In the context of sustainable transformation of the construction industry, this research was carried out to review the impact of the carbon footprint emitted by the construction industry and get some insights about the participants' perceptions of circular economy in the industry. A questionnaire survey was performed to collect the opinions of 59 participants distributed among civil engineers, project managers, researchers, environmentalists, and architects. Preliminary findings from this study recommend MMC as a promising alternative to traditional construction to reduce wastage. The results also show a strong consensus among the questionnaire respondents regarding the alignment of MMC with a circular economy in construction. The results from this study are limited to the small sample of the participants, and caution should be made to avoid generalizing the findings to reflect the opinions of the entire industry.

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Non-Destructive Testing of the Unique Structure Made of Post-Tensioned Concrete

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Abstract
The paper describes the non-destructive in situ testing of the unique worldwide post-tensioning concrete load-bearing structure of a two-segment high building, which has been in operation for over 40 years. The scope of the tests included the determination of the number and location of the prestressing cables and the filling of the cable ducts with cement injection, which protects the prestressing steel against corrosion. Three complementary nondestructive methods, including ultrasonic tomography, and apparatus equipped with specialized software useful for recording and analyzing the obtained results, were used in the investigation. For the purpose of the conducted research, an original methodology of non-destructive testing of massive post-tensioned concrete structures has been developed, which may also be useful for other researchers who are faced with the problem of testing such structures.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2022.

Keywords: high building, cable-concrete load bearing structure, non-destructive methods, prestressing cables

1. Introduction

Buildings with a cable-concrete structure were erected around the world from around the mid-sixties to around the mid-eighties of the last century. At that time, slightly more than twenty buildings of this type, ranging in height from 70 to 105 meters, mainly for office purposes, were built in various countries around the world. The supporting structure of the core-rope building consists of: a reinforced concrete core on a reinforced concrete foundation, a post-reinforced concrete structure at the top of the core, reinforced concrete slab ceilings and steel ropes [1].

At that time, the innovative technology for erecting these buildings consisted of building a reinforced concrete core and a cable-concrete structure topped with it and then constructing monolithic reinforced concrete floor slabs of individual floors at the ground floor level. These ceilings were then raised to the desired height using a set of hydraulic actuators and fastened on one side to the reinforced concrete shaft, and on the other side hung on steel ropes attached to the post-tensioned concrete topping.

Considering the fact that the core-ropes buildings were built incidentally, according to individual designs, by contractors who have no previous experience in this type of projects, now, after 40 years or even longer operation, questions about their technical condition become justified, including compliance of the execution of the load-bearing structure with the design. Many questions are related to the compliance of execution with the design of large post-reinforced concrete load-bearing structures capped by reinforced concrete cores, which are crucial for the load-bearing capacity and safety of use of core buildings. Virtually every cable-concrete load-bearing structure of this type is unique on a global scale, not only due to its structure but also due to the individual conditions of execution, including, among others, cable tensioning and duct injection in various weather conditions and at high altitudes.

The main questions concern whether the number of prestressing cables, their routing, and position are in accordance with the design and whether the cable ducts are tightly filled with cement injected protecting the prestressing steel against corrosion. Knowledge in this matter is of great importance for a credible expression in terms of load-bearing capacity, further safe use, durability forecasting, purposefulness of modernization activities, etc. This knowledge can be obtained to a large extent through research, using appropriately selected non-destructive methods [2 , 3, 4].

With reference to the above considerations, the paper presents selected results of tests of two identical post-tensioned concrete load bearing structures of a two-segmented shaft building that has been operated for forty years, with the use of complementary nondestructive methods.

The intention of the authors is to share the knowledge and research experience acquired during the nondestructive testing of unique post-tensioned concrete elements that make up these systems, including the original methodology developed for the purpose of the research. This knowledge may be useful to other researchers who face the problem of diagnosing buildings with a core-rope structure.

2. Brief description of the building and of the tested cable-concrete load-bearing structure

The tall molar building shown in Figure 1 is located in Poland and was erected in the years 1979–1982 for office purposes. It consists of two segments, 96 m and 89 m high, respectively.

The supporting structure of each segment is a freestanding reinforced concrete core, terminated at the top with a post-tensioned concrete load bearing structure consisting of four double-cantilever girders prestressed with cables. The brackets are not enclosed from the outside, as shown in Figure 1b. The ceilings of the reinforced concrete slabs are suspended from the supports of the girders, using steel ropes covered with a sheet metal shield.

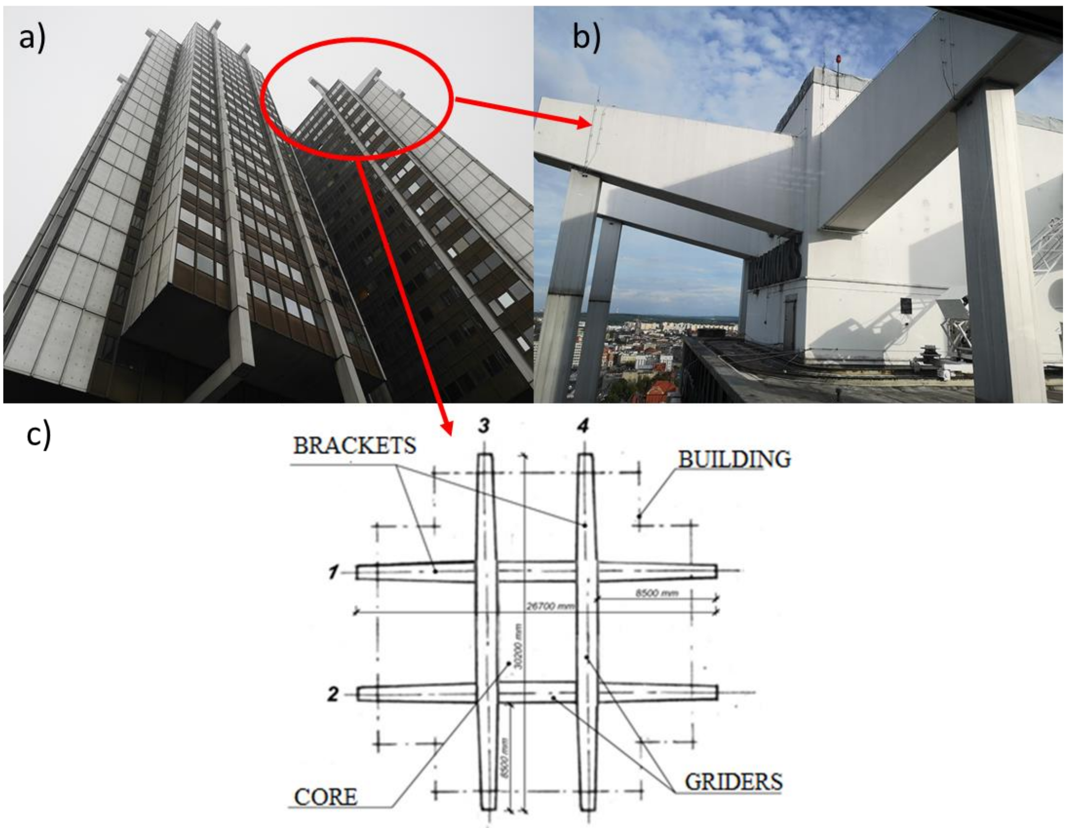


Fig. 1. General view of the building (a) view of the post-tensioned concrete load bearing structure (b) diagram of the reinforced concrete load bearing structure consisting of four girders (c).

The post-tensioned load bearing structures under study are identical in both building segments. Each of them consists of four massive double-cantilever post-tensioning girders made in one plane, with the pairs of girders mutually perpendicular to each other, as shown in the diagram in Figure 1c. The lengths of the girders are 30.20 and 26.70 m, and the length of the brackets is 8.60 m. The cross section of all the girders in the middle part is 1.50 x 3.50 m and is tapered on the brackets and amounts to 1.00 x 1.80 m at the end of the bracket.

According to the design, each of the girders provides 8 prestressing cables with a circular bundle of 72 prestressing wires with a diameter of 6 mm each. Each bundle of wires was placed in a 60mm guided tubular sheath made of steel sheet. After the cables were stressed, the project envisaged a cement injection inside the tubular sheath to fill all voids, wrap the wires, and protect them against corrosion. In addition to the prestressing cables, the girders also have traditional reinforcement of ribbed bars φ 16 and φ25 mm, above the cables at the upper edge of the cross-section and at the lower edge of the girders cross-section and at the side surfaces of the girders.

3. Research methods and methodology used

After analyzing the design documentation, three complementary nondestructive electromagnetic, ultrasonic tomography, and impact echo methods were selected for the study of the load-bearing structure consisting of massive post-tensioned concrete girders. The research methodology was then developed, the general scheme of which is presented in Figure 2 and is described below.

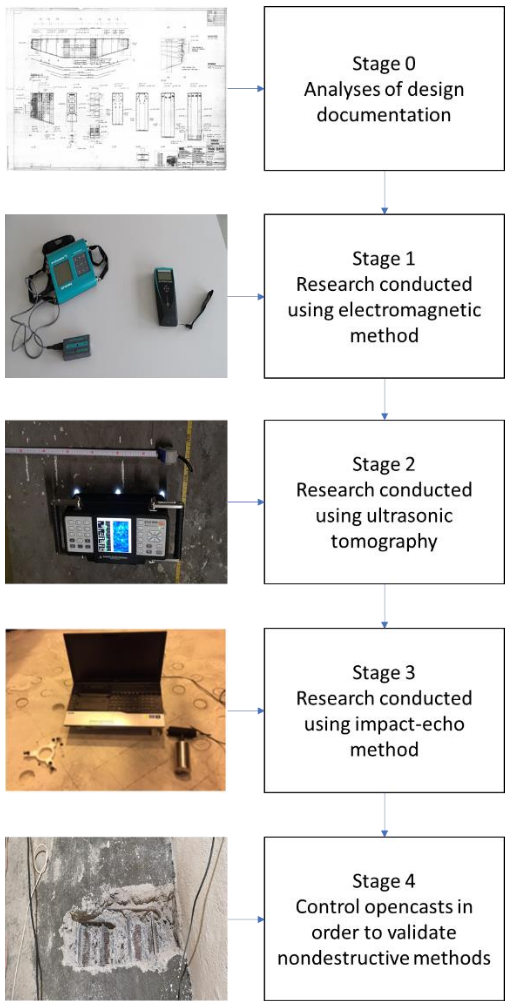


Fig. 2. General scheme of the methodology for the non-destructive testing of post-tensioned concrete beams.

First, research using the electromagnetic method was carried out (stage 1) [2, 3]. They were used for control tests preceding ultrasonic tomography tests. With the use of a device called Profemetr, the subsurface zone of post-tensioned concrete girders on their upper surface and, moreover, on the side surfaces of the brackets, was examined on an ongoing basis to locate the location of traditional reinforcement in the form of longitudinal and transverse steel reinforcement bars placed in the concrete. Knowledge of the position of these rods was helpful for the tests carried out with the ultrasonic tomography method.

In stage 2, the ultrasonic tomography method [3, 4, 5] was used to locate the route of the cable conduits and the position of the prestressed cables, and to assess the quality of the concrete concreting of these channels and to locate possible air and under-concrete gaps. For this purpose, a Mira A1040 ultrasound tomograph was used. To determine the location of the prestressing cables and reference the obtained results to the design documentation, it was assumed in the test methodology that each of the girders would be examined in detail in nine characteristic cross sections. These were the sections for which the location of the prestressing cables was shown in the design documentation. Only in these sections were possible to compare the results of nondestructive tests with the assumptions given in the design documentation. In each girder, eight of these nine characteristic cross sections were in the brackets (4 on the left and 4 on the right), while one was in the middle of the girder length (inside the reinforced concrete core of the building), as shown in Figure 3.

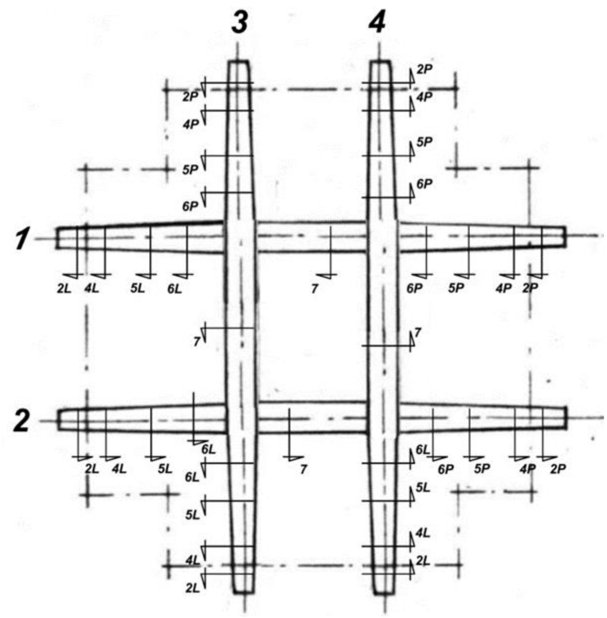


Fig. 3. Scheme of the distribution of characteristic cross sections in the tested post-tensioned concrete girders forming the load bearing structure.

For each measurement site, in each of these characteristic cross sections, the results obtained were recorded as a graphic image, determining the location of individual prestressing cables after a detailed analysis.

In stage 3, the impact-echo method was used [2, 3, 4, 5]. After locating the cable ducts in the post-tensioning girders in stage 2 with the use of an ultrasonic tomography, this method was used to locate the holes not filled with cement injection. The impact-echo method is based on the excitation and introduction to the tested spar, at individual test points, of an elastic wave by means of an inductor placed on the measuring head, and the returning elastic wave is picked up using the same head. On the basis of this analysis, the dominant frequency in the obtained spectrum is distinguished, corresponding to the thickness of the spar, and the frequency corresponding to the reflection of the elastic wave from the prestressing cable or from the air void, if such a void exists in a given testing place. The lack of a tight filling of the cable duct with a cement injector creates such a void. The research sites for this method were spaced approximately every 20 cm along the length of the cable ducts located by ultrasonic tomography. It was assumed that only those amplitude-frequency spectra would be saved in the computer's memory, which would raise the suspicion of the existence of an air void in a given research site and, therefore, require careful analysis in studio conditions.

The test results obtained with nondestructive methods were authenticated by means of control opencasts (stage 4). In each load-bearing structure, a strip cut of a small width was made on a post-tensioned concrete girder, so it was possible to measure the axial spacing and the depth of the position of the prestressing cables. Then, the sheet metal conduits of the cables were opened in the place detected by the nondestructive method of the lack of tight filling with cement slurry and in the place that did not raise any doubts.

4. Sample results and their analysis

As a result of the tests carried out in accordance with the methodology given in point 3, examples of the results of tests of one of the post-tensioned concrete girders in the middle section marked as 7 are presented below. These results were then marked on the cross section 7 of the girder, available in the design documentation, thus obtaining a comparison of the location of prestressing cables according to non-destructive tests (red) and according to the design documentation (black) Fig. 4e.

The tests show that the number of prestressing cables in the girder is 8, which is in line with the design. It also shows that the position of the prestressing cables slightly deviates from that given in the design, i.e. practically all prestressing cables in cross section 7 are located about 10cm higher than in the design.

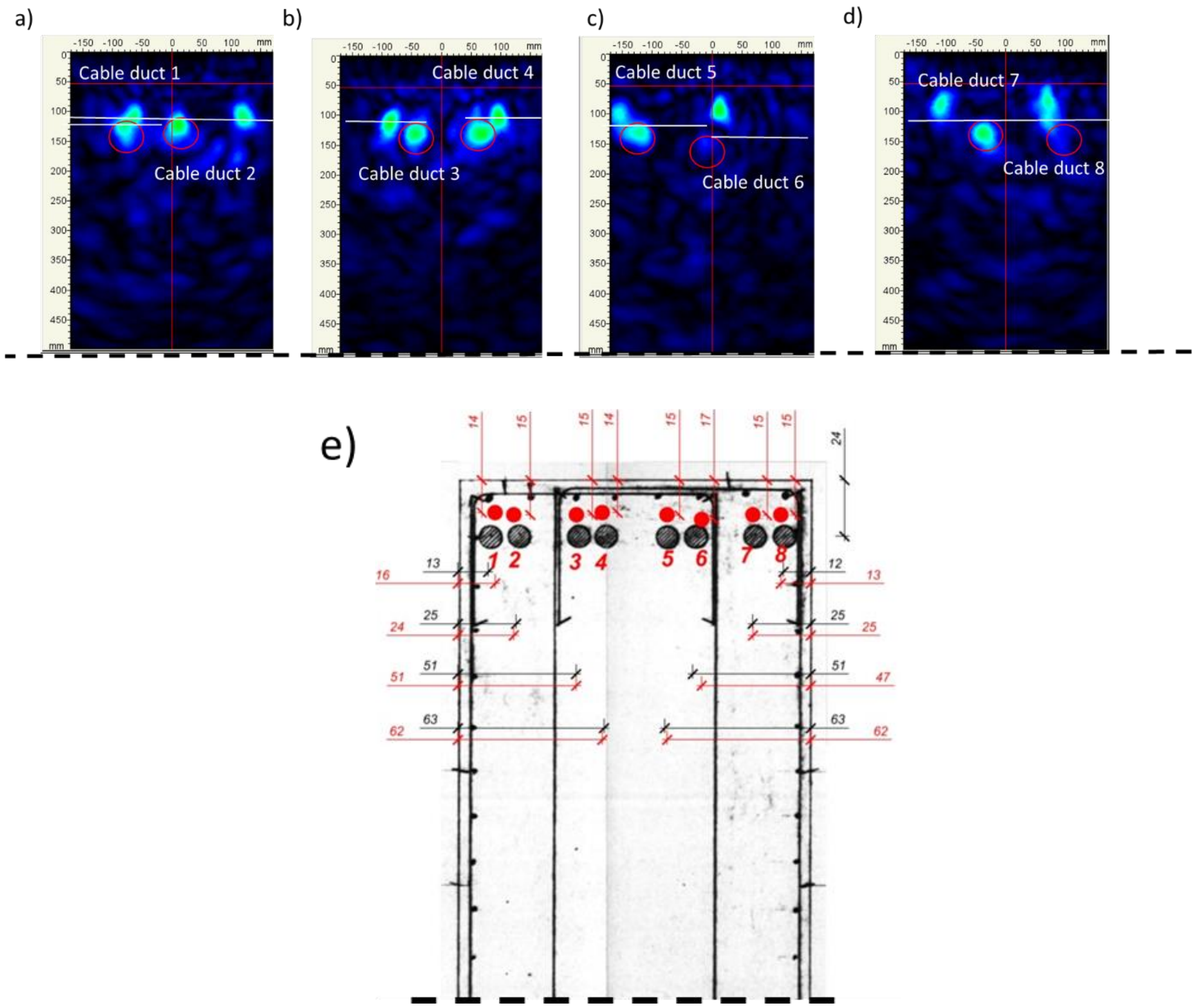
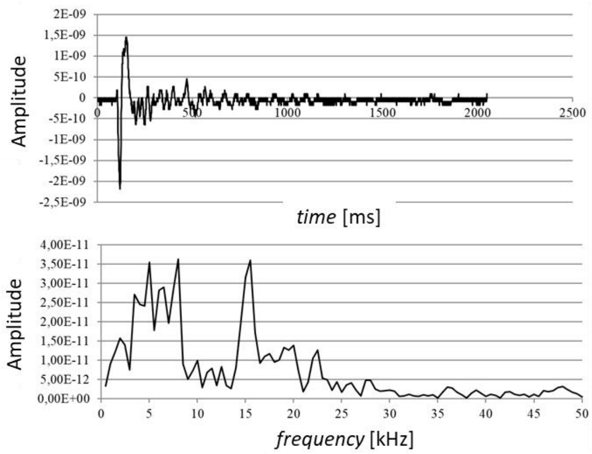


Fig. 4. Examples of illustrating the position of prestressing cables in one of the tested post-tensioned concrete girders in cross section 7, cables 1 and 2 (a) cables 3 and 4 (b) cables 5 and 6 (c) cables 7 and 8 (d) and a comparative table of their location according to tests nondestructive red and according to the design documentation (black).

In turn, Figure 5 presents examples of the results of tests that examine filling cable ducts with cement injection, obtained with the nondestructive impact-echo method. These results concern the same spar and were also obtained in cross section 7 in the place where the control opencast was made after the completion of the research. The amplitude-frequency spectrum shown in Figure 5a for channel 5 indicates that the cable channel is not tightly filled at this point with cement injection. This fact was confirmed by the control outcrop made here, shown in Figure 5b, which consisted of removing the metal sheet and opening the cable channel for a length of approximately 20 cm.

a)



b)

Fig. 4. An exemplary result of the leakage test of the cement injection filled cable conduit 5 in cross section 7: the amplitude-frequency spectrum obtained with the hammer method indicating the lack of tight cement injection filling (a) view of the open cable conduit with leaky cement injection filling (b).

5. Summary

The article presents selected results of research on reinforced concrete load-bearing structures in a high two-segment building that has been in operation for forty years, carried out with the use of complementary non-destructive methods. The massive double-cantilever post-tensioning girders that make up these structures were tested in terms of non-destructive determination of the number and location of the prestressing cables located in them and the tightness of filling the cable ducts with cement injection.

Three complementary nondestructive methods were selected for testing this unique cable-concrete structure in the world: electromagnetic, ultrasonic tomography, and impact echo. The work includes the original methodology developed for nondestructive testing, which was used during the research conducted, and the results of nondestructive testing were validated with opencast control.

The research results obtained were compared with the design assumptions. The number of prestressing cables in the girders has been shown to be consistent with the design, while their location slightly differs from that provided in the design. It has also been shown on the basis of nondestructive tests that there are deficiencies in the tightness of the cable duct filling with cement injection.

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Older Homes & Thermal Comfort: Homeowner Satisfaction in a Southern U.S. City

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Abstract

This research study evaluated the impact of older home ownership on thermal comfort and overall homeowner satisfaction. Homeowners living in houses built 50 or more years ago in the Crescent Hill neighborhood of Louisville, Kentucky were surveyed. Homes studied were built between 1865 and 1963. The results of this 20-question survey were analyzed to form conclusions as to whether there is a link between thermal comfort, the age of older homes, and overall home satisfaction. The following themes immerged from the results of the analysis: (1) Are Homeowner's thermal needs being met by their HVAC system? (2) What impact does thermal comfort have on overall home satisfaction? (3) Has the experience of living in an older home impacted their likelihood of living in an older home in the future? The data analysis supports the conclusion that many homeowners living in older homes deal with a broad range of thermal comfort issues which detract from their thermal comfort. While most respondents indicated satisfaction with their homes, these homeowners often experienced negative thermal phenomena and over half of the homeowners supplement their home's primary HVAC system with additional heating and cooling products. The results of this survey also indicate that these reported thermal comfort issues have caused a clear shift in the respondents' reported importance of thermal comfort as a consideration when purchasing a home.

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Keywords: Residential, HVAC, Thermal Comfort, Home Satisfaction

1. Introduction

There are many elements that make up an individual's overall satisfaction with their home. Elements such as home size, location, privacy, outdoor location, and resident age are only some of the examples that impact home satisfaction. (*A Happy Home: Identifying the Factors That Influence Home Satisfaction*, n.d.) With so many factors impacting overall homeowner satisfaction, it is productive to look at a narrow focus of specific elements that impact overall homeowner satisfaction. A specific focus that has received little attention in the area of homeowner satisfaction and housing research is the impact of older homes on homeowner satisfaction. (Peek & Carswell, 2018) This area is worth researching as, according to Eye on Housing, the share of owner-occupied housing built 46 years or more in the past has increased from 31% in 2006 to 38% in 2016. In contrast to this, the estimated percentage of owner-occupied housing built in the year 2000 or later makes up only an estimated 20% of housing. (*Half of US Homes Built before 1980 | Eye On Housing*, 2018) With this large portion of the U.S. housing stock being nearly 50 years or older, the impacts of home age on residential satisfaction is of particular importance as the stock of new homes continues to be outpaced by an aging U.S. home stock.

As the U.S. housing market ages, it becomes vital for prospective homebuyers to recognize that the average U.S. home has changed as well. The fact that approximately 38% of U.S. homes are 46 or more years old is made more relevant to homeowner satisfaction as homes can be classified as old aged at 50 years or more after construction (*RDH Building Science | How Long Do Buildings Last?*, 2015). Many universal features have become common in the typical home that were previously not available such as ubiquitous energy-efficient heating and cooling systems or complete plumbing facilities.(*1900 TO 2010: EVOLUTION OF THE AMERICAN HOME TODAY: FUN HOUSING FACTS. - Chicago Tribune*, n.d.)

In addition to this lack of now common new build construction features, there are many negative attributes specifically associated with older homes including outdated plumbing, single-panel windows, non-working windows, and overall energy-efficiency issues. (White, 2014) These issues often manifest themselves in energy inefficiency, which creates a more challenging environment for residents to maintain overall satisfaction with their home's thermal comfort.

2. Background

Thermal comfort is of particular interest when researching homeowner satisfaction with older homes. The reason for this is "the thermal environment has a great influence on human behavior, productivity, satisfaction, and well-being." (Wells et al., 2015) As this element can have such a large impact on a wide variety of elements, it is important to isolate as a uniquely important factor which may impact homeowner satisfaction.

Research into older buildings and the associated thermal comfort has been a topic of growing interest. (Martínez-Molina et al., 2016) However, much of the study that has been completed focuses on the energy performance of historic buildings. Moreover, according to Martinez-Molina, "These studies primarily focused on buildings from the 20th, 19th, and 14th centuries, which were generally located in Italy, UK, Spain and China." This clearly demonstrates that the primary areas of focus in the existing body of research predates much of the average U.S. housing stock and may contain local or historic differences in construction practices. By combining the factors of non-U.S. construction and a focus on homes which go well beyond the average age of homes in the U.S. it is difficult to draw conclusions applicable to currently aging U.S. housing market regarding thermal satisfaction and its overall effect on homeowner satisfaction. The challenges associated with these truly historic homes surveyed are unique and separate from the challenges that likely face homes which are considered old in the U.S.

When reviewing research into older homes in the United States, much of the focus tends to be on best practices regarding housing retrofits in historic homes, often with an emphasis on energy savings and efficiency improvements that can be made. As a result, what information there is in this area leaves room for new research to be conducted regarding actual living conditions homeowners experience and the impact those conditions have on overall homeowner satisfaction.

One indicative study shows a common area of focus in the field of older homes. Mukhopadhyay assessed the impact of housing retrofits in Havre Monta. (Mukhopadhyay et al., 2019) However, this assessment focused heavily on the methodology of retrofitting buildings and the follow-on effects that this has on energy savings and carbon emissions. This assessment does identify that there are increases in thermal efficiency and quality of performance regarding these homes' HVAC systems, but ultimately does not provide an analysis of the user experience associated with these improvements.

Despite the lack of research into the homeowner's lived experience in this topic, there is a proven relationship between low levels of thermal comfort and overall homeowner satisfaction. ("The Relationship between Thermal Comfort and User Satisfaction in Hot Dry Climates," 1997) Specifically, this study found that "in its strong positive correlation with overall user satisfaction, thermal comfort should be given a special weight and consideration by architects in the design of housing in hot dry climates." This outcome provides us the information that thermal comfort is uniquely important to overall user satisfaction.

3. Research Methodology

To develop a greater understanding of the impact overall thermal comfort has on occupants of older homes, a study was conducted in the Crescent Hill neighborhood in Louisville, KY. Louisville was determined a strong area to survey regarding homes aged 50 years or more as approximately 53% of homes in the Louisville metro area were built in 1974 or earlier according to the 2013 American Housing Survey (Bureau, n.d.) It was determined that gathering quantitative data would be most appropriate as there is a large population of homes aged 50 years or older and there is a lack of broad qualitative surveys conducted in researching this topic.

A 20-question survey was distributed via a social media website Nextdoor and was restricted to verified members of the Louisville Crescent Hill neighborhood. The survey was available online for one week. When developing the questions, the author targeted the following three categories of homeowner satisfaction information.

1. Are Homeowner's thermal needs being met by their HVAC system?
2. What impact does thermal comfort have on overall home satisfaction?
3. Has the experience of living in an older home impacted their likelihood of living in an older home in the future?

To survey whether their home sufficiently meets the homeowner's thermal comfort needs, the author adapted a sample thermal environment satisfaction survey provided in ASHRAE Standard 55 (Atlanta, n.d.). The survey gathered home demographic information requesting home age, home square footage, number of bedrooms, number of stories, and years lived in the home. The survey further asked respondents to rate their home comfort and identify the frequency of negative thermal phenomena, and whether supplemental air conditioning/heating products are used. If they were used, the survey requested participants to identify their corresponding importance to overall home comfort. The survey then asked homeowners to rate their overall thermal satisfaction. The survey then asks respondents to rate the importance of thermal satisfaction to overall home satisfaction, how important of a factor thermal satisfaction was at the time of home purchase, how important of a factor thermal satisfaction would be if they were purchasing a new home, and whether they would consider purchasing an older home again in the future. There were 44 responses to the survey though some respondents did not answer all questions.

4. Data Analysis

4.1 Demographic Information

A breakdown of respondent demographic information is as follows:

- Average home was built in 1925 with respondents' homes overall built between 1865 and 1963
- Average home sq. footage is 2105 sq. feet with respondent homes ranging between 980 to 10,000 sq. feet
- The average respondent has lived in their home for 17 years with respondents ranging between 1 and 30 years
- Most homes were 3 bedrooms and 2 stories with the following percentage respondent breakdown
    - 1 Bedroom – 2.27%
    - 2 Bedrooms – 25.00%
    - 3 Bedrooms – 38.64%
    - 4 Bedrooms – 25.00%
    - 5 Bedrooms – 9.09%

    - 1 Story – 20.45%
    - 2 Stories – 61.36%
    - 3 Stories – 15.91%
    - 4+ Stories – 2.27%

This indicates that the average demographic of all respondents' home's is approximately 96 years old with 2105 sq. feet, 3 bedrooms, and 2 stories. In his article providing an overview of the U.S. building stock, Dr.

Diamond states “the average existing single-family home has 3.0 bedrooms and 1.5 full bathrooms, for a total of 2280 ft2 of floorspace…” (Richard C. Diamond, 2001). Therefore, we can conclude that the number of bedrooms and square footage of the homes identified in the survey are roughly indicative of the average existing single-family home. As this is the case, we can more accurately correlate any thermal dissatisfaction associated with the properties associated with an older home and not necessarily differences in the number of rooms or square footage differences between respondent homes and average home properties.

4.2 Home Sufficiency of Meeting Thermal Requirements

The analysis of Question 6 regarding respondents’ satisfaction with the temperature of their home is broken down in Table 1 below:

Table 1. Home temperature satisfaction

Question 6: How Satisfied are you with the temperature in your home?		
Range of Satisfaction 0 (Highly Satisfied) - 6 (Highly Dissatisfied)	Number of Responses	Percent of Responses
0	4	8.89%
1	10	22.22%
2	12	26.67%
3	10	22.22%
4	6	13.33%
5	2	4.44%
6	1	2.22%

This shows 57.78% of those surveyed expressed satisfaction (rating 0, 1, or 2) with the temperature of their home compared with 22.22% expressing a neutral opinion of their home’s temperature and 19.99% of respondents indicated dissatisfaction (rating 4, 5, or 6) with their home’s temperature. This shows that despite most survey respondents expressing satisfaction with their home’s temperature, a significant percentage of respondents (42.21%) did not have a favorable view of their home temperature.

An analysis of Question 7: regarding frequency of negative environmental phenomena is broken down in Table 2 below:

Table 2. Frequency of negative thermal phenomena

Question 7: How Often do you experience any of the following?										
Question	Never		Rarely		Sometime		Often		Almost Always	
Temperature too hot	8.89%	4	26.67%	12	44.44%	20	15.56%	7	4.44%	2
Temperature too cold	8.89%	4	42.22%	19	42.22%	19	6.67%	3	0.00%	0
Humidity too high (Damp)	26.67%	12	42.22%	19	22.22%	10	6.67%	3	2.22%	1
Humidity too low (Dry)	40.00%	18	46.67%	21	13.33%	6	0.00%	0	0.00%	0
Air movement too high (Drafty Air)	42.22%	19	46.67%	21	8.89%	4	2.22%	1	0.00%	0
Air movement too low (Stagnant Air)	33.33%	15	44.44%	20	13.33%	6	8.89%	4	0.00%	0
Drafts from windows	40.00%	18	26.67%	12	22.22%	10	8.89%	4	2.22%	1
Drafts from vents	51.11%	23	37.78%	17	8.89%	4	2.22%	1	0.00%	0
Uneven room temperature	11.11%	5	31.11%	14	28.89%	13	20.00%	9	8.89%	4
Totals	N/A	118	N/A	155	N/A	92	N/A	32	N/A	8

The above illustrated Table 2 indicates two negative environmental thermal phenomena that occur in a statistically significant frequency. The first negative environmental thermal phenomenon respondents identified as often or almost always being experienced is uneven room temperature making up 28.89% of responses. The second most common phenomenon identified as being often or almost always experienced is the temperature being too hot. This phenomenon makes up 20% of responses. This suggests a statistical correlation between older homes and the temperature being too hot or rooms being unevenly heated. Uneven heating between rooms can often be the result of HVAC/ductwork being improperly sized or laid out for a home.

Respondents indicating dissatisfaction with their home's temperature (Rating between 4-6) as identified in Figure 1 above, provide corroborating responses regarding the frequency of their home being often too hot among those who are dissatisfied with their home. The breakdown of questions 8 and 9 is demonstrated in Figure 1.

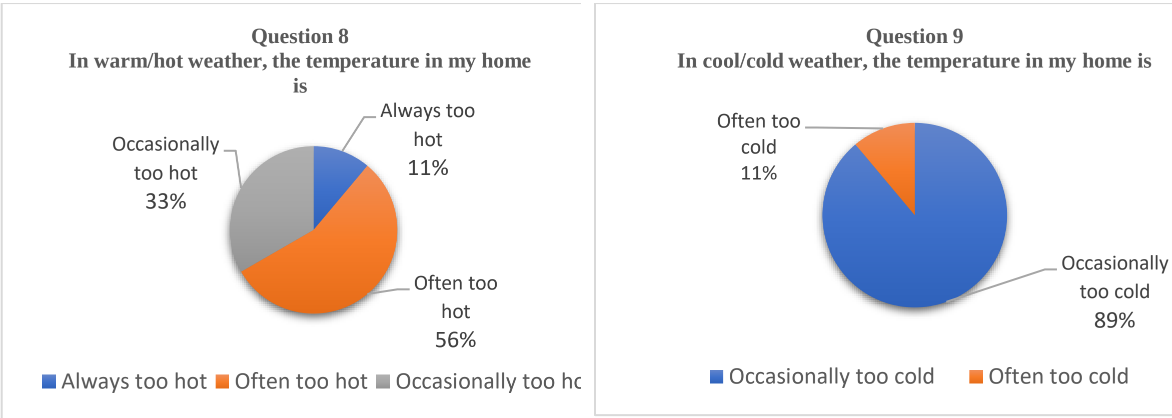

Figure 1. Frequency of unsatisfactory home temperature among respondents dissatisfied with their home's temperature

Figure 1 indicates the primary element of discomfort is experienced during warm/hot weather as 67% responded that their home is often or always too hot as indicated in Figure 1 above. In cool/cold weather, 89% of these respondents indicate that they only occasionally experience the temperature in their home being too cold.

Of respondents who indicated they were satisfied with their home's temperature (rating 0, 1, or 2) in Table 1, 51.43% indicated they supplement their HVAC system with additional heating/air condition products while 48.57% of respondents did not. A breakdown of how important supplemental heating/air condition products are to home comfort is below in Figure 2.

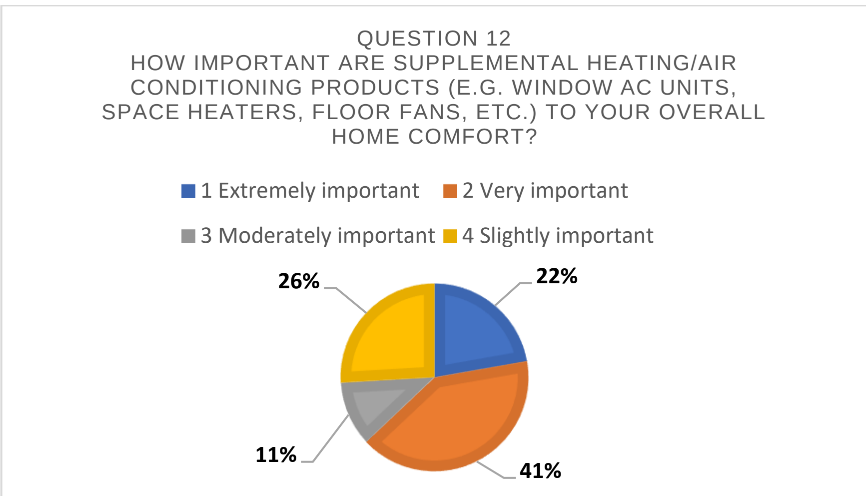

Figure 2: Importance of supplemental heating/air conditioning products among those who supplement

Looking at those who reported supplementing their HVAC system, 62.96% of respondents indicated that their supplemental heating/air conditioning products were very or extremely important to their overall home comfort. This response pattern indicates that while most respondents report overall satisfaction with their home's temperature, this satisfaction is achieved through the use of supplemental heating/air conditioning products.

4.3 Impact of Thermal Comfort on Overall Home Satisfaction

A majority of respondents, consisting of 79.55%, indicated overall, they were satisfied with their home's thermal comfort including their primary HVAC system and any supplemental equipment. Most respondents further indicated that thermal comfort was very or extremely important to their overall home satisfaction. This indicates that most respondents achieve a state of home satisfaction despite the age of their homes and corresponding challenges in maintaining a comfortable thermal environment in their home.

There were nine respondents who indicated they were neither satisfied nor dissatisfied, somewhat dissatisfied, or extremely dissatisfied with their home's thermal comfort. Table 3 provides a breakout of overall home satisfaction among those who indicated they were not satisfied with their home's thermal comfort.

Table 3: Overall home satisfaction among respondents not satisfied with home thermal comfort

Question 15: Overall, how satisfied are you with your home?	%	Count
Extremely satisfied	11.11%	1
Somewhat satisfied	55.56%	5
Neither satisfied nor dissatisfied	11.11%	1
Somewhat dissatisfied	11.11%	1
Extremely dissatisfied	11.11%	1

Further analysis of this group's response to question 15 shows that 66.67% of respondents were somewhat satisfie0d or extremely satisfied with their home. Further, only 22.22% of these respondents expressed dissatisfaction with their home overall. Therefore, while respondents living in these older homes could generally achieve greater satisfaction if their home were able to achieve greater thermal comfort, respondents are able to achieve satisfaction with their home despite the acknowledged challenges faced in maintaining their thermal comfort.

4.4 Occupant Likelihood of Living in and Older Home in the Future

The data from questions 16 and 17 regarding the importance of thermal comfort is broken-down and summarized in Table 4.

Question Percent is in top cell while number of answers is in the bottom cell	Not at all Important	Slightly Important	Moderately Important	Very Important	Extremely Important
Question 16 How important was your home's overall thermal comfort to you when deciding to purchase your current home?	27.27%	29.55%	29.55%	9.09%	4.55%
	12	13	13	4	2
Question 17 How important would a home's thermal comfort be to you when deciding to purchase a new home?	2.27%	13.64%	22.73%	38.64%	22.73%
	1	6	10	17	10

Table 4: Home thermal comfort importance at original purchase vs. new purchase importance

The data shown in Table 4 indicates that 56.82% of respondents found their prospective home's thermal comfort to be not at all or slightly important as a factor when deciding to purchase their home. Only 13.64%

of respondents indicated that their home's thermal comfort was very or extremely important when deciding to purchase their current home. 29.55% of respondents found this factor to be moderately important in their decision to purchase their current home.

In contrast to the results of question 16, 61.37% respondents indicated that a home's thermal comfort would be very or extremely important as a factor to consider when deciding to purchase a new home. This represents a 31.82% increase in the those stating it would be very or extremely important when deciding to purchase a new home. In support of this, 15.91% of respondents indicated it would be not at all or slightly important which represents 40.91% decrease among respondents who indicate thermal comfort would be not at all or slightly important when deicing to purchase a new home. This indicates that while many respondents did not initially consider thermal comfort heavily when purchasing their current older home, the experience of living in an older home has significantly increased the importance of thermal comfort as a factor when making a new home purchase decision.

This change in opinion is somewhat mitigated by the results of question 18 where respondents were asked about their likelihood to consider purchasing an older home again in the future. The responses to this question are broken down in Table 5 below.

Question 18: If you were to purchase a new home, how likely would you be to consider purchasing an older home?	%	Count
Extremely likely	47.73%	21
Somewhat likely	27.27%	12
Neither likely nor unlikely	22.73%	10
Somewhat unlikely	2.27%	1
Extremely unlikely	0.00%	0

Table 5: Likelihood of purchasing an older home

Table 5 shows us that 75% of respondents would be somewhat or extremely likely to consider purchasing an older home in the future. Furthermore, only a single respondent indicated that they would be unlikely to consider purchasing an older home in the future. This suggests that while many respondents report an increased likelihood to heavily consider thermal comfort when purchasing a home in the future as indicated in Table 4, most respondents still find the prospect of living in an older home to be an attractive prospect.

5. Conclusions and Future Research

The results of this study indicate that most homeowners occupying older homes in the Crescent Hill Neighborhood of Louisville, Kentucky (79.55% of respondents) are satisfied with their homes. While many of the respondents reported that there are issues with their home's ability to achieve a fully satisfactory thermal environment, respondents are overall satisfied with their homes. As Abidin indicates, residential satisfaction is a complex construct to evaluate as it consists of socio-demographic characteristics, housing characteristics, neighborhood characteristics, and behavioral characteristics.(Abidin et al., 2019) As thermal comfort is only one element impacting housing characteristics, it is understandable that, while important, challenges with thermal environment alone are not enough to drive the satisfaction level of homeowners.

The results of this survey do support the conclusion that many homeowners living in older homes deal with a broad range of thermal comfort issues which detract from their thermal comfort. While most respondents indicate satisfaction with their homes, these homeowners often experience negative thermal phenomena and over half supplement their home's primary HVAC system with additional heating/cooling products. The results of this survey indicate that these reported issues have caused clear shift in the respondents' reported importance of thermal comfort as a consideration when purchasing a home. As indicated in Table 4, from the time respondents originally purchased their homes to the point at which they have taken the survey. It is apparent that the experience of living in an older home, and subsequently dealing with the thermal satisfaction challenges associated with older homes, has increased their personal awareness of the importance of considering a home's ability to meet their personal thermal comfort needs.

A factor not evaluated in this study was the frequency, extensiveness, and overall impact thermal improvements and HVAC retrofits have on overall homeowner satisfaction with older homes. The impact of retrofits and other modernization efforts can make to the ability of older homes to maintain a comfortable thermal environment is a worthy area of further study. There are studies indicating that thermal comfort and overall indoor air quality are improved through energy efficient retrofits. (Fisk et al., 2020) However, due to the wide variety of possible thermal improvements and HVAC retrofits that homeowners can implement, any attempted research on this topic could be challenging to accurately conduct on a large basis as it is reliant on homeowner knowledge of improvements home improvements.

Another worthwhile area for potential future research could be to evaluate homeowner priorities when purchasing an older home and conducting follow-on interviews or surveys as time passes to study the impact of a homeowner's lived experience and associated changes in priority of the elements which were considered during the purchase of the home. This could provide useful information to prospective homebuyers regarding whether there is a trend of home buyers purchasing older homes without properly considering the specific challenges that this research has indicated. The findings of this paper may ultimately be helpful to those who are considering purchasing an older home. While many homeowners achieve overall satisfaction with their home, prospective buyers should be made aware that there are real and unique areas of challenge associated with achieving a satisfactory thermal condition in older homes. The trends identified during this research should be thoughtfully considered by prospective homeowners.

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Potential of Parametric Modeling for Structural Optimization A Variant Study of Industrial Buildings with Different Timber Structure Systems

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Abstract

Global warming and global scarcity of resources drive the need for optimization of industrial buildings. The construction industry is one of the most resource-intensive economic sectors and at the same time belongs to most of the man-made raw material storage. To contribute to a resource-efficient future in the construction sector, a multi-objective optimization (MOO) of the supporting structures can be created within the framework of the planning phase in which numerous case-studies are carried out. Due to the uniqueness of each construction project and the complex technical model data input, very few case-studies can be carried out in the phase of conservative planning. On this occasion, a generative tool for the parametric optimization of industrial timber-specific supporting structures has been created within the scope of this paper. A novel optimization approach used in this work represents the concept of MOO based on the parametric structural modelling. Due to the above-mentioned aspects, the developed tool has been named "*MOPTS*" (*M*ulti-objective *op*timization of *t*imber *s*tructures). As part of the research presented in this paper, a test case was carried out on an already built-up object. It was demonstrated that by *MOPTS* tool assisted structural planning almost 5 tons of timber material were saved also by using fewer bearing elements.

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Keywords: industrial buildings, parametric modeling, structural optimization, timber structure systems.

1. Introduction

The quest towards material savings, efficient planning and sustainability is becoming increasingly important in the construction industry. The emphasis of this undertaking in the future must not be limited to rare megastructures, but also to simple common structural parts and elements in civil engineering. In fact, the latter represent the bulk of material consumption in the construction sector [1]. Due to the uniqueness and complexity of each construction project, very few case-studies can typically be carried out during a conservative planning phase, a constraint which often leads to inefficient constructions. Also current powerful *modelling and analysis tools don´t allow designers to integrate structural performance as an objective during conceptual design* [2]. On the other side, more and more developers try to implement optimization tools into their software, such as [3] and [4]. However, their functionality is often limited due to inability of defining optimization parameters and targets freely and depending on the situation. Additionally, *many traditional optimization methods have seen only limited application in the conceptual design of buildings, despite* *the emphasis contemporary designers place on building performance* [5]. Integrating generative processes of parametric modelling and the approach of multi-objective optimization (MOO) in the structural planning allows for overcoming this limitation.

In more detail, a parametric optimization tool for industrial timber structures named "*MOPTS*" (*m*ulti-objective *op*timization of *t*imber *s*tructures) is developed herein. It intends to serve as an aid to engineers, planners, investors, and stakeholders in order to find sustainable and economical solutions of industrial timber bearing systems in the very early phases of construction planning by using optimization processes with the help of parametric modelling.

2. Methodology

The *MOPTS*-tool is developed within the commercial Software *Rhinocero3D* [6] with the help of the visual-based programming language *Grasshopper3D* [7]. The structural modelling, based on computational parametric algorithms of the *Grasshopper3D*-environment, the finite element (FE) analysis with *Karamba3D* [8] and the optimum´s evaluation with assistance of MOO constitute the functional and methodological approach of the *MOPTS*-tool, see also **Fig. 1**.

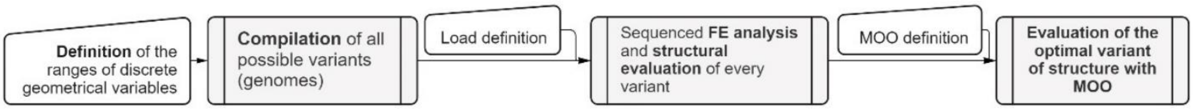

Fig. 1: Methodological approach of the *MOPTS*-tool.

The functionality of parametric algorithms allows to define structural-topological data of (FE) models depending on each other. *Sakamoto* describes the essence of parametric design in his work "*From Control to Design"* [9] as follows: "*based not on fixed constant metric quantities, but on consistent relationships between the objects"*. Thus, changing one input parameter will affect subsequent changes in other corresponding data. The parametric algorithms available in *Grasshopper3D* play an indispensable role in the structural optimization within the *MOPTS* tool and provide flexibility in the structural modelling and in the result evaluation.

The finite element analysis (FEA) with *Karamba3D* provides deformations, inner forces, and stresses. They are subsequently used for the structural design according to the building codes – in the case of *MOPTS* tool – according to Eurocode (EC) with the usage of Austrian National Application Document (NAD).

The concept of MOO is considered within the *MOPTS* tool. Thus, the optimization's problem represents a multi-criterial state, that means that more than one target function (fitness function f_v) is to be optimized concurrently. *Improvements in one objective function can lead to deterioration in other objective functions*, as Stein states in [10].

One of the most popular ways of solving MOO problems is establishing the *Pareto front*, which is *represented by not (weakly-) dominated efficient points (solutions)* [11]. The *scaling method* is used as an aid to the solution´s finding for multi-objective optimization within the *MOPTS* tool. Within the framework of this method, the multi-dimensional problem is aggregated into a one-dimensional stage with the usage of so-called weight factors $\lambda_v \in \Sigma$ as stated in (1).

$$\min_x \sum_{v=1}^{N} \lambda_v f_v(x) \qquad s.t. \qquad \Sigma := \left\{ \lambda \in \mathbb{R}^N | \lambda \geq 0, \sum_{v=1}^{N} \lambda_v = 1 \right\} \tag{1}$$

3. Framework

The MOPTS tool can be subdivided in several parts, namely in *data input*, *compilation* of variants, Finite Elements (*FE) analysis*, *optimum evaluation*, and finally verification. The individual components together with their dependencies are depicted in **Fig. 2**.

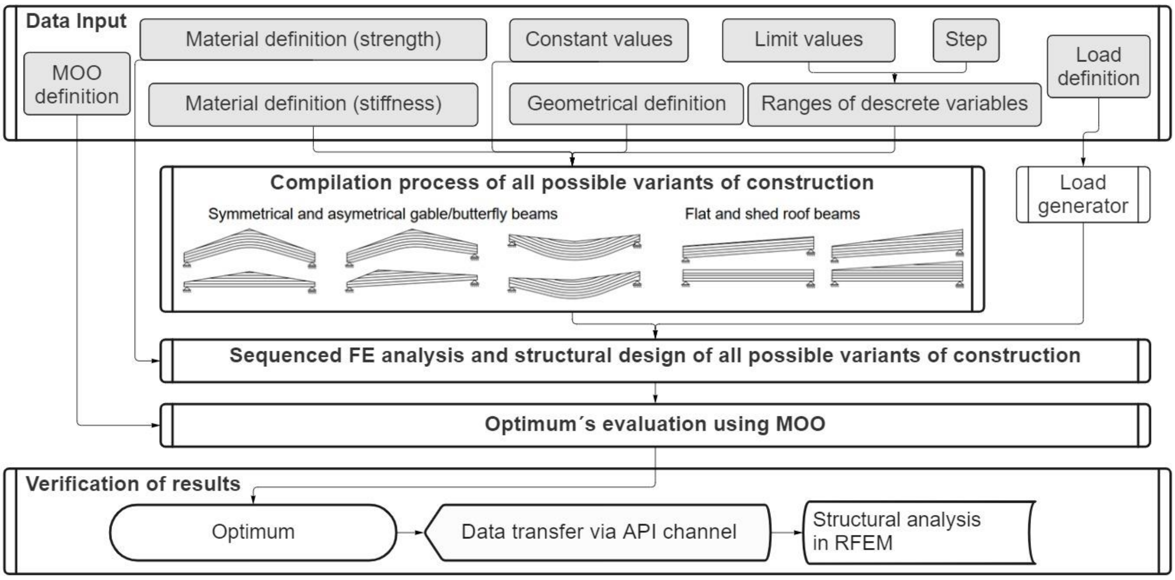

Fig. 2: Componential functionality of the *MOPTS* tool.

3.1. MOO parameters

With the help of minimum/maximum values and increments (steps), the *ranges of discrete variables* will be defined. They help to compile all possible variants of the structural and geometrical model topology. If a range of the discrete variable consists only of one integer, then this value will be considered as constant for the whole optimization process. The discrete ranges of variables can be defined for the beam parts and components (depending on type and shape). The MOO parameters are listed in **Table 10** and depicted in **Fig. 3**.

Table 10. MOO parameters in *MOPTS* tool

Variable parameters for MOO (ranges of discrete variables)	Constant parameters for MOO
Roof inclination α_1, α_2.	Coordinates of the start point (left supporting node).
The inclination of the bottom edge β_1, β_2.	Vector of the beam´s direction in cartesian space.
Fillet radius of the bottom edge R (if possible).	Span length (industrial hall´s width).
Cross section´s height at supporting points h_1, h_2.	Industrial hall´s length (second dimension).
Cross section's width b_{QS}.	
Height difference between supporting points Δh.	
The distance between bearing frame elements a_{frame}.	

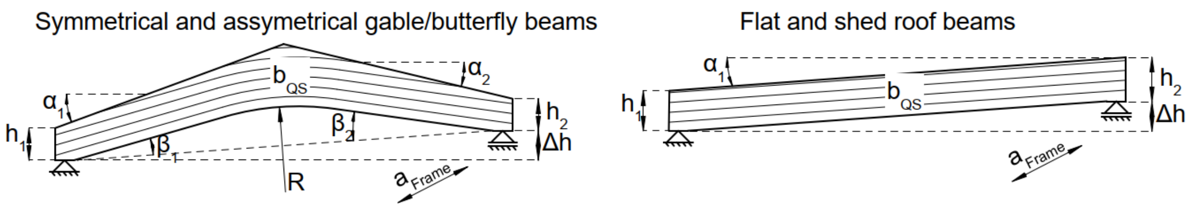

Fig. 3: MOO parameters in MOPTS tool (depending on the form type).

The compiled construction variants will be dispensed if the geometry is obviously not possible, e.g., the bottom edge intersects the top edge, or the fillet radius is too big. All possible variants of geometry will be saved in random-access memory (RAM) buffer and undergo the further analysis (FEA and MOO). This novel approach replaces evolutionary solvers within the *MOPTS* tool.

3.2. Structural design

Structural FE modeling and design within the *MOPTS* tool is carried out with the linear-elastic orthotropic material properties of *glued laminated timber Gl24h* (GluLam) according to ÖN EN 14080 [12]. However, due to limited functionality of *Karamba3D* version 2.2.0, the orthotropic stiffness definition is given without the differentiation regarding not only *local load direction* (parallel and perpendicular to wood fibers) but also *load type* (axial and/or bending). Neuhaus [13] gives the comparison of the stiffness parameters of timber products depending on the local load direction and load type. This shortcoming of *Karamba3D* is overcome by assumption of the sufficient bracing of the timber structure in the *MOPTS* tools. As a result, there *is no risk of global or local stability loss*. Thus, one can neglect the initial imperfections due to high eigenvalue of the beam under the loads in ultimate limit state (ULS) and only take membrane forces into the account.

Loads are defined in compliance with the EC and Austrian NAD with the usage of *Grasshopper´*s parametric algorithms. Only *basic information* about the loads, such as the dead load per unit area g_k (e.g., from insulation layer), reference wind speed pressure $q_{b,0}$ according to Austrian Standards ÖN EN 1991-1-4 [14], ÖN B 1991-1-4 [15] and also characteristic value of the snow load on the ground s_k according to ÖN EN 1991-1-3 [16] and ÖN B 1991-1-3 [17] must be defined by the user. The standard-compliant load combinations will be automatically defined depending on the roof type and shape. In addition, one load situation with internal pressure (IP) and another one with internal suction (IS) is defined for each wind load scenario. Only the wind loads perpendicular to the length of the hall are considered within the structural analysis in *MOPTS*. Payloads of category "H" (maintenance and repair) are not considered within the framework.

A horizontally stiffened simple single-span beam is considered as the structural system. The ULS is thus defined by *stress analysis in the cross-section* according to ÖN EN 1995-1-1 [18] and ÖN B 1995-1-1 [19]. The serviceability limit state (SLS) is defined by the limitation of deformations both in the initial state (elastic deformation in the characteristic SLS) and in the final state (long-term deformation in the quasi-permanent SLS). Both aspects are considered in the framework of the structural design in *MOPTS* tool.

3.3. Optimization

All utilization criteria for cross-section´s and deformation´s evaluation according to ÖN EN 1995-1-1 and ÖN B 1995-1-1 serve as constraints for MOO, whereby the limit values must be defined by the user. The possible variants of construction whose limit values are exceeded within the structural design in SLS and ULS, won´t be used for the evaluation of the optimum. These variants are considered as *not standard-compliant*. Four fitness functions are defined in the *MOPTS* tool. These fitness functions are the *total mass of all timber beams* f_m, the *ratio between the usable inner volume and maximal volume* f_{vol}, targeted *utilization in SLS* f_{SLS} and targeted *utilization in ULS* f_{ULS}. Thus, a four-dimensional optimization problem is solved in MOPTS, reading as

$$min[(\lambda_m f_m + \lambda_{vol} f_{vol} + \lambda_{ULS} f_{ULS} + \lambda_{SLS} f_{SLS})^{-1}], \quad (2)$$

whereby λ_v are weight factors which must be defined by the user. Notably The fitness functions are designed in such a way, that the mass of all timber beams is minimized, the ratio between the usable inside volume and maximum volume is maximized and absolute difference between targeted and calculated utilization in SLS and ULS, respectively, is minimized.

All fitness functions f_m, f_{vol}, f_{ULS} and f_{SLS} need to be standardized in order to be aggregated to one-dimensional equation according to (2). Thus, the best solution for *every fitness function* of all calculated standard-compliant construction variants (genomes) will be rated with value 1 and the worst genome with 0. Other variants in-between these two extremes will be linearly interpolated, so one can state that $f_v \in [0; 1]$. The standard-compliant genome with the minimal value according to minimization problem (2) can be considered as optimum solution.

4. Case Study

To prove the plausibility of the developed *MOPTS* tool, a test study was carried out based on an already built-up object. The object represents an industrial hall with rectangular shape (Width/Length = 27m/40m), considered of two partitions with 17.65m and 9.25m span length. The bearing structure is defined by frame elements (with a distance of roughly 5m) consisting of GluLam timber beams which are situated on reinforced concrete columns. The cross-section of the GluLam beam has a rectangular shape with variable heights ($Height_1$~$Height_2$/Width = 125cm~80cm/22cm). The horizontal loads, e.g., wind loads, are transferred to the foundations via wind braces. The sufficient stiffening of the upper edge of the wooden beam is given by the trapezoidal steel sheet and wind bracing. **Fig. 4** displays the structural system. The load values are based on the test case object and defined as follows: $g_k = 0.67\ kN/m^2$, $s_k = 0.65\ kN/m^2$ and $q_{b,0} = 0.40\ kN/m^2$ (Terrain category "*landlocked*").

Fig. 4: Structural model of the test case object.

The MOO process was executed with the following weight factors: $\lambda_m = 0.50$, $\lambda_{vol} = 0.30$, $\lambda_{SLS} = 0.10$ and $\lambda_{ULS} = 0.10$. Two test case structures were considered: a hall with a single beam spanning over the whole 27m wide hall (Test case 1), and a hall with a middle support column after 9.25m with two separated beams (Test case 2, matching the constructed hall).

5. Discussion

As one can state after the optimization´s process was finished, the flat roof represents the best solution with defined weight factors. Compared to the comparison object (**Fig. 4**), the solutions from both test cases have advantages regarding the needed amount of bearing frame elements (6 elements instead of 9). The optimum from test case 2 would have granted almost *5 tons of material saving*, the construction of a single-parted hall (optimum from test case 1) would only be possible with an additional consumption of approx. 6 tons of timber. However, the additional costs due to the special transport of long timber beams ($L \approx 27m$) must be taken into account. It can be reimbursed through necessity of only two support columns. The results of MOO process of the two test cases and their comparison to the already built object are displayed in **Fig. 5**

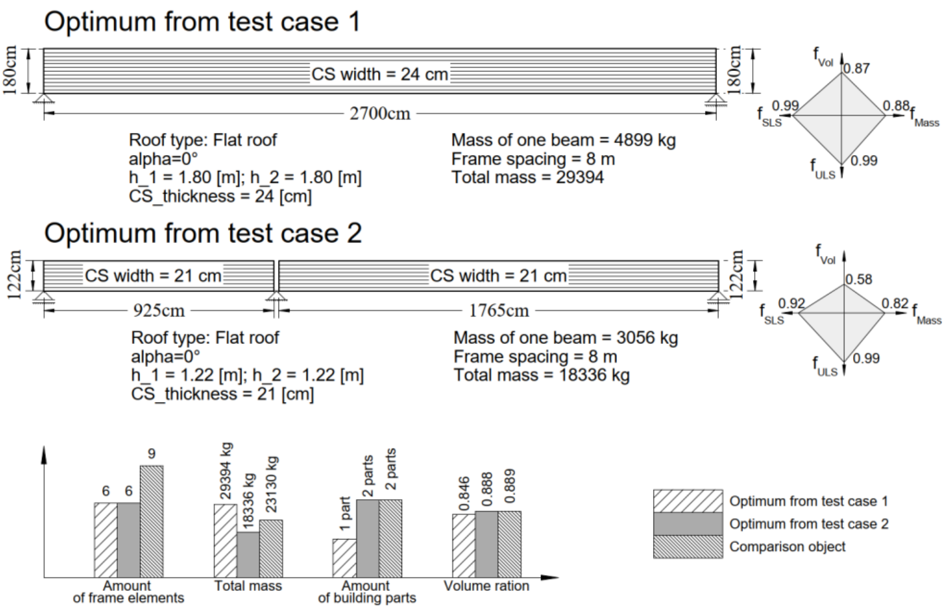

Fig. 5: Comparison of both optimal variants from test cases and the already built object.

Due to nearly equal ratio between usable inner volume and the maximal volume of all three variants in **Fig. 5**, the final decision regarding the bearing structure can be made with the help of another MOO process. The fitness functions in this case would be represented by the *amount of hall partition* and *total mass* of all beams with corresponding weight factors. Those factors can be chosen by the user or rather the investors.

Clearly, the result of the MOO process of the *MOPTS* tool can only support the final decision. The geometry of the flat roof GluLam beams may be adjusted, e.g., to ensure the roof´s inclination for water drainage. Small adjustments of the structural topology are possible without greatly effecting the results of MOO.

The research results of this paper and presented novel approach of *MOPTS* tool confirmed the efficiency of structural design and optimization with the usage of parametric modelling, as also the research in [20] shows. In summary, a plausible, sustainable, and cost-saving variant of the bearing structure can be chosen already in the early phases of planning by examining numerous possible solutions and comparing them with the help of the novel concept and the MOO methods described in this paper.

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Safety Climate in Small and Medium Construction Enterprises

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Abstract

Construction is characterized in a highly hazardous and complex work environment, materializes in a high fatality rate, and a need for development of designated methods and tools for the branch. One of the pitfalls of the construction sector is small and medium enterprises (SMEs), often characterized by loose commitment to safety. The level of adherence of small and medium enterprises to safety and occupational health is not adequate due to many hindering factors such as: multiple small projects, lack of administrative critical mass on site, budget constraints, etc. This research examines the core parameters of safety climate in small and medium enterprises through a model of the fish bone diagram, which divides the safety climate into four core domains: workers, equipment, management, and environment. A field survey that includes 42 questions, aligned with the model was distributed, in 20 construction sites in Eilat, Israel. workers received an average rating of 3.7, equipment 4.2, management 3.6 and environment 4.1 (all rating are on a 5-point Likert scale). The sample results indicate marginal safety climate which is expressed in multiple light and moderate accidents, and in partial assimilation of safety protocols, control and training. The research results were validated by statistical inference using a T test to examine the results. The model significance was found to be significant at a level of $\alpha<0.05$. Furthermore, a case study carried out on the best and worst projects. The case study indicates that the model predicts in a good significance the safety climate performance and that its implementation is a tool for assurance of safety climate. Finally, the results of the model were examined and validated by comparing subgroups, as well. Correlation between the project scope and safety climate was tested. recommendations and conclusions for further research deduced.

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Keywords: Construction, environment, management, safety climate, small and medium enterprises (SMEs)

1. Introduction

The construction industry contributes significantly to the global economy. The expected expense on construction in 2025 will be 9 trillion dollars (Al Mawli et al 2021). The construction industry is considered as one of the most dangerous industry branches with high, frequent and various occupational risks. The common practice is that construction enterprises avoid certain safety activities in order to elude from getting the projects delayed, a step which is not beneficial for safety and might cause accidents and as a result would bring additional costs.

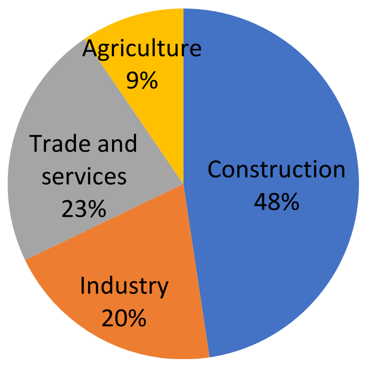

Figure 1: division of fatalities due to work accidents (2019 report, Israeli safety administration)

It is possible to see in the Figure 1, that the share of construction in fatalities due to work accidents is almost half, even though its share in the worker's number and economic size of the branch is much lower. The frequent changes in the construction site, the dusty environment, the hard conditions of working in the height, the mechanical equipment and more, make the construction work environment dangerous.

Safety climate is a relatively new approach, by which the management of an organization takes a proactive approach for promoting project and organizational safety culture and allocates resources for that purpose on different layers (guidance, control, equipment and safety encouragement). The management should encourage the workers to report safety events and reward them for initiating and assimilating processes for safety improvement. Safety climate encourages organizations to report on impairments in processes that might cause failures and work accidents, and assures the personal safety of the reporters on such impairments. Instead of an investigation committee, a friendlier version would be appointed, which its role is to analyze and explain the circumstances of the safety event, with an emphasis on processes for improvement of the work environment and for the creation of work conditions that will assure safety, hygiene and also efficiency of the working process. Organizational safety climate is defined as common conceptions among managers and workers relating to what is rewarded, expected, valued and is getting reinforcement in the workplace when it comes to safety (Zohar, 1980).

A research from Ghana (Kheni, Gibb, & Dainty, 2010), compared the matter of occupational health and safety (OH&S) between large construction enterprises and small and medium ones. According to the research, the larger the enterprise is, the frequency of injuries as a result of work accidents goes down. The small and medium enterprises usually have less resources, a thing that makes it harder to manage safety and hygiene. The major care of these companies is to survive, and therefore not enough attention is given to safety. Since the safety of the workers depends on the safety cost, there are many times conflicts of interest between safe conduct and environment and safety investments in projects (Khoshnava et al. 2020).

According to Predo (Predo, 2020), Organizations with safety climate attribute importance to: Showing managerial commitment, Assimilation and combination of safety as a value with importance to the organization's activity, Assuring of all employees being held responsible in all levels of the organization, Improvement of safety leadership on work sites, empowering workers and increasing involvement, Improvement of communication, training in all levels and encouragement of owners / client involvement. Following these principles of safety help to achieve good safety outcomes.

In the research of Rahamim Bachar from Ben Gurion University (Bachar and Shohet, 2021) focused on the parameters for investment in safety in small and medium projects. This research investigated optimal level of resource of resource allocation in construction safety, using empirical data gathering and simulation. The optimal level was found to be 1% of the project scope. However the research focused on the entire population of construction projects, primarily big, mega and medium projects. It was recommended to elaborate the research to SME's. It was found that in projects where the safety investment is higher, there were less accidents and the safety climate was significantly better.

Another finding of the research is that the ideal minimum for safety investment ratio in small projects is at about 3.8% of the project scope. The investment ratio required in small projects is much higher than what is needed is large projects.

In industry branches such as marine drilling, chemistry and aviation reports of near miss events are being used for a relatively long period. In the drilling industry it was found that a report rate of 50% reduces by 75% the number of safety events (mostly the light ones). The thing is not the same in the construction branch, where near miss events reporting is not common.

An article from Alabama university (Awolusi et al., 2016) introduced an advanced model of near miss events management program as a basic methodology for safety managers in construction sites for collecting, analyzing and making an efficient use of safety data. The model includes identification of the event, reporting it, preforming a root cause analysis, determining a solution, and decision making.

2. Methodology

The SMEs safety climate model developed in the research divides the safety factors into four core domains: (1) workers, (2) equipment, (3) management and (4) environment, which lead to safe or rather unsafe conduct.

The SMEs safety climate model's components:

1. **Equipping the construction site with the necessary safety measures –**The construction site should be safe for the workers.
2. **Moral and physical support to the workers –** this component includes matters that relate to managerial support in the workers, communication, cooperation between colleagues and medical insurance policy.
3. **Healthy work environment –** this component emphasizes the importance of a work environment with comfortable conditions for the workers.
4. **Assuring the safety of the construction site from falling objects and workers falling from the height –** This component relates to the component emphasizes the importance of executing actions and using measures for preventing the falling of workers from height (scaffolding, ladders, temporary structures) and to the fall of objects.
5. **Proactive activity for accidents prevention –** this component includes steps that assist in preventing accidents, as well as willingness of the company to receive safety complaints and feedbacks from workers and to manage a data-base of the accident's history of the company.
6. **Supply of equipment and zones for safety and comfortability of the workers –** one of the basic elements of worker's safety is the supply of personal protection equipment (PPE). Moreover, allocation of safe storing zones has a major influence on safety conditions and worker's safety since it keeps hazardous materials in safe places.
7. **Avoidance of mental and physical overexertion of workers –** this component gives attention to the action of overloaded employees who are working beyond their capacity. Tired workers tend to compromise safety.
8. **Fire and heat hazards –** this component is meant to prevent the risk of fire by supplying fire extinguishing systems.
9. **Knowledge and skills –** It is necessary to assure that safety procedures are the first issue that a worker is exposed to when he starts to work on the site.
10. **Safe conduct** – this component checks the probability for negligence and mistakes in judgement by the workers.

11. **Safety control** – this component is meant to check the level of control and inspection of equipment and of the work conditions in the site, since many accidents occur due to impaired equipment.
12. **Hazards assessments and risk factors** – the enterprise is required to execute hazards and risk factors assessments as a routine, and also in the different stages of construction.
13. **Adjustments for workers** – age and experience are highly important constituents in the conception of safety climate among workers.

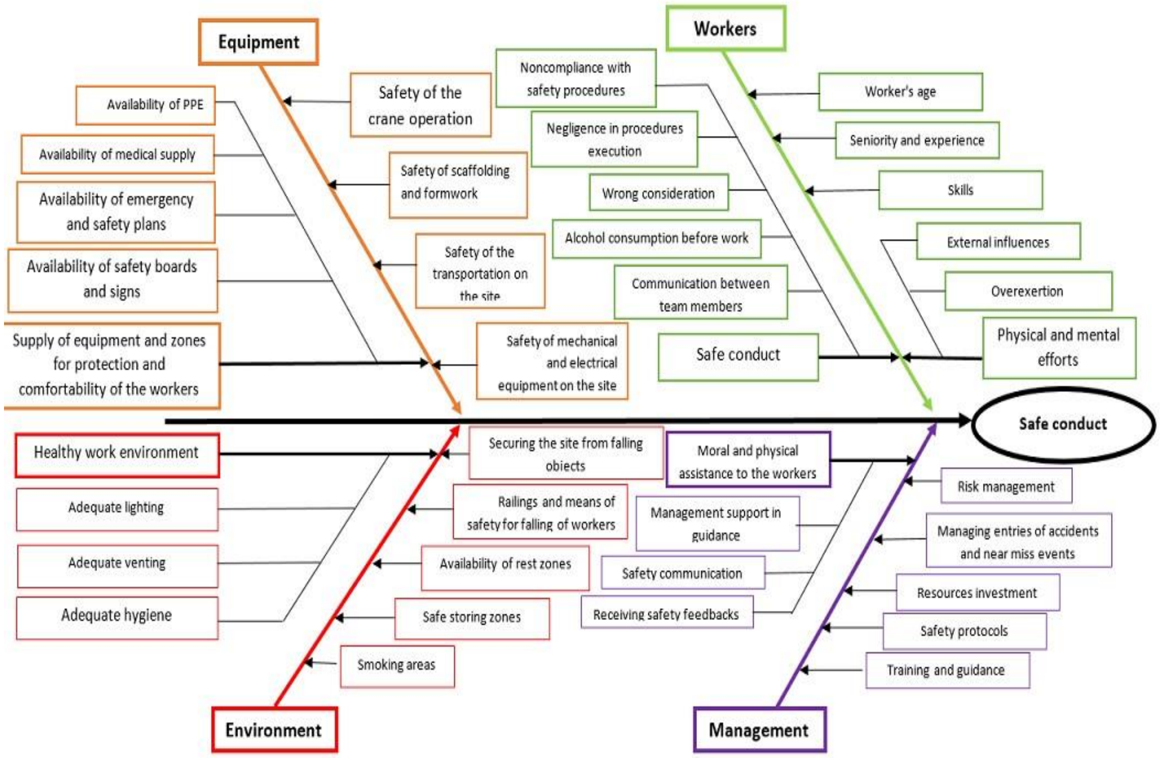

Figure 2: model of safety climate in small and medium construction enterprises

The research methodology encompasses field survey of 20 sites covering 42 parameters and variables of the model, allowing to assess the safety climate on a representative sample, inferential statistics, case study and conclusions.

3. Results and discussion

The field survey results are summarized in Table 1 below, the survey was carried out with the Likert 5-Point ranking scale and the core variables of the SMEs safety climate model were categorized into four categories: A – Equipment, B – Management, C - Employees, and D – Environment.

Table 1 defines the safety performance variables and delineates the means and Standard Deviations. In average four accidents in a project, 3.1 light, 0.9 moderate and 0.1 severe. No fatal accident reported. And the average nears-miss events reported is 0.9, indicating low level of reporting. Table 2 and Figure 3 depicts the SMEs safety climate mode equipment core which shows that this core is relatively at sufficient level safety climate adherence except the adoption of emergency and emergent safety plans. Table 3 and Figure 4 indicate the SMEs safety climate at the management level – it is apparent that most management component are at mediocre or low implementation particularly: B4 – Exposure of workers to safety records, B5 –

Encouragement of senior management to report near miss events, and B9 - Conduct if daily risk assessment surveys. Table 4 and Figure 5 depicts the Workers core variables of the SMEs safety climare model – it is indicated that the workers safety climate adherence is relatively low (3.7), particularly, C2 – Workers at work oveload, C3 – insufficient cinsideration of exterior factors affecting the work conditions (extreme hot weather in Eilat city are), and C10 - Capability of workers to assess fall from height hazards, Electrocution, Heat hazards and excavations hazards, Table 5 and Figure 6 depicts the SMEs safety climate environment factors inicating the this core of the SMEs safety climate is at aaceptable average level of 4.1 with exception of ventilation conditions at the work station and the hygiene and sanitary contions which are both below expected levele (4).

Table 1: Construction safety performance

Variable	Mean	Std. Dev.
No. of light work accidents	3.1	1.61
No. of moderate accidents	0.9	0.68
No. of severe accidents	0.1	0.30
No. of fatal accidents	0.0	0.00
No. of Near miss events reported	0.9	2.39

Table 2: SME safety climate model equipment variables (A)

Variable	Symb.	Mean	Std. Dev.
Availability medical equipment and first-aid	A1	4.2	0.96
Availability of emergency and safety plans at site.	A2	3.9	0.89
Site safety signage	A3	4.2	0.73
Prevention of falling of objects from height	A4	4.3	0.56
Inpection of safety equipment (scaffoldings, harnesses, crane)	A5	4.6	0.67
Mean		4.2	0.76

Table 3: SME safety climate model management variables (B)

Variable	Symb.	Mean	Std. Dev.	Remark
Encouragement of safety climate by the company management	B1	4.1	0.77	
Safety information tranfer into the site	B2	3.8	0.68	
Safety climate feed-back initiated by management	B3	3.7	0.96	
Exposure to safety records history	B4	2.7	1.62	
Encouragement to report mear-miss events	B5	2.1	0.89	
Allocation of safety climate resources by management	B6	3.9	0.99	
Clearity of safety protocols and regulation	B7	4.7	0.56	
Conduct of safety supervision at site	B8	3.7	0.64	
Conduct if daily risk assessment surveys	B9	3.4	1.02	
Update of safety regulations according to project progress	B10	3.9	0.77	Frequently carried out only once at beginning of project
Safety risk assessment by the company management	B11	3.6	0.86	
Mean		3.6	0.89	

Table 4: SME safety climate model employee's variables (C)

Variable	Symb.	Mean	Std. Dev.	Remark
Encouragement of safety climate by the peers	C1	3.8	0.75	
Work overload on your peers	C2	3.2	1.01	
Extrior factors affecting safety	C3	3.4	0.79	Hot weather condions affect safety equipment
Clarity of safety protocols and regulations	C4	4.7	0.57	
Sufficiency of training sessions (Work and the height, safety general, electricity, Work in Hot conditions)	C5	4.1	0.44	
Workers qualified for their tasks	C6	3.8	0.70	
Implementation of safety regulations	C7	3.7	0.57	
Do you feel qualified for risk assessment at marginal conditions such as heavy loads lifting, work at height, heavy earthmoving mechnical equipment, etc.	C8	4.3	0.43	
Peers consuming alcohol during work	C9	4.4	0.97	
Capability of workers to assess fall from the height hazards, Electrocution, Heat hazards and excavations hazards	C10	3.2	0.75	
Mean		3.7	0.69	

Table 5: SME safety climate model environment variables (D)

Variable	Symb.	Mean	Std. Dev.	Remark
Sufficient light conditions at work station	D1	4.1	1.08	
Sufficient ventilation of work station	D2	2.4	0.86	
Sufficient hygiene conditions	D3	3.5	1.12	
Safety measure for fall of workers from the height	D4	4.4	0.49	
Protection from Electrocution	D5	4.7	0.46	
Sufficient rest areas in the site	D6	4.8	0.54	
Storage areas are well fenced signed accessibke	D7	4.3	1.14	
Smoking areas exist	D8	4.3	1.10	Most workers smoke during work
Fire protection at the site	D9	4.7	0.56	
Mean		4.1	0.82	

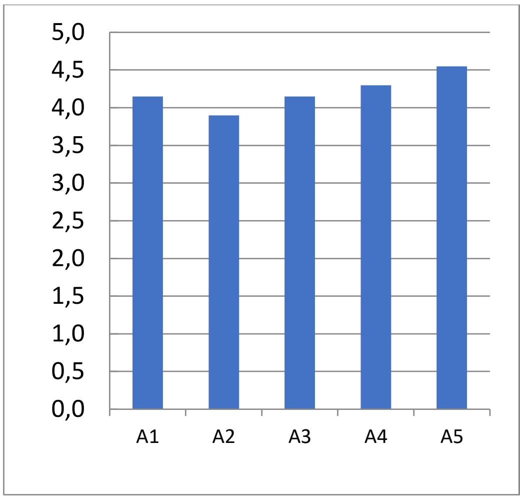

Figure 3: Equipment category ranking

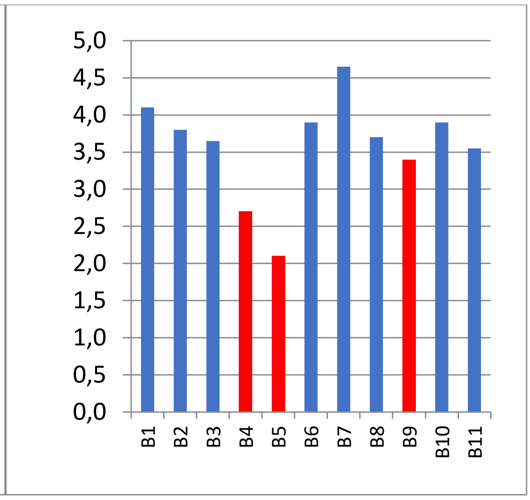

Figure 4: Management category ranking

(in red – low safety)

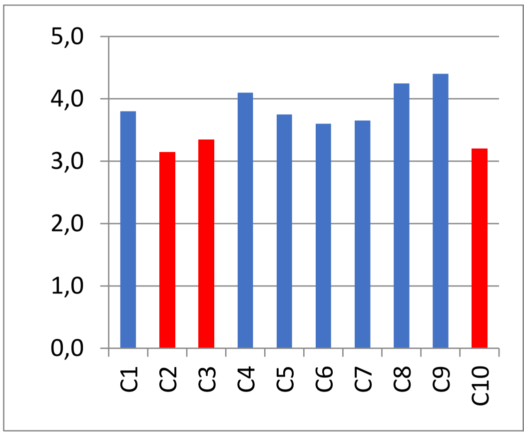

Figure 5: Employee category ranking

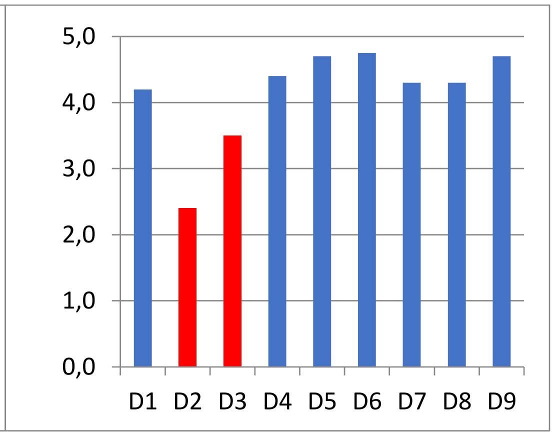

Figure 6: Environment category ranking

The foremen thought that the equipment category is the best with an average rating of 4.2, while in the management domain the rating was the lowest with 3.6 and the highest standard deviation of 0.89 which indicates on big variance between some projects with good and some with poor safety. The workers category had medium rating of 3.7, and in the environment category there was a relatively high rating of 4.1.

It appears that the lower rated categories are the ones related to the manpower – both management and workers.

4. Inferential statistics

In the sake of validating the model that was developed in this research, two subgroups of projects, that represent the model characteristics in its both poles (high and poor safety climate) – subgroup A with model variables higher than 4, and a subgroup B with model variables lower than 3.5. subgroup A included 5 projects and its average is 4.26. Subgroup B included 4 projects, and its model variables average is 3.34. both groups characterize in relatively small standard deviations (0.2 and 0.16 in accordance), a datum that allows to perform a T test in a good significance of 0.05.

The safety performance as measured in the survey has a significant and critical influence on the accidents number (Figure 7). The average of the light accidents number in subgroup A, with the good safety executions, is 3, compared to 3.75 in subgroup B. There were 0.8 moderate accidents in subgroup A, compared to 1.5 in subgroup B. there were no severe accidents in subgroup A, while in subgroup B there were 0.25. generally, there were 3.8 accidents in subgroup A and 5.5 accidents in subgroup B, a difference of about 44%.

This data indicate that the model and the survey questionnaire were validated, and show of direct connection between the estimated safety executions and their results.

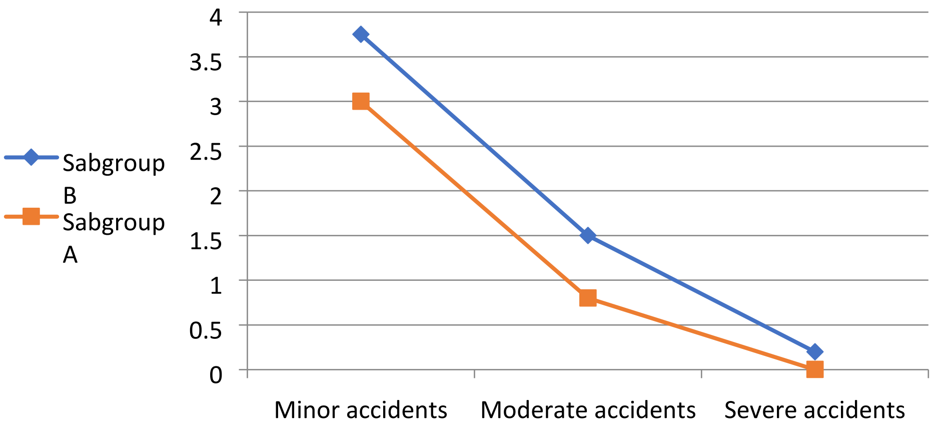

Figure 7: Average accidents in 2 groups according to safety performance

Siginificance of the findings - T test

Comparing the groups averages according to a T test in α=0.05 significance it was found that T=8.59 beyond the limit value which is 2.365 and it allows to reject the null hypothesis that the means of both groups of safety climate projects are equal in 0.05 significance. Meaning, it was validated that there is a significant difference in safety performance indicators between projects that the SMEs safety climate model identified as having high safety executions, and ones that were identified as having low safety executions.

Case study

The analysis of the results of two projects, A, with the best results in the survey (avg. rating of 4.54 and a cost of 9.1 million$), and project B, with the lowest results (3.09 avg. rating and a cost of 2.4), is being used here as a mean for validating the research's conclusions.

Project A with the best results in the field survey, had high ratings in almost all parameters, besides factor related to heat. Project B with the lowest results in the survey got low ratings in almost all variables, specifically in the ones that are related to management, communication and control. Between both projects, one invests much in safety and the other one does not. A is much larger and according to the size it is expected to have 3-4 times more accidents – there were no accidents at all at project A, while in project B there were 3 light accidents and one medium.

Correlation between the project scope and safety climate

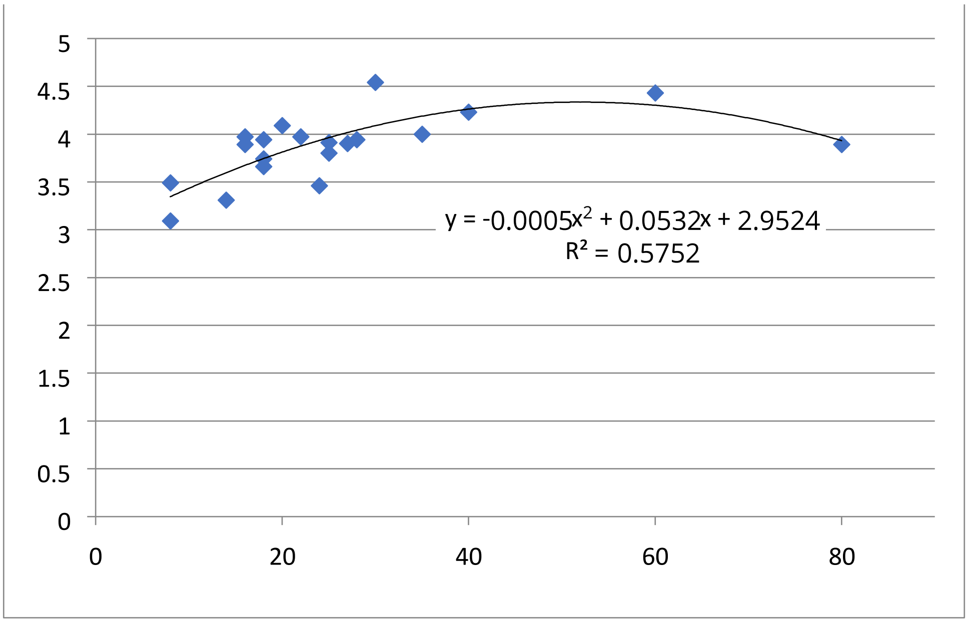

Figure 8: Safety climate Vs. project scope (M ILS)

Pearson correlation coefficient: R^2=0.575. It shows that there is a positive second-order parabolic connection between the project's scope and the safety climate quality, and that The model predicts the safety climate up to a project scope of 80 M ILS (23 M USD).

5. Summary and conclusions

This research examined the safety climate in small and medium construction enterprises. The core of the model was examination of the different components that were presented in the fish bone diagram – workers, equipment, work environment and management, in the different construction enterprises that were surveyed.

The construction sites that were examined are located in Eilat area (in the Israeli desert), and therefore are characterized with an extremely hot and desert climate. The research shows in a clear way the influence of the environment on the safety climate. There is often a loosening in the safety discipline due to the severe heat load that induces fatigue, lack of concentration and giving up on personal protection gear.

Likewise, it is possible to see that foremen are nearly entirely not exposed to historical entries of work accidents and don't keep making risk surveys consistently in all project stages, there are almost no near miss reports and the safety communication was found as impaired.

The importance of this research stems from the fact that it examines the safety climate in small and medium enterprises with no big budget like big enterprises have. In the research, there was found a certain correlation between the project's scope and the safety climate with a coefficient of 0.5. meaning that usually, the bigger the project's scope is, the safety budget is bigger and the safety itself is better.

In the research, there was developed a safety model that is built on four aspects: management, environment, workers and equipment. The model was examined through a survey of project managers and foremen in small and medium construction enterprises. The field survey, that was conducted at the city of Eilat in Israel – that is affected by a desert climate – showed that the safety climate in small and medium construction enterprises is at borderline levels with an average of 3.9 (from 1 to 5), that indicates of medium-borderline safety climate.

The relatively large standard deviations (equipment – 0.76, management – 0.89, workers – 0.69, environment – 0.82) indicate on a large variance between the sites, and on the need for improvement in regulation and inspection in the enterprises operating those sites.

The SMEs safety climate model was validated using inferential statistics on two categories of projects: group A - with high safety climate features, and group B – with medium-low safety features. The test found that the model predicts the safety performance at high level of significance (α=0.05), and that its implementation assures high safety climate and performance indicators.

The questionnaire was handed to foremen in projects, and sometimes their answers are biased by their positions as the safety manager in chief at the site level. it is recommended to conduct future research, in which it is possible to distribute the survey to the workers themselves, then the number of questionnaires would be large, and in addition the answers will be more demonstrative.

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Seismic Risk Mitigation and Management for Critical Infrastructures using an RMIR Indicator

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Abstract

Recent earthquake events have highlighted the importance of critical infrastructures (CI) resilience, as a strong correlation was found between the economic loss and the severity of CIs damage. CIs are characterized by a complex structure composed of sub-components that are essential for the continuous performance of the system. CIs owners and governments allocate ample of their resources in retrofitting and upgrading CIs systems and components to increase the resilience of CIs and reduce the risk they are exposed to in case of seismic events. Governments and decision-makers must manage and optimize the retrofit efforts to meet the budget and time constraints. This research presents a probabilistic methodology for seismic risk mitigation and management in CIs. The risk expectancy is appraised according to an FTA-based simulation. The simulation includes the development of exclusive fragility curves for the CI and an examination of the expected damage distribution as a function of the earthquake intensity. Furthermore, this research proposes a novel RMIR (Risk Mitigation to Investment Ratio) indicator for priority setting of seismic mitigation alternatives. The RMIR is a quantitative indicator that evaluates each alternative's cost-effectiveness in terms of risk expectancy mitigation. Following the alternative's RMIR value, it is possible to prioritize the alternatives meeting the budget and time constraints. This paper presents the implementation of the proposed methodology through a case study of a generic pumping station. The case study includes twelve mitigation alternatives examined and evaluated according to the RMIR indicator.

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Keywords: Critical infrastructures; Earthquake; Risk Mitigation; Risk management.

1. Introduction

Damage or disruption to critical infrastructures (CIs) can have a significant adverse effect on the economy, safety, and wellbeing of the public and private sector [1]. Recent earthquake events have highlighted the importance of critical infrastructure resilience, as a strong correlation was found between the economic loss and the severity of CI damage [2,3]. Furthermore, over the last decades, along with the development of CIs, gradual increasing essential services depend on the continuous performance of one, two, or even more critical infrastructures such as energy, power supply, water supply, communications, etc. [4–8]

CI systems are characterized by a complex structure that is composed of various essential components and subcomponents. The full functionality of the system requires a continuous performance of all components. Subsequently, the CI resilience is derived from the resilience, robustness, and redundancy of its core components and subcomponents. Studies show that there is a consistent interdependency across sectors of CIs systems as most of the CIs are connected and dependent on each other, and damage to one critical infrastructure will, most likely, lead to other CI failures [9–11]. Consequently, a failure of a single CI component can lead to a series of propagating disruptions of other CIs and affects a wide range of consumers from different sectors. The CIs systems' interdependent structure increases vulnerability for cascading and rippling effects that increase the impact and the magnitude of each damage or disruption by initiating multi-hazard events [12]. The growing dependency on CIs, the interdependency between different infrastructures, and the growing number of infrastructures significantly increase critical infrastructure's seismic risk. Therefore, there is a vital need to protect and ensure the continuous performance and resilience of critical infrastructures systems and assets after extreme seismic events.

In general, risk is defined as a measure of the probability and severity of adverse effects (Lowrance 1976; Haimes 2009). In the case of seismic risk, it should reflect the value of the potential consequences resulting from possible earthquakes throughout a defined duration of time [13].Since the risk is calculated for CI in a specific location, the occurrence probability of possible earthquakes should be represented as the exceedance probability for certain severity of IM in the location of interest. The deterministic approach focuses on a single earthquake, a small number of earthquakes, or a specific ground motion value [14–16]. However, the deterministic approach does not consider the uncertainties of the time, location, and magnitude of possible earthquakes. Moreover, targeting the retrofit efforts based on deterministic risk assessment may mislead the decision-makers due to possible ignoring of possible events, and subsequently, avoiding the optimal alternative. The probabilistic seismic hazard analysis (PSHA) aimed at considering all possible earthquake scenarios and ground-motion levels that can occur in the system's location. The PSHA process produces a hazard curve that presents the annual rate of exceedance for any value for IM [17,18]. The probabilistic approach is widely used over the last decades for assessing risk and development of seismic hazard maps [19–23].

Consequences are the outcome and the effects of an earthquake event. An examination of previous earthquakes reveals inconsistency in the severity of the post-earthquake consequences [1]. For a specific earthquake event, there is a wide range of damage levels observed in similar types of structures and infrastructures at the same place. Many parameters can influence the actual consequences, such as maintenance, quality of the materials, quality of construction, the degree of supervision during the construction, and more. Fragility curves are traditional damage functions to evaluate the expected damage distribution of CIs due to earthquake events. [24–34]. A variety of generic fragility curves for CI systems and components are presented [35–38]. However, generic fragility curves do not necessarily reflect the actual system layout and the system's components. (Urlainis and Shohet 2022) presented a comprehensive methodology for developing exclusive fragility curves for CI by decomposing the system into subcomponents and a Fault Tree Analyses to determine the system's failure mechanisms.

CI owners and governments allocate ample of their resources in retrofitting and upgrading CIs systems and components to upgrade the resilience of CIs and reduce the risk they are exposed to in case of seismic events. However, the governments and decision-makers have to consider several possible mitigation strategies and choose the best solution to reduce the risk under budget constraints, i.e., the optimal mitigation strategy/alternative. Several fundamental questions must be addressed in this process: how many earthquakes and what intensities should be considered for risk assessment, what are the exceedance probabilities of certain intensity in a specific location, what are the expected consequences for a given earthquake, how to asses the effectiveness of a mitigation alternative, and more. However, no comprehensive and universal framework offers a systematic decision support tool for CIs seismic risk assessment and risk mitigation.

There is a lack of risk-based Key Performance Indicators in the literature; several past studies offer approaches to measure risk management performance and risk management indices (IDB 2010; Carreño, Cardona, and Barbat 2007). The model proposed by [41] evaluates and quantifies the performance indicators by the opinion of local experts; hence, the values are based on expert opinions and are not fully objective parameters. [42] propose prioritizing the risk reduction according to Disaster Risk Management index (DRMi), physical risk factors, and aggravating coefficient. However, in their study, the DRMi was also evaluated by a survey of experts and not by fully objective values and parameters. Furthermore, [43] proposes a scenario-based model to evaluate the effectiveness of earthquake emergency management by simulations of possible earthquake disaster scenarios. However, this model is a scenario-based, meaning it does not cover all possible seismic threats and therefore may present a limited risk assessment that depends on the selected scenario.

This paper presents a comprehensive and efficient framework for CI seismic risk assessment and management. The proposed framework intends to address three key issues: (1) seismic risk assessment, (2) quantification of mitigation alternative effectiveness, and (3) prioritization of alternative mitigation strategies.

2. Methodology

A four-step methodology is proposed: (1) Determination of the seismic Scenarios, (2) Calculation of CI system vulnerability, (3) Quantitative assessment of risk, (4) Implementation of risk-mitigation alternatives and Prioritization of the risk-mitigation alternatives.

2.1. Determination of the seismic Scenarios

The first step of the risk appraisal process is the definition of the threat scenarios that Critical Infrastructures (CIs) components are exposed to. Which, in our case, is an occurrence of an earthquake event and its' subsequent effects on the CI. An earthquake can occur at various locations and with different intensities. However, the on-site ground motion will determine the impact on a specific CI system after the earthquake. In this research, the seismic scenarios are defined by a hazard curve. The seismic hazard curve is derived using a PSHA, and it determines the annual probability of exceeding a peak ground motion in a specific location. Theoretically, the hazard curve represents possible seismic scenarios and their occurrence probabilities. The hazard curve can be derived based on the probabilities of exceedance of 10%, 5%, and 2% in 50 years, or by a producing a complete PSHA process.

2.2. Definition of System's Seismic Vulnerability

The seismic vulnerability of the system is represented by an exclusive fragility curve. The exclusive fragility allows to perform a customized in-depth risk analysis and later to examine the effectiveness of various retrofit alternatives. The exclusive curves are derived following the methodology presented in [44].

The fragility curves for CI systems are formed as lognormal cumulative distribution function (CDF) that expresses the probability of reaching or exceeding certain damage state (ds) for a given level of ground motion intensity (e.g., PGA, PGV, and PGD). This fragility function is defined by the median capacity to resist the damage state i (θ_i) and the standard deviation of the capacity (β_i), as illustrated in eq. (1). Eq. (2) calculates the probability to exceed a specific damage state.

$$P[DS \geq ds|IM = x] = \Phi\left(\frac{ln(x/\theta_{ds})}{\beta_{ds}}\right) ; ds \in \{1,2, \dots N_{DS}\} \tag{1}$$

$$P(DS = ds_i|IM) = \begin{cases} 1 - P(DS \geq ds_i|IM) & i = 0 \\ P(DS \geq ds_i|IM) - P(DS \geq ds_{i+1}|IM) & 1 \leq i \leq N_{DS} - 1 \\ P(DS \geq ds_i|IM) & i = N_{DS} \end{cases} \tag{2}$$

When P stands for a conditional probability of being at or exceeding a Damage State (DS) for a given seismic intensity, x defined by the earthquake Intensity Measure (IM). Where,

DS Damage state of a particular component {0,1,... N_{DS}}

ds_i A particular value of DS

N_{DS} Number of possible damage states

IM Uncertain excitation, the ground motion intensity measure (i.e. PGA, PGD, or PGV)

x A particular value of IM

Φ Standard cumulative normal distribution function.

θ_{ds} The median capacity of the component to resist damage state ds measured in terms of IM

β_{ds} The logarithmic standard deviation of the uncertain capacity of the component to resist damage state ds

2.3. Quantitative assessment of risk

The product of this step is a seismic risk curve that expresses the expected annual risk for any given value of IM. Since risk represents the potential impact and loss and it is defined as the product of the occurrence probability and the expected consequences, this curve is constructed by multiplying the annual rate of exceedance curve with the direct damage curve by matching between the IM values in both curves and links the expected consequence and its probability to occur. This matching produces a curve that correlates the annual risk expectancy and the IM value.

The total risk expectancy for a T-years life-span TRE_T (eq. (4)) expresses the overall risk that the system is exposed to earthquake events among the system's life-span. The TRE_T is calculated based on possible seismic scenarios, their occurrence probability and the expected consequences. The R_U (eq. (3)) express the overall consequences that are expected in case of complete damage to the system, which is expressed in terms of cost (USD).

$$R_U = (\sum C_R + \sum C_D) \cdot C_I \tag{3}$$

Where,

C_R Repair cost (US$)

C_D Direct loss (US$)

C_I Indirect loss coefficient

$\mathrm{R_U}$ Overall consequences (US$)

$$TRE_T = \left[\sum_{IM} \left(\sum_{i=1}^{N} P(ds_i|IM) \cdot DR_{ds_i} \right) \cdot PE_A(IM) \right] \cdot R_U \cdot T \tag{4}$$

Where,

TRE_T Total risk expectancy for T years

DR_{ds_i} Damage rate of damage state i

$P(ds_i \mid IM)$	Conditional probability of being in a certain damage state i for a given IM
T	Design life-cycle
$PE_A(IM)$	Annual rate of exceedance of a given IM

2.4. Implementation of risk-mitigation alternatives and Prioritization of the risk-mitigation alternatives

Based on the derived risk curve and the total risk expectancy (TRE), mitigation alternatives are considered, to find to most beneficial one. The mitigation alternatives are examined to predict its cost-effectiveness on the preparedness level of the CIs by quantifying the reduction of risk. Each alternative has different effects on the robustness and the resilience of the system, which is reflected through the fragility curve parameters. The change of the fragility parameters will subsequently affect the system's level of risk. The optimal strategy is selected according to the risk reduction level and economic considerations. To examine the cost-effectiveness of the mitigation alternative, a novel RMIR (Risk Mitigation to Investment Ratio) performance indicator is proposed. The RIMR is a quantitative indicator that attempts to calculate the overall value of the examined alternative (eq. 5). The RMIR is the ratio of the expected risk mitigation along T years of service life (ERM^T), expressed in monetary term, to the estimated mitigation cost (EMC). **Figure 7** present the general flowchart of the risk-mitigation alternative's prioritization process.

$$RMIR = \frac{ERM^T}{EMC} \tag{5}$$

Where,

RMIR – Risk Mitigation to Investment Ratio
ERM^T – Expected Risk Mitigation along T years of service life
EMC – Estimated Mitigation Cost for the alternative

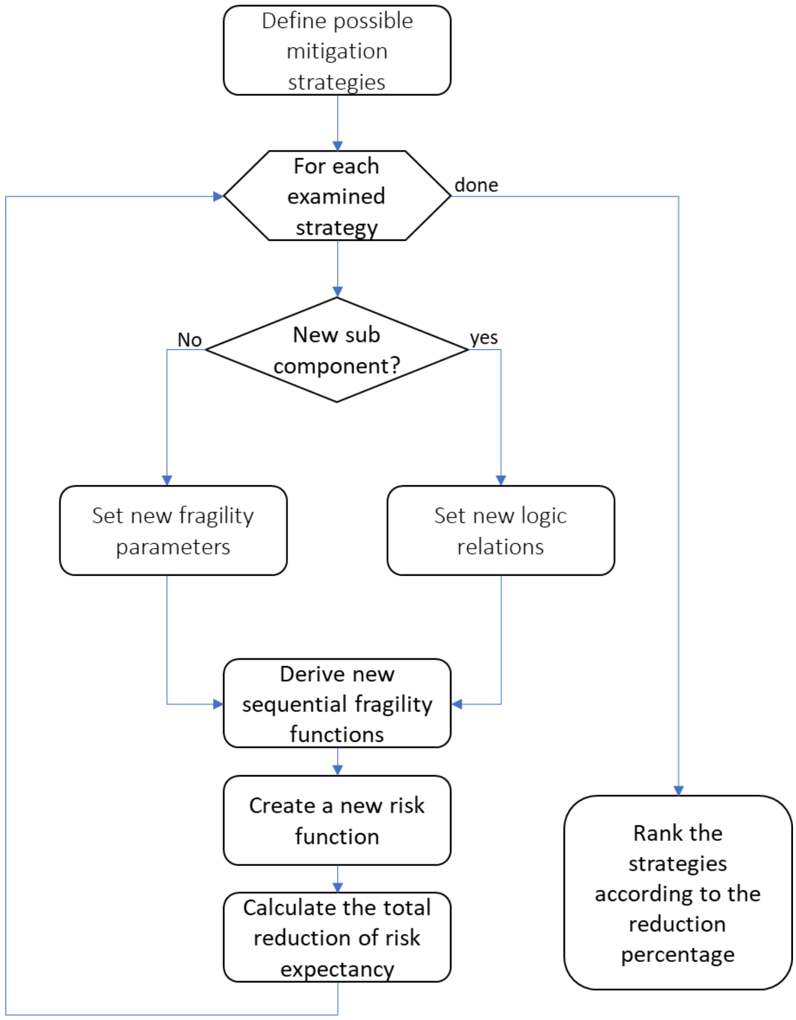

Figure 7 - Flow chart of the risk mitigation process

3. Case Study

3.1. Introduction

This chapter presents an implementation of the methodology through a pumping station facility case study. This case study is based on the generic pumping station presented in [44]. The generic pumping station is composed of four main subcomponents that are vital for the functionality of the pumping station: building, pumps, electro-mechanical equipment, and power supply. The fragility parameters and curves of the station are presented in **Figure 8**.

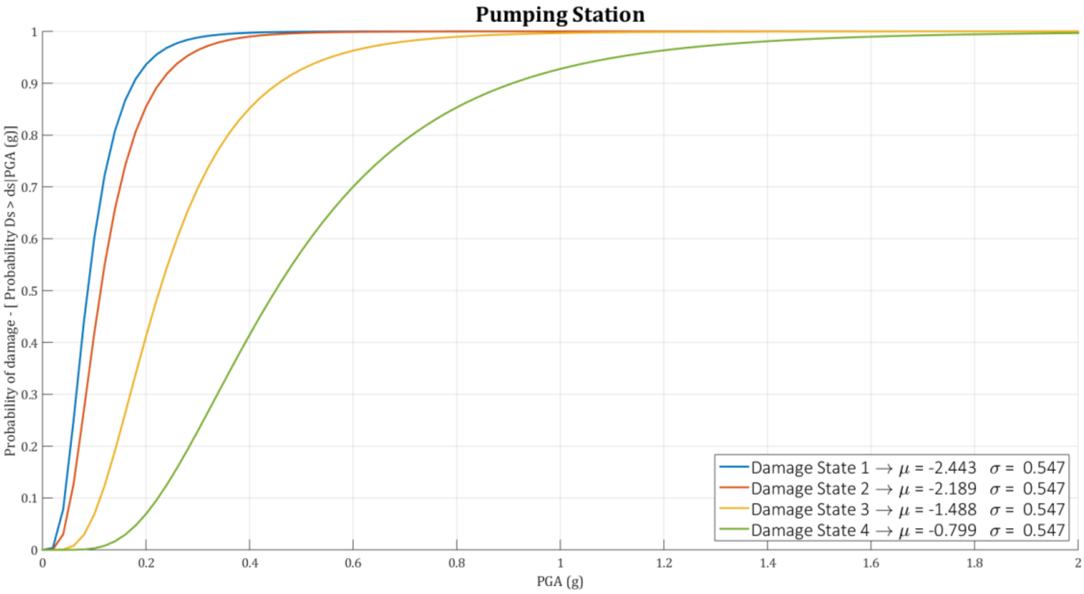

Figure 8 - The exclusive fragility curves that were derived for an oil pumping station

The risk appraisal processes were performed for two regions in Israel: Beer Sheva region and Bikat Hayarden region. The hazard curves (**Figure 9**) were approximated according to the Geophysical Institute of Israel (GII) data of annual rate ground motion for 2%,5%, and 10% probability of exceedance in 50 years [45].

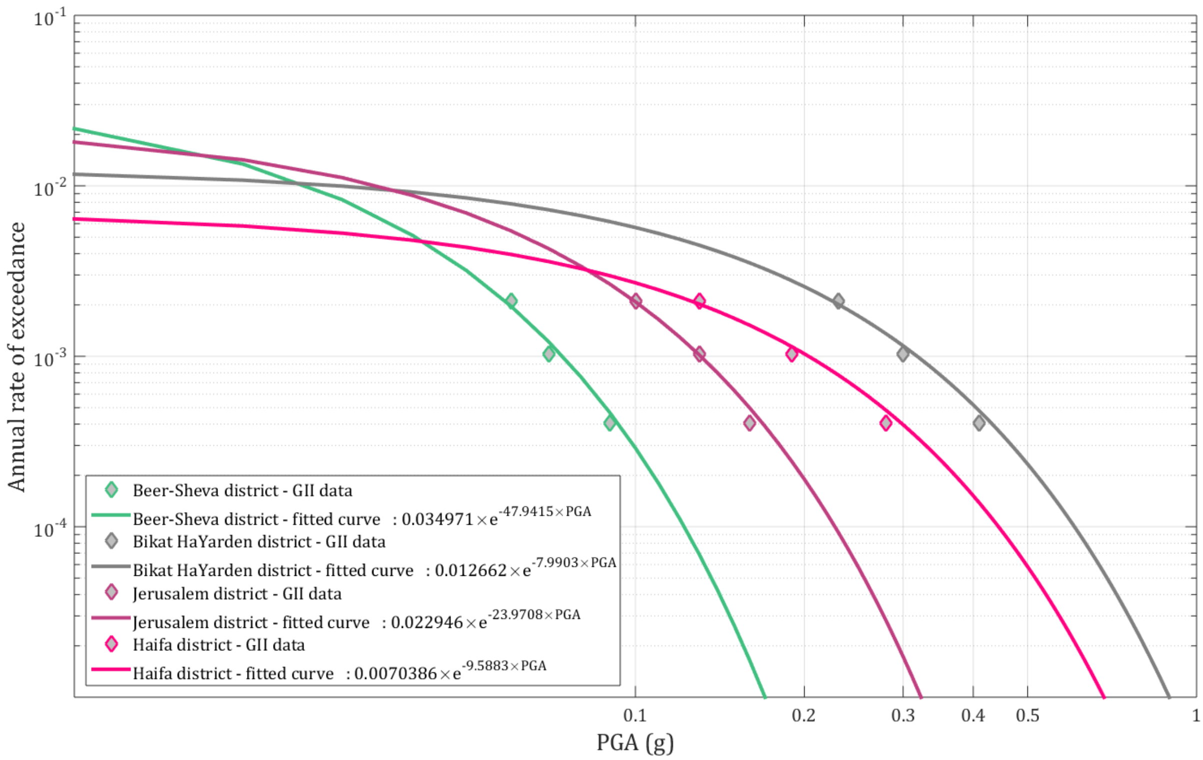

Figure 9 - Hazard curve for different areas in Israel

Following the methodology, the risk curves for each region were yielded (figure 4). The yielded risk curves are the composition of the rate exceedance and expected damage of a specific value of the PGA. Afterwards, the total risk expectancy for a life span of 50 years was calculated (figure 5).

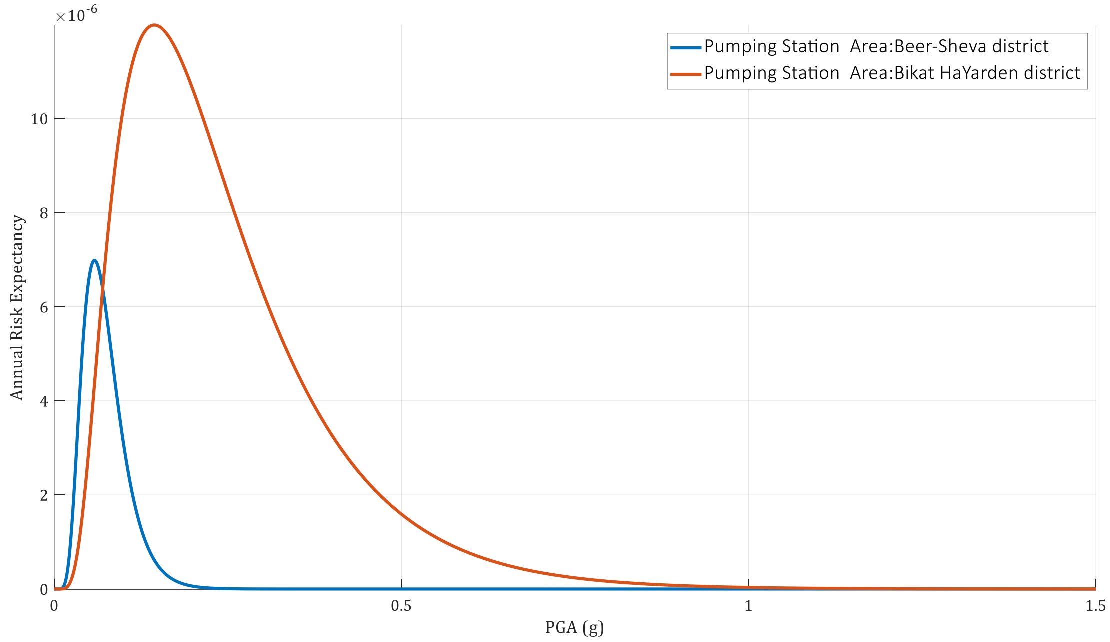

Figure 10 - Risk Curve for beer Sheva and BIkat HaYarden regions

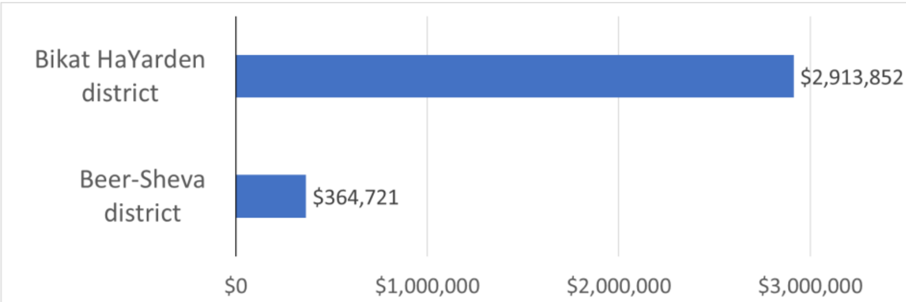

Figure 11 - total risk expectancy for a life span of 50 years

3.2. Examination of possible mitigation alternatives

In the risk management process, the mitigation alternatives are aimed to reduce the vulnerability of the sub-component and subsequently decrease the vulnerability of the pumping station. The examined mitigation alternatives are focused on the sub-components of the station: pump layout (single pump or two pumps), the power supply (power grid only, power grid with backup generator, power grid with seismic Isolation backup generator), and the building type (concrete moment frame building (C1L) or concrete shear walls building (C2L)). In total, twelve alternatives were examined for each site, to find the most beneficial one. The mitigation alternatives compose of different combinations of the sub-component's layout. Table 11 presents the different alternatives, pumping and power supply configuration and their estimated costs.

Table 11 - Alternative mitigation strategies

Alternative #	Building	Pump	Power supply	Estimated cost ($)
1	C1L	single pump	Only Grid	-
2	C1L	single pump	Grid + Generator w/o	70,000
3	C1L	single pump	Grid + Gen with Isolation	80,500
4	C1L	two pumps	Only Grid	250,000
5	C1L	two pumps	Grid + Generator w/o	320,000
6	C1L	two pumps	Grid + Gen with Isolation	330,500
7	C2L	single pump	Only Grid	100,000
8	C2L	single pump	Grid + Generator w/o	170,000
9	C2L	single pump	Grid + Gen with Isolation	180,500
10	C2L	two pumps	Only Grid	350,000
11	C2L	two pumps	Grid + Generator w/o	420,000
12	C2L	two pumps	Grid + Gen with Isolation	430,500

The risk management process is intended to indicate the optimal mitigation alternative; the optimal alternative will be derived base on the cost of the alternative and the risk reduction percentage and the overall risk reduction in terms of USD. The overall risk reduction in terms of USD is based on the location of the station.

3.3. Results and discussion

For each region the proposed mitigation alternatives were investigated. Table 12 presents the total risk expectancy for 50 years span-life (TRE_{50}), the estimated risk mitigation (ERM^{50}) and the calculated RMIR for each alternative. Figure 6 and Figure 7 present the percentage of risk mitigation and risk mitigation to investment ratio (RMIR).

Table 12 - Total risk expectancy for 50 years span-life (TRE50), estimated risk mitigation (ERM) and calculated RMIR for different mitigation alternatives

Mitigation alternative		**Beer-Sheva region**			**Bik'at Ha'Yarden region**		
#	Estimated Mitigation Cost [$]	TRE_{50} [$]	ERM^{50} [% ($)]	$RMIR$	TRE_{50} [$]	ERM^{50} [% ($)]	$RMIR$
1	-	364,721	0% (0$)	-	2,913,852	0% (0$)	-
2	70,000	292,256	19.9% (72,465$)	1.035	2,731,600	6.3% (182,252$)	2.604
3	80,500	291,842	20% (72,879$)	0.905	2,725,695	6.5% (188,156$)	2.337
4	250,000	364,692	0% (30$)	0	2,913,062	0% (789$)	0.003
5	320,000	292,208	19.9% (72,514$)	0.227	2,730,594	6.3% (183,257$)	0.573
6	330,500	291,772	20% (72,949$)	0.221	2,724,603	6.5% (189,249$)	0.573
7	100,000	267,820	26.6% (96,901$)	0.969	2,601,564	10.7% (312,288$)	3.123
8	170,000	177,057	51.5% (187,665$)	1.104	2,303,721	20.9% (610,131$)	3.589
9	180,500	176,453	51.6% (188,268$)	1.043	2,294,304	21.3% (619,548$)	3.432
10	350,000	267,810	26.6% (96,911$)	0.277	2,600,415	10.8% (313,437$)	0.896
11	420,000	176,955	51.5% (187,766$)	0.447	2,301,969	21% (611,882$)	1.457
12	430,500	176,380	51.6% (188,341$)	0.437	2,292,495	21.3% (621,356$)	1.443

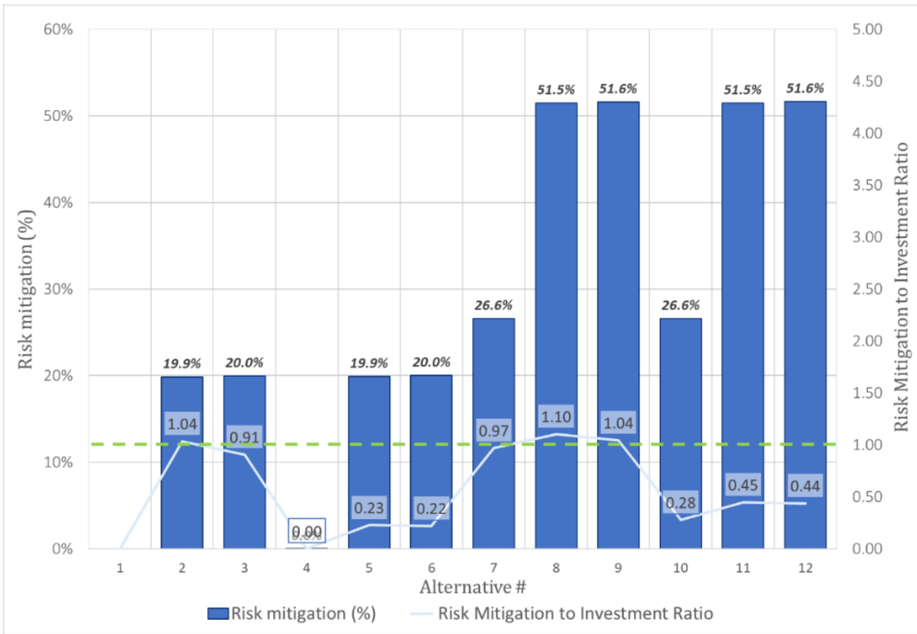

Figure 12 - Analysis of the mitigation alternatives by the percentage of Risk mitigation and RMIR case of Beer-Sheva Region

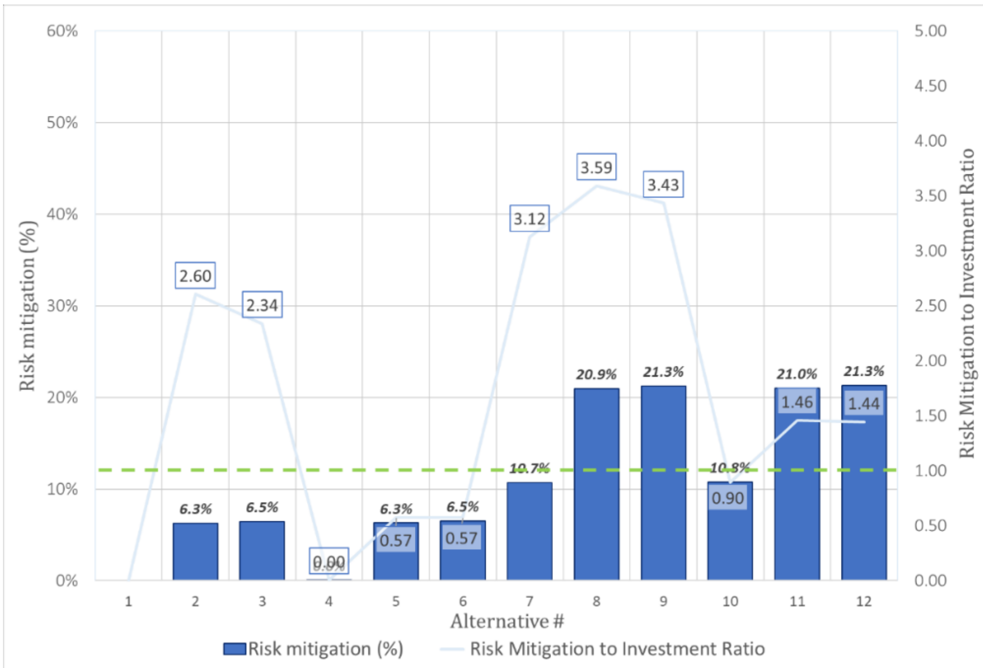

Figure 13 - Analysis of the mitigation alternatives by the percentage of Risk mitigation and RMIR, case of Bik'at Ha'Yarden region

4. Conclusion

This research introduces a comprehensive methodology for seismic risk appraisal and management. The proposed methodology examines the preparedness of critical infrastructures through an appraisal of the risk that CIs are exposed to in case of extreme seismic events. This research establishes a probabilistic quantitative model that assesses the total risk expectancy of CIs to extreme earthquake events and produces a decision support tool that allows decision-makers to manage and analyze alternative courses of action in order to mitigate the risk considering a wide range of risk scenarios. The proposed methodology was illustrated thorough a case study of an oil pumping station. In this case study, three alternative mitigation strategies were examined: additional pump installation (redundancy), installation of diesel generator with and without seismic isolation (redundancy) and building retrofit (robustness). Furthermore, any possible combinations of those strategies were examined. It was found that additional pump (pump redundancy) yields only minor contribution to the risk mitigation, whereas the building retrofit yields the most significant impact on risk mitigation. The pump sub-component is not vulnerable to low accelerations; therefore, it has a low impact on the overall risk. In contrast, according to the structure sub-component fragility curve, it is vulnerable to low to moderate acceleration intensities, and consequently, its effectiveness on the overall risk is high.

In addition, this study proposes the RMIR (Risk Mitigation to Investment Ratio) as a novel quantitative indicator in order to examine and prioritize alternative mitigation strategies. The proposed RMIR indicator evaluates alternative mitigation strategies based on cost-effectiveness of the mitigation strategies, considering integrated probabilities of all damage states and all possible seismic scenarios. This indicator is unbiased and depends on quantitative values and objective estimates of the seismic risk the CI resistance. Moreover, we propose an indicator that covers all possible seismic scenarios due to the PSHA approach that is being implemented systematically in the methodology. The RMIR examines and prioritize the alternatives based on the Risk Mitigation to Investment Ratio; If an alternative has an RMIR greater than 1.0, the alternative is expected to be efficient in terms of risk mitigation. On the other hand, If the alternative has an RMIR lower than 1.0, then the alternative is considered to be un-efficient in terms of risk mitigation, meaning that the investment is higher than the expected benefits of risk mitigation. In addition, the higher the value of RMIR, the higher the cost-effectiveness of the mitigation alternative. The benefits of the proposed indicator were illustrated in the case study. The indicator allows to examine the cost-effectiveness of the alternatives and prioritize the mitigation alternatives according to decision-makers policies.

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Sustainable Site Selection: An AHP-MAUT Decision-Making Approach using a GIS Platform

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Abstract

While green building rating systems allow for projects to follow a set of guidelines to construct a healthy, resource-efficient building, a building should only be considered sustainable, in a holistic sense, if a similar level of thought is placed on the project's site. The US Green Building Council's Leadership in Energy & Environmental Design (USGBC LEED) rating system provides a set of credits related to the site's location in its Sustainable Sites, Location & Transportation, Energy & Atmosphere, and Regional Priority categories, however these parameters cannot account for the feasibility of these solutions or their financial effectiveness. This study proposes to mitigate this problem utilizing a combined Analytical Hierarchy Process (AHP) and Multi-Attribute Utility Theorem (MAUT) decision-making tool that will assess several desired site attributes (e.g. cost, distance to public transportation, solar potential) using a set of user-defined attribute weights, via pairwise comparisons, to produce a site score that outlines each location's desirability and allows for comparisons between the alternatives. The study proposes assessing the desirability of four potential sites (in the state of Florida in the United States) for the location of a low-rise office building seeking LEED certification. A GIS model, constructed predominately from information provided by the Florida Geographic Data Library, will allow for estimating several site parameters that would otherwise be difficult to obtain without on-site analysis. The four project alternatives will be compared based on their site scores and how well they meet the project's individual goals.

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Keywords: analytical hierarchy process, decision-making, geographic information systems, multi-attribute utility theorem, sustainability.

1. Introduction

While any client making the decision to have their building project pursue certification with a sustainable rating system (e.g., the US Green Building Council's Leadership in Energy and Environmental Design [LEED], Building Research Establishment Environmental Assessment Method [BREEAM]) is trying to incorporate sustainability as a major aspect of their project, its inclusion in a construction project often leaves the question of how to consider the trade-off between a project's sustainability goals and its financial goals. Sustainable construction can often be viewed as a more expensive venture than typical construction practices and past studies have found that LEED construction typically incurs a cost premium in the range of 2% [1,2]. Given that sustainable construction may be more expensive, the decision-maker may encounter the question of 'How much am I willing to spend to achieve to obtain a more sustainable project?' We are often conditioned to look for an objective method to solve this tradeoff problem but this type of problem is subjective in nature. When expanding this subjectivity to other aspects of the problem, a decision-maker will find that several project parameters contribute to the desirability of a project but may lack an identifiable tradeoff relationship with each other. For example, when selecting a residence/building to purchase/rent, the decision-maker will consider the purchase cost of the building will be of great importance, but the location of the project, the size of the building, and its proximity to other amenities or transportation networks may also be influencing factors. Without any guidelines, it can be difficult to understand how to model tradeoffs between the size of the building and its location. As such, an ideal decision-support system should be flexible (i.e., capable of considering multiple competing goals) and should be able to incorporate a decision-maker's own subjective bias. Based on these criteria, the Analytical Hierarchy Process (AHP) was implemented to assist in applying a set of user-defined weights/biases to create a decision-support system that can compare numerous competing project goals and assess their relative importance to the overall desirability of a project. It can assist the decision-maker in identifying their own biases and using them to understand how they view the tradeoff between a project's sustainable and financial goals. While AHP is effective at allowing the decision-maker to conceptualize the relative importance of a project's criteria, it doesn't provide a method for determining how well any given alternative meets the goals of a criteria (i.e., it tells us the relative importance of sustainability on a project, but not necessarily how well a given alternative meets the sustainability goals). The inclusion of the Multiple Attribute Utility Theory (MAUT) allows for modeling the relationship between project parameters and their overall desirability to the project. This combined AHP-MAUT decision-making approach takes the weighting system from AHP and combines it with the goal achievement modeling from MAUT to produce a flexible decision-support tool that takes objective project information (e.g., project cost, site solar energy potential) and subjective preferences to produce a decision-making tool that assists the decision-maker in selecting a preferable option from a set of alternatives.

AHP and MAUT are relatively straightforward systems, but it can be difficult for those unfamiliar with the systems to understand how to apply them to the decision-making process. As such, the objective of this research is to provide a framework for the AHP-MAUT decision-making approach and explain how it can be used for decision-support on projects looking to pursue some form of sustainable certification. The study will introduce a case study where a set of four different low-rise office buildings will be assessed by their ability to meet the financial and sustainable project goals, the approach's framework will be introduced, and an analysis of the model output will provide a clear understanding on how to interpret the results. Several site characteristics will be extracted from publicly available GIS data to better assess the attractiveness of the site to the decision-maker.

2. Literature Review

The Analytical Hierarchy Process (AHP) describes a decision-making process wherein the decision-maker is looking to compare two or more alternatives using multiple, competing criteria. The process described in [3,4] involves modeling a problem so that the decision-maker can identify their goal, alternatives (i.e., solutions to the problem), and the criteria that will be used to define how well an alternative solves the problem. Four different steps that AHP uses to support the decision-making process include: 1) definition of the problem; 2) structuring the decision hierarchy (typically with the goal at the top, followed by the criteria, the subcriteria, and with the alternatives at the bottom); 3) the development of pairwise comparison matrices (where each criteria's subcriteria are compared against one another); 4) using the weight values from the pairwise comparison matrices to determine each element's global priority (i.e., how important an individual element is to the overall goal) until the final priorities of the alternatives are known [4]. The definition of the problem and structuring of the hierarchy requires identifying the project's overall goal (e.g., construction of an office building), the criteria that act as barometers to determine how well an alternative has met the overall goal (e.g., building cost, number of LEED points obtained), and the sub-criteria that define the level of attainment an alternative achieves with the individual criteria (e.g., building size, facility maintenance costs, points obtained in the Energy & Atmosphere category). Each upper-level element (e.g., project goal, criteria) requires the development of a pairwise comparison matrix that will rank the elements in the level below. The decision-maker will use Table 1 to perform this action thereby defining the relative importance of each subcriteria in meeting the objectives of the criteria. For example, if a project has a cost criterion, then the pairwise comparison matrix will be used to define the relative importance of each cost subcriteria (e.g., building cost, maintenance cost, property taxes) in achieving the goals of that criterion. Once performed for the project's criteria and subcriteria, each element's global priority will be known, thus providing the decision-maker with both a ranking of each element and an understanding of the relative difference in the importance between any two elements.

The flexibility of the Analytical Hierarchy Process allows for it to provide decision support on problems from a multitude of disciplines. Previous literature has attributed the ease of handling multiple, diverse criteria [5,6,7], capable of working with both qualitative and quantitative data [5], and ease of use [5,7] to AHP. In the area of sustainability, methodologies involving AHP in the decision-making process have included those for prioritizing the most relevant sustainability initiatives in a business [8], the selection of a socially sustainable supplier [9], selecting a building alternative based on sustainability and cost parameters [10], and the selection of sustainable materials for construction projects [11].

Table 1. The fundamental scale of absolute numbers [4].

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgement slightly favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgement strongly favor one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity I has one of the above non-zero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	A reasonable assumption
1.1-1.9	If the activities are very close	May be difficult to assign the best value but when compared with other contrasting activities the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities

Given the method's flexibility and qualitative nature, AHP was selected for use in this study, as comparing sustainability goals to cost goals requires some level of subjectivity. However, while AHP is beneficial for obtaining an exact weighting system for the model's elements, it lacks the ability to determine how well a given alternative achieves each goal. This requires a method that can objectively assess goal attainment, which is where the multiple attribute utility theorem (MAUT) is applied in the model. This paper will follow a similar application of MAUT as those from [10,12] where each alternative will be assessed for how well it can meet the goals of each element in the AHP hierarchy. To determine how well an alternative meets an element's goals, the decision-maker will produce an upper bound value U_H and lower bound value U_L for each model element. These two user-defined values provide a best-case scenario (U_H) and worst-case scenario (U_L) for how well an alternative meets the objectives of an element. For example, if a consumer is looking to purchase a fuel-efficient vehicle then the U_H and U_L values provide the highest and lowest expected fuel efficiency values that the consumer could expect to encounter, respectively. U_H represents a highly desirable outcome and gives a utility value of 1.0, while U_L depicts an undesirable outcome and provides a utility value of 0.0. In the instance where any values exceeding U_H or below U_L are encountered, they will be assigned the utility values of 1.0 and 0.0, respectively. Any value (x_i) between the U_H and U_L will be assigned a value between 0.0 and 1.0 based on an assumed linear relationship between the two points, as shown in Equation 1. This 'risk neutral' behavior, along with other theoretical non-linear risk seeking behaviors are visualized in Figure 1 [10,12].

$$uy_i = \frac{(x_i - U_L)}{(U_H - U_L)} \tag{1}$$

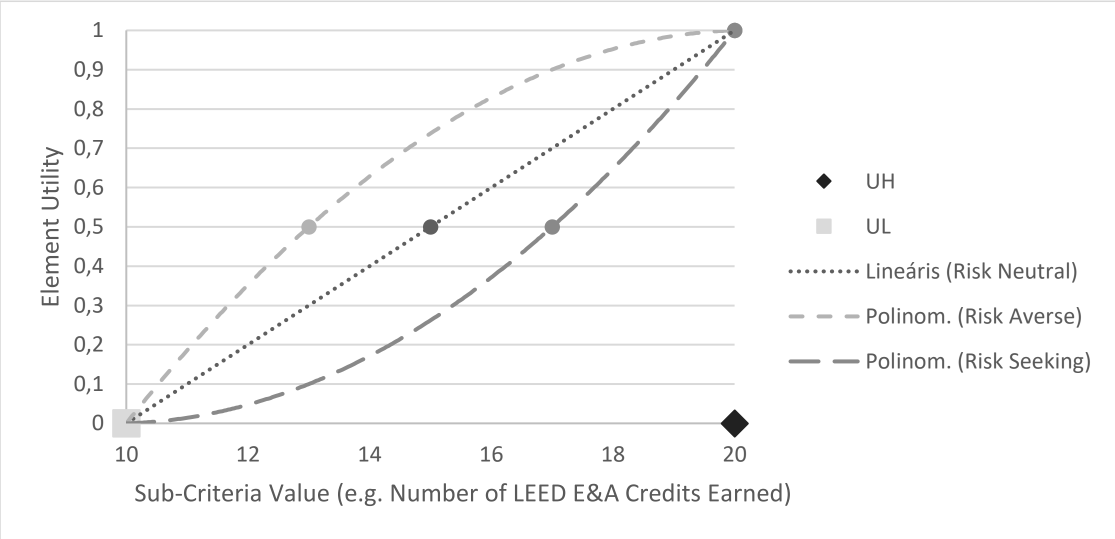

Fig. 1. Example Utility Curves [10].

Each alternative will have every element's utility determined, thus providing the model with an understanding of how well the alternative meets the goals of each subcriteria. When combined with the AHP weighting system, the model can assess the overall utility of each alternative. Once performed for every alternative, the one with the highest overall utility will be the superior option, at least based on the parameter input and the decision-maker's own subjective analysis.

3. Methodology

Four potential vacant, low-rise office building sites across the state of Florida, in the United States, were assessed for their ability to meet a set of author-defined financial and sustainability goals. Project goals are defined in Table 2 based on their position on the AHP hierarchy as either criteria or subcriteria. Certain environmental goals (i.e., Transportation Access, Brownfield, HUD/Enterprise/Empowerment Zone, FAR, and Diverse Uses) are based on LEED credit requirements, so the project goals will align to the LEED code requirements.

Environmental data from the Florida Geographic Data Library, the National Renewal Energy Laboratory, and SolarGIS were checked to ensure a consistent datum (GCS_WGS_1984) and avoid any x-y positioning errors. A new feature class was created for the four office buildings and a basemap was added to the file to assist with their placement. The office building layer extracted data from the environmental sources either via manual entry (for vector files) or using the 'Extract Values to Points' (for raster files). Any GIS data where the only input was whether or not the building was located in a specific area (i.e., Brownfield, Public Transportation Access, HUD/Enterprise/Empowerment Zone) was recorded as a binary value, where '0' represented a case where the building wasn't located in a zone and '1' indicated that the building was in a zone. All other data simply extracted its information directly from where the point intersected the raster file. Samples of the two project locations from Jacksonville and the project from Orlando are shown in Figure 2.

Some of the GIS analyses required the inclusions of a buffer zone to ensure consistency with LEED credit guidelines. This was the case for the 'Public Transportation' layer, as it was buffered using a distance of 400 meters to keep it in line with LEED's 'Access to Quality Transit' requirements. A similar 800-meter buffer was placed around each building to assess the surrounding land uses, as per the LEED 'Surrounding Density and Diverse Uses' credit, however the actual site assessment (i.e., determining the number of diverse facilities around the building site) was performed using a visual assessment via Google Maps.

Table 2. Project Element Hierarchy and Data Sources.

Goal/Project Parameter	Hierarchy Level	Associated Criteria	Method obtained
Cost/Location	Criteria	-	-
Renewable Energy	Criteria	-	-
Sustainable Site	Criteria	-	-
Purchase Cost	Sub-Criteria	Cost/Location	Online Commercial Property Search (loopnet.com)
Office Size (Area)	Sub-Criteria	Cost/Location	Online Commercial Property Search (loopnet.com)
Number of Parking Spaces	Sub-Criteria	Cost/Location	Online Commercial Property Search (loopnet.com)
Trip Time to Nearest Airport	Sub-Criteria	Cost/Location	Online Commercial Property Search (loopnet.com)
Global Horizontal Irradiance (Solar Potential)	Sub-Criteria	Renewable Energy	SolarGIS: https://solargis.com/maps-and-gis-data/download/world
Average Wind Speed (Wind Potential)	Sub-Criteria	Renewable Energy	National Renewable Energy Laboratory: https://www.nrel.gov/gis/wind-resource-maps.html
Public Transportation Access	Sub-Criteria	Sustainable Site	Florida Geographic Data Library: Public Transit Routes in Florida - 2019
Brownfield	Sub-Criteria	Sustainable Site	Florida Geographic Data Library: Brownfield Areas in Florida - May 2021
HUD, Enterprise, or Empowerment Zone	Sub-Criteria	Sustainable Site	Florida Geographic Data Library: HUD, Empowerment Zones, and Enterprise Communities in Florida - 2016
Number of Diverse Uses	Sub-Criteria	Sustainable Site	*Visual Assessment from Google Maps
Floor-to-Area Ratio (FAR)	Sub-Criteria	Sustainable Site	Online Commercial Property Search (loopnet.com)

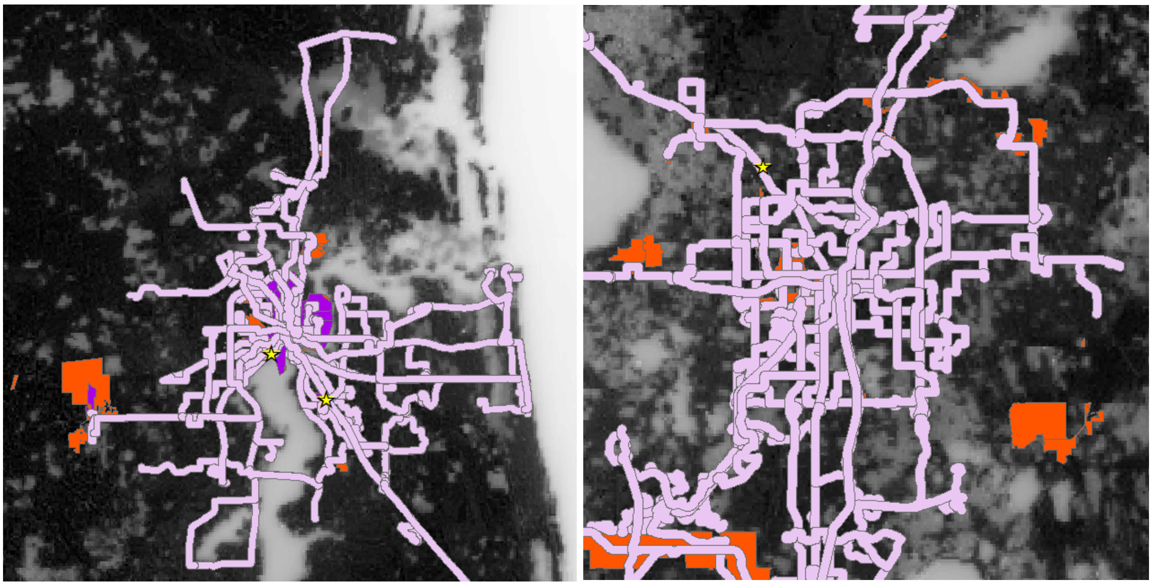

Fig. 2. GIS Models for (a) Alternatives 1 and 4; (b) Alternative 2.

Name	City	Area (sq ft)	Parking Spaces	Cost ($)	FAR	Airport Travel Time (min)	Public Transportation	Brownfield	HUD_Ent_Emp	Wind Speed (m/s)	DIF (kWh/m2)	Diverse Uses
Alternative A	Jacksonville	10365	35	2750000	0.55	26	1	0	0	2.83	4.88	5
Alternative B	Orlando	6478	15	899000	0.31	36	1	0	0	2.97	5.02	2
Alternative C	Tallahassee	7817	22	899000	1.99	18	1	0	0	2.17	4.86	6
Alternative D	Jacksonville	6412	40	681000	0.17	32	1	1	1	2.28	4.91	3

Fig. 3. Case Study Data.

After extracting all GIS data from the vector and raster files, the information for all four alternatives was added to the Excel file. Determining how well each alternative manages to achieve its criteria and subcriteria goals requires the development of utility curves for each subcriteria. As the risk behavior of the decision-maker is assumed to be 'risk neutral', the utility curve will simply consist of a linear line that spans between two boundary conditions (U_L and U_H). These two conditions should be defined by the decision-maker and will provide a worst-case scenario and best-case scenario for each subcriteria. While scenarios may exceed the U_H value or be lower than the U_L value, their overall desirability/utility will not be any different than they were directly equivalent to the U_H or U_L. Equation 1 is applied for any cases where the subcriteria value falls between the two boundary conditions (Table 3). All subcriteria where the input is binary were exempted from this process.

Table 3. Example MAUT Calculation for Alternative 2 Purchase Cost.

Case	Cost ($)	Desirability/Utility
U_L	1500000	0
U_H	750000	1
Alternative's Value	899000	0.80

After calculating each subcriterion's utility, the model has completed the MAUT analysis and requires the development of the AHP pairwise comparisons. Each level of the hierarchy needs to be independently assessed using Table 1 with the goal of ranking the elements and determining how much weight they add to the model (i.e., how important the model element to the project's overall goals). As this case study has identified three criteria (i.e., Cost/Location, Renewable Energy, and Sustainable Sites) and their associated subcriteria, four different pairwise matrices must be developed. Each subcriteria matrix provides weights for each of its elements so as to define how important each subcriteria is to the overall criteria's goals. Similarly, the criteria matrix provides weight values to define the relative importance of each criteria to the project's overall utility. An example of a questionnaire developed to produce the pairwise comparisons is provided in Figure 4.

Pairwise Comparisons	
Level 2 - Criteria Comparisons	
	Input Values in this column
For this project, I feel that achieving **Cost/Location** goals are of ____ importance compared to achieving **Renewable Energy** goals:	3
For this project, I feel that achieving **Cost/Location** goals are of ____ importance compared to achieving **Sustainable Site** goals:	5
For this project, I feel that obtaining **Renewable Energy** goals are of ____ importance compared to achieving **Sustainable Site** goals:	3
Level 3 - Sub Criteria Comparisons	
Cost/Location	
Achieving a lower **Purchase cost** is of ____ importance compared to getting the right **Office size (square footage)** :	3
Achieving a lower **Purchase cost** is of ____ importance compared to **Parking** :	4
Achieving a lower **Purchase cost** is of ____ importance compared to minimizing **Airport travel time** :	7
Achieving the right **Office size (square footage)** is of ____ importance compared to getting the right **Parking** :	2
Achieving the right **Office size (square footage)** is of ____ importance compared to minimizing **Airport travel time** :	6
Achieving the project's **Parking goals** is of ____ importance compared to minimizing **Airport travel time** :	3
Renewable Energy	
Achieving a higher **Global Horizontal Irradiance** is of ____ importance compared to maximizing **Average Wind Speed** :	5

Fig. 4. Example Pairwise Comparison Questionnaire (partial)

Prior to assessing model results, the pairwise comparisons must be assessed to ensure consistency in their assumptions (e.g., If parameter A is considered to be of equal importance to B and strongly more important than C, then it isn't logically consistent to state that parameter B is of equal importance to C) by calculating their consistency ratio. The process requires normalizing the columns in each matrix (i.e., dividing each cell value by the column summation), developing an nx1 eigenvector matrix (by averaging each row in the normalized matrix), multiplying the original pairwise comparison matrix by the eigenvector matrix to produce a transition matrix, and calculating the dominant eigenvalue (λ_{max}). The consistency ratio can be calculated using Equation 2 and the information from Figure 5. If the calculated consistency ratio is less than 0.10, then the provided pairwise comparisons are said to be sufficiently consistent and they can be used for the analysis. This procedure can be seen in greater detail in [3,4,10,12].

$$Consistency\ Ratio = \frac{\lambda_{max} - n}{(n-1) * RI} \tag{2}$$

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Fig. 5. Consistency Ratio Table [4].

The final calculation of an alternative's overall utility (i.e., how desirable an alternative is to the decision-maker) is a function of the summation of each individual subcriterion's utility multiplied by the AHP-derived criterion/subcriterion weight factors. Equation 3 provides the generalized formula for determining an alternative's utility, where C_i and S_i are, respectively, the appropriate criteria and subcriteria weight factors taken from their eigenvector matrices.

$$u(y_i, y_{i+1}, \dots, y_n) = \sum_n^i C_i S_i * uy_i \tag{3}$$

4. Results & Discussion

Calculating the utility values for each subcriterion and criterion, developing the pairwise comparison matrices, and calculating the utility value for each of the four alternatives produced the model output in Table 4. The top three rows provide an assessment of how well the alternative manages to meet the individual criterion goals. The decision-maker should be of the mind that each alternative meets the project's renewable energy goals, while also believing that the other two criteria are more mixed in their results. The decision-maker should review the alternatives and their ability to meet each of the project's criteria goals to identify any potential bias in the selection of possible alternatives or if the subcriteria boundary conditions require modification. The fourth row provides the overall utility for the project, thus providing the decision-maker with a value that should express the desirability of the project when considering the goals of all three criteria. Theoretically, the decision-maker can simply choose the alternative with the highest project utility value as this is the one that best aligns with their overall project goals and their tradeoffs. Given the results provided in Table 4, Alternative 4 is the most desirable of the four options and is the one that should be pursued. This conclusion may require addition analysis and introspection when there are one or more alternatives that have similar levels of attainment, as a small change to one of the original input parameters could change the output enough to cause a ranking change. To address this concern, the study performed a sensitivity analysis through the introduction of three additional scenarios where the AHP weight factors (obtained from the eigenvector matrices) were adjusted to see if a change in the weighting system may introduce a change in the alternative ranking.

Table 4. Calculation of Criteria and Project Utility Values.

Criteria	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Cost/Location	0.37	0.47	0.60	0.67
Renewable Energy	0.81	0.94	0.72	0.78
Sustainable Sites	0.57	0.37	0.71	0.62
Project	0.51	0.58	0.64	0.70

The three additional scenarios considered are as follows:

- Increasing the weight of the Cost/Location criteria by 10%
- Reducing the weight of the Cost/Location criteria by 10%
- Changing the weight of the Sustainable Sites criteria to equal 25%

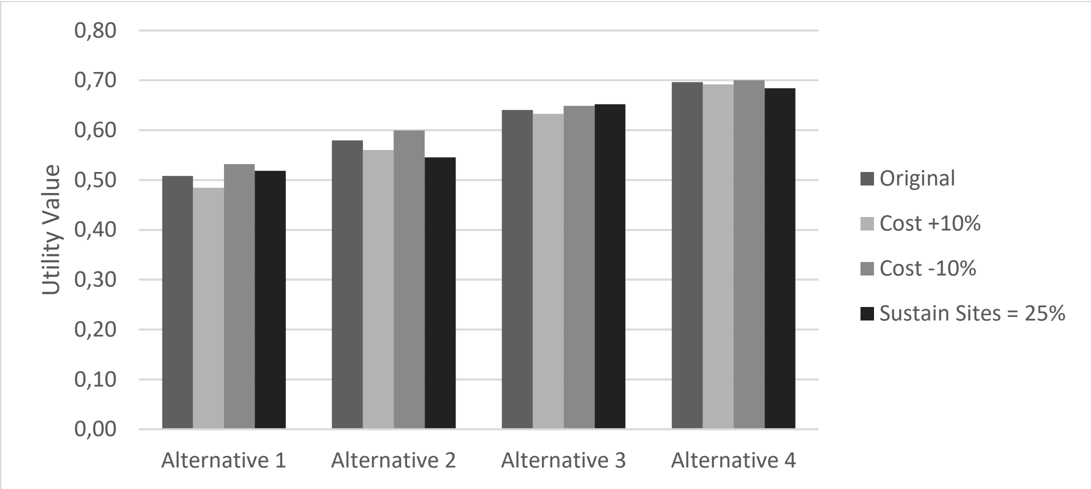

Fig. 6. Project Utility Values with Sensitivity Analysis.

The results from Figure 6 don't identify any cases where the project utility from Alternatives 1, 2, or 3 manage to surpass Alternative 4, though changing the Sustainable Sites criteria weight to 25% does manage to narrow the gap between Alternatives 3 and 4. No changes in the alternative ranking means that the decision-maker should be more confident in their selection since the introduction of some level of controlled volatility to the weighting system didn't produce a significant difference. In a theoretical scenario where the ranking does fluctuate based on the sensitivity analysis, the decision-maker should consider which scenario(s) best align with their convictions but should also realize that the alternatives may be quasi-interchangeable when considering their overall utility.

5. Conclusions

With the growing popularity of green building rating systems and continued push from government initiatives and regulations, decision-makers need a platform to conceptualize tradeoffs between project finance and sustainability goals. This process for competing criteria is made more difficult when they aren't directly comparable (e.g., costs versus LEED credits), thus requiring some method that can bridge the gap and allow for proper tradeoffs to occur.

The goal of this study is to provide a basic AHP-MAUT decision-making approach framework that can provide a decision-maker with a model capable of taking their own preferences, multiple alternatives, and site/building parameters with the goal of identifying the most desirable alternative. The study provides an example of the framework being used through the introduction of a case study involving four alternative office buildings and a set of cost/location, renewable energy, and sustainable site criteria and subcriteria. An example of the model set up, GIS mapping, steps used to calculate the alternative utility, an analysis of the case study output, and a discussion of the results from a sensitivity analysis provide an overview on how the framework can be used for decision-makers when considering similar project goals. However, the main takeaway from the study is to provide a framework that can be adapted by decision-makers to meet the needs of their project. Examples may include utilizing different project criteria (e.g., schedule or safety in place of renewal energy, obtaining LEED credits instead of sustainable sites), different subcriteria (e.g., property tax, project aesthetics, air pollution), and their own sensitivity analysis cases. Since every project has its own unique considerations and goals, the framework should be flexible enough to accommodate for these changing situations while also being logically consistent (e.g., consistency ratio, risk behavior).

As the proposed AHP-MAUT decision-making approach incorporates subjective data, through the form of pairwise comparisons and boundary conditions, the output relies on the decision-maker to validate their own results. The goal of the framework is to provide the decision-maker with a conclusion based on their own input and biases, which contrasts with more typical, objective decision-making approaches in construction (e.g., life cycle calculations). The inclusion of a sensitivity analysis can provide some insurance to the decision-maker by providing a method to create controlled shifts in the model's criteria weights with the goal of seeing if the alternative utilities shift enough to produce a change in the alternative rank. This will not remove the subjectivity from the analysis, but it does protect against concerns that slight model input changes could significantly affect the overall conclusion.

Future research can further investigate the inclusion of non-linear risk behaviors (i.e., risk aversion, risk seeking) in the MAUT calculations to potentially better map how changes in model parameters contribute to model utility. While the proposed framework was used for decisions involving sustainable office building projects, it can be implemented for any projects where the decision-maker needs to perform tradeoffs between dissimilar, competing criteria.

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Synergies Between Construction 4.0 Technologies and Sustainable Construction: A Bibliometric Analysis

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Abstract

In November of 2021, world leaders united in the 26th UN Climate Change Conference (COP26), and they set a Building Vision for a Zero Emission and Resilient Built Environment, Regions and Cities. The Architectural, Engineering, and Construction industry (AEC) is responsible for the design, planning, construction, and maintenance of the built environment- thus, playing a critical role in supporting and leading these endeavors. With the ongoing efforts to digitize the AEC industry by implementing and integrating innovative technologies in the industry's main practices, the aim of this research is to investigate the contribution of three major technologies that are considered under the umbrella of Construction 4.0 namely Building Information Modeling (BIM), advanced manufacturing (including 3D printing, modular construction, offsite construction, and prefabrication) and Digital Twins. Building on insights collected from the extant research corpus through a systematic literature review of the published scientific research, this paper proposes a blueprint for the three Construction 4.0 technologies and their overarching influence on the achievement of Sustainable Development Goals (SDGs). Bibliometric analysis was employed to map the currently discussed technologies, and group them into themes based on their "combat capabilities" and contribution to sustainability. The analysis resulted in three major clusters: (1) Sustainable Design and Modelling lead by BIM, (2) Lifecycle Sustainability Assessment led by prefabrication, modular construction, and offsite construction, and (3) Sustainable Construction and Performance led by Digital Twins and 3D printing. Findings of the paper will serve as the foundation for future work that will map the expand on the clusters and mark their respective technologies to the SDGs.

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Keywords: 3D printing, building information modeling, digital twins, offsite construction, sustainable Development Goals (SDGs)

1. Introduction and Background

As of November 4, 2016, actions resulting from the Paris Agreement on Climate change was commenced after 55 countries responsible for 55% of the total greenhouse gas emission agreed to work toward limiting the global temperature rise to below 2 degrees Celsius. The Paris Agreement aligned with the efforts initiated by the United Nations (UN) in 2015 toward achieving the 17 Sustainable Development Goals (SDGs), initiating a global roadmap to achieve an essential transformation of energy access and transition by 2030, and contributing to net zero emission by 2050 [1]. However, in 2019, the COVID-19 crisis was an inflection point which changed the course toward sustainable development. While progress toward the 2030 target goals has been made before the pandemic, the pace of change toward the 17 SDGs was not as desired [2]

[3]. The authors of [4] showcased how the pandemic disrupted the progress toward SDGs especially in developing countries. Moreover, [3] highlighted that SDGs' priorities will shift due to funding disruptions. The pandemic crisis provided clear evidence that the lack of focus on SDGs, especially the ones related to people and the environment, played an important role in the emergence and spread of infectious diseases, including COVID-19 [5]. Consequently, the chaotic environment that was caused by the pandemic has spurred a shift in goals and investments towards health and infrastructure [6]. The pandemic has accelerated the shift toward social infrastructure projects that will target urbanization, healthcare, infrastructure, and Global Water, Sanitation, & Hygiene (WASH) projects which will help cities to face future pandemics [7] [8].

However, regardless of the challenges facing the SDGs, various publications have highlighted the important role SDGs have in recovery. The authors of [2] [5] [9] argued that SDGs can be the blueprint of response and recovery. Moreover, United Nations Environment Programme (UNEP) listed four SDGs that are anticipated to help in the post-pandemic recovery, including Responsible Consumption and Production, Climate Action, Life on Land, and Life Below Water [10]. Also, the authors of [11] explained how SDGs such as Climate Action Partnerships and Reduced Inequality are considered the cornerstone for a successful recovery and transition to sustainability. In addition to being an important aspect of strong sustainable recovery, previous work highlighted how SDGs are beneficial for various industries including the Architectural, Engineering and Construction (AEC) industry. Corporate Citizenship provided a detailed overview of how different SDGs benefit different businesses. For instance, the Architectural, Engineering, and Construction (AEC) industry can benefit from affordable and clean energy goal, a benefit that is becoming critical for the future market, and for improving operational efficiency in addition to the benefits for the environment [12]. Other goals such as Industry Innovation and Infrastructure, Life on Land, and Life Below Water will aid in the prevention of adverse environmental incidents, proactively manage operational health and safety, and help to maintain trust with key stakeholders which can have a long-term positive effect on future projects.

By the same token, governments around the world are considering several actions to address the sustainable issues of the AEC industry, including high carbon emission, health and safety risks, low productivity, and increasing costs. Thus, implementing and adopting Construction 4.0 technologies within the AEC industry was considered as a potential solution to address and overcome the industry's sustainable challenges [13] [14]. [15] investigated the existing research work that categorized Construction 4.0 technologies and identified 17 different technologies that are considered under the umbrella of Construction 4.0, namely: Artificial Intelligence (AI), Additive Manufacturing, Augmented Reality/Virtual reality, Automation and Robotics, Big Data, Building Information Modelling (BIM), Cloud Computing, Cypher Physical Systems (CPS), Digital Twins, Geographic Information System (GIS), Internet of Thing (IoT), Laser scanners, Modular Construction, Offsite Construction, Prefabrication, Sensors, and Unmanned Aerial Vehicles/Drones.

The authors of [16] conducted a bibliometric analysis of the construction education studies published between 1983 and 2017 to highlight the current trends in the construction education research. This study found that emerging concepts like BIM and sustainability are trending. This finding indicates the increasing interest of researchers in investigating sustainable construction. Similarly, [17] conducted a bibliometric review to document the trending research in the field of sustainable construction over the last 25 years and determined that the dominant topics were alternative materials for sustainable construction, sustainable construction management, recycling and waste reduction, and social sustainability in construction management. Moreover, [13] further discussed that understanding the implementation of Construction 4.0 technologies in the AEC industry and its contribution to sustainability is not clear yet, however, the authors found that positive impact of Construction 4.0 technologies on the environmental and economic sustainability surmounts its negative effect, but its impact on social sustainability is still questionable. Thus, it is critical to upskill the level of knowledge about the capabilities of Construction 4.0 technologies, investigate the different applications for trending technologies, and consider technologies that are expected to have a significant impact in the future. This knowledge and understanding will increase the awareness of the potential of Construction 4.0 technologies in addressing the sustainable concerns facing the industry and will enable the stipulation of policy interventions that would mitigate the negative impacts related to sustainability. Therefore, the aim of this paper is to further investigate the contribution of adopting Construction 4.0 technologies in the AEC industry toward achieving the overarching SDGs and supporting the post-pandemic recovery.

2. Research Approach

This research paper is part of an ongoing effort to investigate the influence of Construction 4.0 technologies on the achievement of the Sustainable Development Goals (SDG). This overarching objective is achieved through a series of intermediate objectives: (1) conduct a bibliometric review of research aimed to document and articulate research trends in the integrated domain of sustainable construction and the implementation of Construction 4.0 technologies; (2) cluster the technologies based on their keyword co-occurrences and identify existing themes; (3) identify the contribution of the investigated Construction 4.0 technologies toward sustainability by extracting empirical evidences of this contribution from literature; (4) map the influence of Construction 4.0 technologies to the SDGs; and (5) develop a quantitative measure to quantify the direction of influence of the investigated Construction 4.0 technology toward achieving SDGs (i.e., no influence, positive influence, or negative influence) and the aggregated influence of all investigated technologies toward the achievement of the SDGs. This paper only covers the first three tasks and investigates the major technologies that are considered under the umbrella of Construction 4.0, namely Building Information Modelling (BIM); advanced manufacturing including the following technologies: 3D printing, modular construction, additive manufacturing, offsite construction, and pre-fabrication; and Digital Twins.

2.1. Data collection

Web of science (WOS) was considered as the data collection source. The unit of analysis used was “term extracted from title or abstract” which is considered one of the most used bibliometric techniques [18]. Based on the Web of Science settings, all research written in English were selected. To ensure a good representative selection of the collected data, different queries were used. Moreover, to better focus the scope of the search and limit unnecessary burden, the focus was on articles that contained the searched query term(s) in their title or abstract. Table 13 summarizes the queries used for the data collection. The collected data was exported to both text and CSV files.

Table 13. Summary of the queries used for the data collection

First Search	((TS=("Construction") OR TS=("AEC") OR TS= ("Architecture Engineering Construction") OR TS= ("Built Environment")) AND	(TS= ("Building information Modeling") OR TS=("BIM")) AND (TS=("Sustainability")))
Second Search	((TS=("Construction") OR TS=("AEC") OR TS= ("Architecture Engineering Construction") OR TS= ("Built Environment")) AND	(TS= ("Modular Construction") OR TS= ("3D Printing") OR TS= ("Additive Manufacturing") OR TS= ("three-dimensional printing") OR TS= ("Offsite Construction”) OR TS=("Prefabrication")) AND (TS=("Sustainability")))
Third Search	((TS=("Construction") OR TS=("AEC") OR TS= ("Architecture Engineering Construction") OR TS= ("Built Environment")) AND	(TS= ("Digital Twin*) AND (TS=("Sustainability")))

2.2. Quality assessment and normalization

A total of three searches were conducted as shown in Table 1. Each query search was conducted separately to ensure better quality assessment and quality control. The search resulted in a total of 979 papers, distributed as follows: 651 papers resulted from the first search, 302 papers were obtained from the second search, and 26 papers were gathered from the third search (refer to Table 1). After each query search, the abstracts were investigated, and, if the topic of the research was found to be relevant to the current study, the research was selected. This selective process enabled the selection of the research work that is only specific to sustainable construction in the AEC industry and the selected Construction 4.0 technologies. As such, 358 papers were selected from the first search, 174 papers from the second search, and 24 from the third search. Therefore, a total of 556 papers were considered for further data analysis.

The final set of 556 papers was then categorized according to the type of technology adopted. Moreover, to ensure a required level of quality control, the Document Type (DT) as identified by WOS [19] was further investigated. As shown in Fig. 14., most of the selected papers for the different technologies were articles (i.e., a published research paper), followed by proceedings paper (papers that have been presented in full at a conference, meeting, symposium or similar gathering, generally published in a book of conference proceedings), then followed by review (i.e., a renewed study or survey of previously published literature providing new analysis or summarization of the research topic).

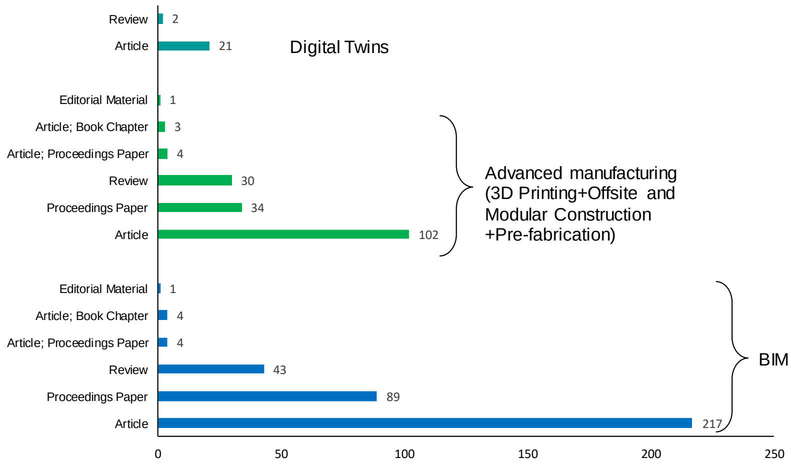

Fig. 14. Distribution of Document Types of the selected papers across different technologies.

3. Results

3.1. Bibliometric analysis

The annual scientific production presented in Fig. 15. shows that the interest in implementing BIM, advanced manufacturing and Digital Twins for sustainable construction fluctuated in early years until 2018. After 2018, the interest in implementing these technologies and their contribution to achieve sustainability continued to increase and peaked in 2021 for all technologies considered in this study. Thus, these trends support the argument that, after the COVID-19 pandemic, awareness of the criticality of achieving sustainable construction by adopting and implementing emerging technologies became evident.

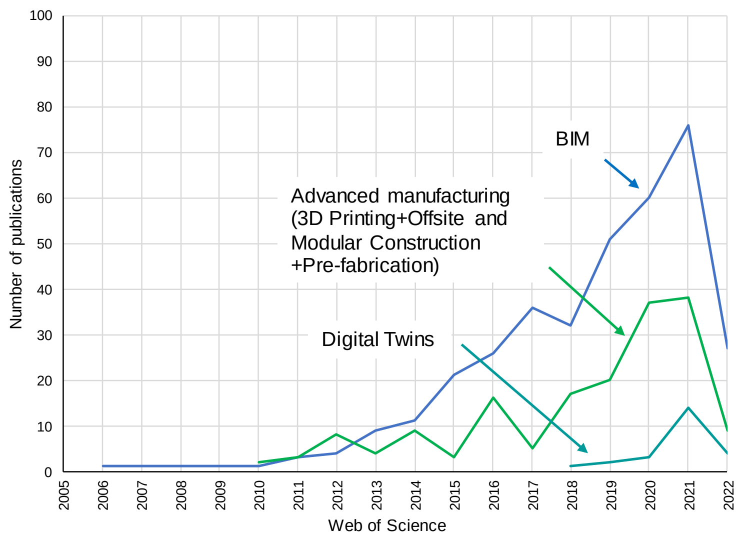

Fig. 15. Published scientific literature (2005-2022)

Moreover, to highlight how the research field is structured, topical analysis was employed. A co-word map was generated in VOSviewer using a threshold of 15 keyword co-occurrences as presented in Fig. 16. Three clusters were identified, each represented by a color and with a minimum size of five keywords. The map in Fig. 16. reveals three themes (1) Sustainable Design and Modelling, (2) Lifecycle Sustainability Assessment, and (3) Sustainable Construction and Performance. As shown in Fig. 3. BIM is in the middle of theme 1 of Sustainable Design and Modelling. This finding is also evident in the work of [20] who investigated the synergies between BIM and sustainability where BIM is said to be mainly associated with sustainability through its capabilities of design optimization, data management and data integration, analysis and simulation. Moreover, for the second theme of Lifecycle Sustainability Assessment, technologies such as off-site construction, prefabrication, and modular construction were included in this theme. This grouping aligns with the capabilities of these technologies that aim to enable the concept of circular economy and reduce the greenhouse gas emission and waste generation [21] [22]. Also, the authors of [23] found that the sustainability performance indicators of these technologies are very important for evaluating lifecycle sustainability of construction. Furthermore, for the third theme of Sustainable Construction and Performance, technologies such as Digital Twins and 3D printing were clustered together. Digital Twins can contribute to sustainability by optimizing performance through its capability of conducting what-if simulations [24] [25]. Additionally, [26] investigated how 3D printing can improve the thermal performance of structures and how it can contribute to waste minimization.

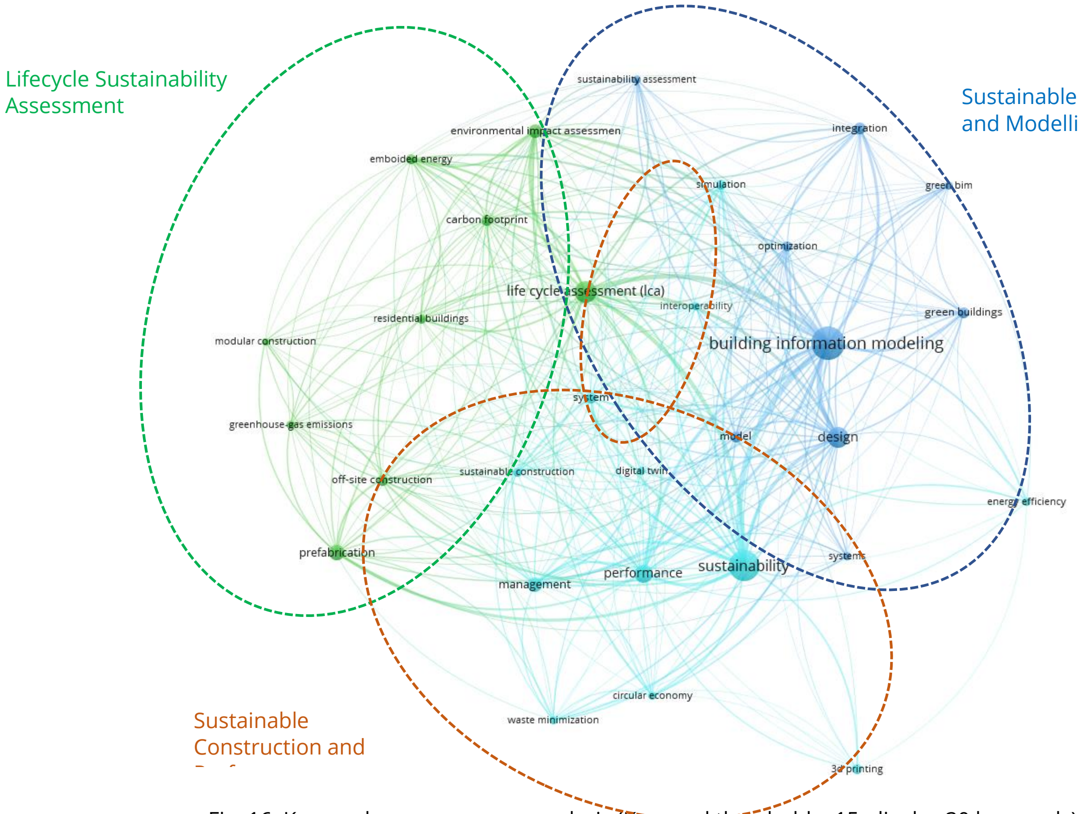

Fig. 16. Keyword co-occurrences analysis (Keyword threshold = 15; display 30 keywords)

Note: Size of node represents the frequency of occurrences of the keyword, proximity of nodes (line width) is based on the frequency of the co-occurrences of two keywords in the selected document, and clustering (by color) is based on the pattern of co-occurrences among multiple keywords in the review document (minimum cluster size = 5 keywords).

4. Conclusion, limitations, and further studies

This paper investigated the construction research corpus to investigate major Construction 4.0 technologies and their contribution to sustainability. A bibliometric analysis and clustering on keyword co-occurrences were conducted. Results showed the distinction of three themes (1) *Sustainable Design and Modelling* lead by BIM, (2) *Lifecycle Sustainability Assessment* where technologies such as prefabrication, modular construction, and offsite construction impacted the direction of this theme, and (3) Sustainable Construction and Performance, where technologies such as Digital Twins and 3D printing are the main contributors to this theme.

Based on the findings of this paper, and part of the ongoing research effort, future work will map the influence of Construction 4.0 technologies onto the Sustainable Development Goals (SDGs) and will quantify the direction of influence towards achieving each goal.

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The Impacts of Pandemict The Challenges of Sustainable Construction

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Abstract

Sustainable construction can be defined as the way of finding an equilibrium between economic, social, and environmental factors in the design, construction, use, and maintenance of buildings. The main objective of this holistic process that was recently introduced is to maximize the value added by a construction project while minimizing the harm to the surrounding environment and local society. However, it is not yet a common application in the construction industry due to a lack of knowledge and awareness. On another side, pandemics have always shaped societies by reflecting on architecture and urban planning throughout history. Since the world faces a COVID-19 pandemic today and other pressing climate change issues, there is a need for change and re-thinking in order to be able to achieve more sustainable construction. The aim of this paper is to present a comprehensive literature review to identify the key issues and challenges facing sustainable construction and determine how pandemics affect some of these challenges. After that, the paper proposes a model to address some of these challenges with a focus on the 15-Minute City concept. This paper provides academic and industry practitioners with strategies to enhance the utilization of sustainable construction in light of the global epidemics.

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Keywords: 15-minute city concept, pandemic, sustainable construction.

1. Introduction

December 2019 was marked as the beginning of a unique disease outbreak which was called COVID-19 by the World Health Organization (WHO) [14]. The world is now facing unique restrictions and most of the world's population is forced to stay in their homes. Quarantine, social distancing, and self-isolation are the response strategies outlined by WHO to the public to diminish the spread of this global epidemic which not only has curtailed the individuals' desire for social interaction, but also has a contradiction with the system of cities, parks, and subways that are designed [8]. Furthermore, majority of countries closed public places, offices, universities, and schools due to the COVID-19 pandemic and necessitating people to work and study from home [14]. Thus, residential buildings have turned out to be a crucial infrastructure that is vital for supporting these disrupted societies and housing has becoming more than just a living space which eventually increasing buildings' resource consumption such as electricity and water [14].

The construction industry performs a key role in fulfilling the society's needs by adding value to health and economic benefits, including contribution to enhancing the way of living; however, it is a major cause of the reduction of natural resources, high energy consumption, global greenhouse gas emissions, waste generation, and air pollution [4]. These negative impacts have led experts and environmentalists call on for a sustainable way of implementing construction activities. Sustainability has turned out to be a general term which is attached to activities that happen with an idea of achieving eco-friendliness [3]. The concept of sustainability is to provide solutions to the human activities which are harmful to the environment and that can be attributed to population growth and economic activities. Sustainability needs have risen to be an emphasis point for many communities and countries since the earth's recourses are under severe pressure due to exponential growth in population and economic expansion [4]. It has been seen that the world population has grown rapidly from 2.5 billion to 7.9 billion from 1950 to 2022 and this growth has placed further burden on the environment, resulting in enormous air pollution, water pollution and soil pollution [3]. Therefore, proactive measures are required via the implementation of sustainable construction to change or to minimize the negative impacts of construction activities to the environment.

Therefore, changes are required to the current world where we live to become more resilient and sustainable to possible forthcoming disease outbreaks and lockdowns, which introduces challenges to the existing residential buildings for adaptation to a new reality [14]. Also, it is necessary to design the cities and the urban environment in such a way that it delivers a healthy environment for individuals as the interrelation between city elements (such as buildings, streets, public parks, and infrastructure of cities) significantly affects the quality and efficiency of life for individuals in cities [8]. Many questions are raised by designers and planners about how to change the trend in the current design to adapt sustainable design. To ensure that we remain resilient and sustainable, future houses and cities need to minimize environmental impacts and improve the comfort of people under epidemic measures [8].

As part of the study, a comprehensive literature review is presented to identify the key challenges and issues related to sustainable construction, as well as to examine how pandemics may impact some of those. Then, this paper discusses how to overcome some of these challenges with a focus on the 15-Minute City concept, providing academics and industry practitioners with strategies to make sustainable construction more widely utilized as a response to global epidemics.

2. Literature Review

Sustainability has become a popular paradigm in the construction industry because of a rising concern that human activities are causing severe negative impact on the environment [2]. It is being recognized worldwide because it is an essential need for the future [4]. After 1987, the term sustainability gained extensive importance when the Brundtland Report from the United Nations World Commission on Environment and Development described sustainable development as "development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs" [3]. Sustainable construction is a holistic process with an aim of restoring and maintaining harmony between the natural and the built environments and establish settlements that sustain human dignity and help economic equity. It integrates the basic ideas of sustainable development along with environmental obligation, social understanding, and economic profitability objectives to the key participants in the built environment [2]. Since building construction which has huge environmental impact is growing rapidly, more attention is required to the creation of further strategies for the improvement of environmental performance in building design [4]. Therefore, sustainable construction is the way of finding an equilibrium between economic, social, and environmental factors in the design, construction, use and maintenance of buildings [2].

Sustainable Construction is important for management and protection of the environment, and its related challenges are the long-term challenge which need to be tackled by human race [3]. Construction industry that will implement a sustainable construction helps to reduce liability on the ecosystem, develop new markets and foster an eco-friendlier construction process that will assist to sustain future and current generations to achieve a better quality of life [3]. Green buildings facilitate the construction industry to have a positive and practical attitude towards environmental resources by emphasizing on the principles of sustainable site, water efficiency, energy conservation and efficiency, resource-efficient materials, waste minimization and ventilation, including other strategies to minimize environmental impacts and resource consumption [4]. Table 1 shows the seven principles of sustainable construction which were given by the Conseil International du Batiment (CIB) 1994 and are used for decision-making during each phase of the design and construction process [4].

Table 1. The principle of sustainable construction [4].

Item	Description
1	Reduce Resources Consumption
2	Reuse Resources
3	Use Recyclable Resources
4	Protect Nature
5	Eliminate Toxic
6	Apply Life-Cycle Costing
7	Focus on Quality

Many other sources (UNEP Industry and Environment 2003, Carter and Fortune 2007 and others) defined sustainable construction as a method to construct, which encourages the achievement of goals associated with the triple pillars has described below [13]:

- Economic sustainability – increasing profitability by implementing more efficient way to use resources including labour, materials, water, and energy.
- Environmental sustainability – avoiding harmful and potentially permanent effects on the environment by efficient use of natural resources, reducing waste, protecting and where viable improving the environment.
- Social sustainability – responding to the people's needs at any stage of construction process (from commissioning to demolition), providing high customer satisfaction and working diligently with customers.

Construction projects are executed with a poor sustainability nature in most developing countries in recent times and research has demonstrated that sustainability level in most developing countries is low [2]. So, it is required to adapt changes in the thinking, behavior, production, and consumption within the construction industry to achieve sustainability and the construction industry shall modify its construction process from linear to cyclic processes which will increase the usage of recycled, renewed, and reused resources, and thereby reducing the usage of energy and other natural resources [2].

Table 2 shows factors and challenges of sustainable construction identified through literature review along with their sources. To present concise factors, only the challenges that were repeatedly raised in scholarly articles have been selected.

Table 2. Key challenges of sustainable construction identified by literature.

Item	Factors / Challenges	Sources
1	Lack of awareness of the benefits, Level of knowledge and awareness	Salama and Hana (2010), AlSanad et al. (2011), Aghimien et al. (2018), Aigbayboa et al. (2017), Abidin et al. (2003)
2	Higher construction cost	Salama and Hana (2010), Aigbavboa et al. (2017), Miranda and Marulanda (2001), Lowe and Zhou (2003), Ametepey et al. (2015)
3	Short-term budget horizons, Budget constraints	Salama and Hana (2010), Aghimien et al. (2018), Ametepey et al. (2015)
4	Lack of clear federal policy, Lack of rules and legislation from government	Salama and Hana (2010), AlSanad et al. (2011), Abidin et al. (2003), Aghimien et al. (2018), Ametepey et al. (2015)
5	Shortage of knowledge for application and implementation technically	AlSanad et al. (2011), Aghimien et al. (2018), Aigbavboa et al. (2017), Ametepey et al. (2015)
6	Lack of knowledge and alternative building/sustainable materials	Aghimien et al. (2018), Abidin et al. (2003)
7	Lack of demand by clients	Djokoto et al. (2014) Opoku and Ahmed (2014), Pitt et al. (2009)

Salama and Hana (2010) conducted a survey based on 9 key challenges of sustainable construction by distributing to 120 practitioners in United Arab Emirates (mainly client, consultant, project manager, supplier) [13]. The factors were: lack of awareness of the benefits, higher construction cost, short-term budget horizons, length of required payback period, difficulty in quantifying benefits, lack of clear federal policy, documentation and cost of certification, more complex construction, and increased operating costs. AlSanad et al. (2011) conducted a survey and distributed a questionnaire to stakeholders within the Kuwait's construction industry to identify their level of awareness and knowledge for different stakeholders in Kuwait on the concept of green buildings and sustainability [4]. The collected data represented that the level of knowledge in construction sustainability is in the range from “moderate to good” level which shows that there is good acceptance of the sustainability concept; however, this awareness is not currently well reflected in the design and construction practices actually being applied and the application of sustainability is still measured to be very low due to many factors such as shortage of knowledge for application, lack of awareness at social levels, poor enforcement of legislation, and poor support from the government.

Miranda and Marulanda (2001) studied sustainable construction in developing countries and pointed out that the major challenge is the fact that sustainable construction is being recognized as a concept which would add cost to the project which was formed without critical evaluation of the whole life-cycle benefits of sustainable construction [9]. Also, Aigbavboa et al. (2017) observed similar result while assessing the sustainable construction practices in South Africa and they discovered that the main challenges are the belief of additional cost to building projects, and limited understanding of sustainable construction’s benefits [3]. The idea that sustainable cost more, with no appropriate assessment, creates a significant challenge in the implementation of sustainable construction systems in most developing countries around the world [15]. Aghimien et al. (2018) conducted a survey on sustainable educational buildings in Nigeria and they concluded that the significant challenges are construction related, sustainability awareness and knowledge related, finance related, and government related [2]. Ametepey et al. (2015) found that there are some other important factors in adoption of sustainable construction methods such as cultural change resistance, lack of government commitment, fear of higher investment costs, lack of professional knowledge, and lack of legislation [6]. Abidin et al. (2003) noticed other issues that affect sustainability such as awareness of the sustainability concept, availability of local sustainable materials, knowledge of the benefits of sustainability in construction, knowledge of sustainable design, technical capability, awareness of all related legislation, compliance to building guidelines or requirements when designing and constructing, workmanship during construction, site management and supervision, use of technology to improve project process and construction methods [1]. Therefore, the rate of improvement in the direction of sustainability in construction depends mostly on enhancing awareness, knowledge and understanding of the impacts of people’s actions [4].

Pandemics have always shaped cities throughout history [8]. COVID-19 pandemic which is caused by SARS-CoV-2 has been zoonotic (originating from animals) like SARS and MERS outbreaks and researchers claim that the amount of novel zoonotic diseases is expected to increase in the future [14]. Availability and existing of markets that sell meat and products from wild animals globally, climate change, extensive land usage for agriculture and construction of infrastructure that impacts wildlife habitat are the reasons for the rise of zoonotic diseases by spreading viruses easily [14,16]. Table 3 shows the history of deadliest pandemic from 165 to 2019 which affected not only the health field but also left urban impacts and economic consequences [8].

Table 3. History of deadliest pandemics [8].

Year	Pandemics	Year	Pandemics	Year	Pandemics
165	Antonine Plague	1800	Yellow Fever	1981	HIV / AIDS
541	Plague Justinian	1817	Cholera 6	2002	SARS
735	Small Pox	1855	Third Plague	2009	Sine Flu
1347	Black Death	1889	Russian Flu	2012	MERS
1520	Small Pox	1918	Spanish Flu	2014	Ebola
1600	17th C. Plague	1957	Asian Flu	2019	Covid-19
1700	18th C. Plague	1968	Hong Kong Flu		

The Black Death crisis triggered the need for urban change; so, designers, and urban planners improved the radical urban of the renaissance along with expanding their cities to prevent overcrowding [17,18]. This pandemic changed the urban design of European societies by launching larger public spaces that gave a better chance for people to connect with nature and decrease isolation [8]. Moreover, the Cholera epidemic which was due to the mixing of clean drinking water with wastewater had a huge impact which helped to improve the urban design field in term of infrastructure design, reducing high population density (greater the population density, greater the risk of infection), managing waste in the streets along with support to have ventilation and daylight in open spaces through which people can move [18,19]. The Victoria embankment along river Thames was constructed in central London and the main sewage system was shifted downriver to safely split wastewater away from clean water supply. Furthermore, Spanish Flu as a deadliest respiratory virus, killed more than 50 million people globally which had a massive impact on deceleration in urban growth and limiting public life for a period to slow the spread of disease by replacing public transportation with walking in uncrowded streets and staying at home [8].

Similarly, COVID-19 which has been the largest global health crisis in decades, affected multiple aspects of our life including economic factors, sustainable development goals, food pathways, education, tourism, urbanization, living spaces, and business [14]. The prominent reason of death in the United States in 2020 was recognized to be the COVID-19 pandemic. It has caused not only the unprecedented number of deaths and hospitalizations but also it has resulted in economic slowdowns, extensive business disturbances, and significant difficulties [5]. According to the United Nations Trade and Development Agency (UNCTAD), the cost of COVID-19 consequences to the global economy in 2020 is around one trillion USD [14, 20]. Also, nationwide economic downturn was the result of COVID-19 pandemic, and the National Bureau of Economic Research (NBER) declared that the U.S. moved into a downturn period in February 2020 which was called the COVID-19 recession [5]. Therefore, the U.S. has suffered record-high unemployment rates due to the economic recession where the rate of unemployment rose from 3.8% in February 2020 to 14.7% in April 2020 [5]. Moreover, people are forced to spend most of their time at home and to work or study from home to prevent viral spread risk during the COVID-19 pandemic, therefore residential building and housing became more than just a living space, as people are staying more at home. This has effects on buildings' resource consumption such as increasing use of electricity and water [14]. Also, COVID-19 had impacts on students' education and their learning capabilities, motivation, and self-discipline due to distant learning during the pandemic. Due to COVID-19, it is expected that future businesses are going to be more digitalized, which will create positive changes including cost-cutting, enhanced business intelligence, and more transparency [14].

3. Problem Identification

According to the available literature review on challenges of sustainable construction, it is noticed that sustainable construction is a skeptical subject for people due to lack of knowledge and awareness (Table 2). Typically, knowledge and awareness are obtained when needed and COVID-19 pandemic which caused by SARS-CoV-2 has triggered this need while COVID-19 is not the first pandemic on this planet and there have been other epidemics that have hit the globe and engulfed millions of people's lives [8].

The globe faces COVID-19 pandemic today which results in a public health crisis, and it is the worst crisis perhaps in more than a century that resulted in the development of many challenges for cities to tackle this pandemic [8]. COVID-19 had brutal impacts on cities socially and economically which lead to increasing inequalities and increasing rate of unemployment worldwide [10]. Also, it has created a great impact on humanity's personal and professional aspects [14]. Due to COVID-19, people are forced to spend most of their time at home to prevent viral spread risk, thus the world needs to adapt quickly to such changes in lifestyle and to transform the perception of the environment in different way, which leads to new urban design and planning [14].

WHO said that "healthy cities and the city planning process are background papers supporting the work of the World Health Organization"; however, the current urban developments have not been very effective in term of urban planning and health [8]. Thus, it is essential to emphasize the importance of re-designing/re-shaping cities and the urban environment in a way that supports a healthy environment for individuals. The interrelation between the elements of city (e.g., buildings, streets, parks, and cities' infrastructure – urban design) radically affects the quality and efficiency of life for individuals in cities [8].

Figure 1. Pillars for achieving sustainability of cities [21].

The social and economic impacts on cities during the COVID-19 pandemic have led to the need for revolutionary re-thinking of cities to adapt to new urban planning mechanism as a way to improve quality of life in cities [10]. When a pandemic spread beyond the country's borders, it is the worst scenario that can happen. When pandemics occur particularly respirational ones, safety measures highlight the need of isolation and shutting down of public spaces which transforms the image of cities and public spaces into empty environments. Therefore, it necessitates a change in the city's functioning or operation to integrate between community health practices and social thinking transforming urban design for proper functioning of cities during pandemics [8]. Above figure 1 shows the pillars for achieving sustainability of cities [21].

Proposal for Solving the Problem

COVID-19 pandemic created an opportunity to optimize cities by joining the social behaviour at epidemic stage through health viewpoint in planning and design [8]; however social behavior and people's awareness reflect a significant factor in dealing with this epidemic [22].

Based on historical deadliest pandemics along with their impacts on cities, it is essential not only to be reactive but also to be proactive in urban planning and city design in term of resilience and sustainability to address any future threat of pandemics in order to minimize the environmental effects and to sustain and improve the well-being of people under epidemic measures. Paris mayor in her recent campaign has proposed that the city shall be decentralizing and deconstructing policy [8]. This idea can decrease extreme density, and promote walkability concept in each neighbourhood, including homes, jobs, facilities, stores, etc [23]. Therefore, the concept of "15-Minutes City" is a solution for urban planning and city design, as a kind of response to any future pandemic to become more resilient and a sustainable city. The aim is to manage pandemic crisis as well as being functional and a sustainable city.

The "15-Minute City" highlights on accessibility and proximity-based planning where an urban community is designed to accommodate an optimum density that would have access to basic essential needs and services within a 15-min walking or cycling distance [10]. It means residents are able to experience a higher quality of life by traveling less (with 15-min radius) to have their basic essential needs and access required facilities/amenities (e.g. work offices, schools, hospitals, parks, shopping centres, food markets, etc). To sustain a higher and decent quality of life, there are six essential urban social functions which include living, working, commerce, healthcare, education, and entertainment [10]. To attain these functions, the urban life style shall be built in such a way as to comply with components such as proximity, diversity, density, and ubiquity (digitalization) to achieve high value of life. This concept provides more time and opportunities to people to interact with each other (members of the community) and to undertake other social functions, which is very important, but have been lacking as a core function of contemporary urban planning models. The components of "15-Minute City" as sustainable construction is explained in detail [10]:

- Density: It is the social sustainability dimension of cities and is paramount to consider the optimal number of people (optimal density) that a given area can comfortably sustain in terms of urban service delivery and resource consumption. Optimal density allows to effectively plan the available space in such a way that all residents can access their essentials without the need for time and energy consuming automobiles. It also allows to create locally based solutions in areas such as energy generation, food supply and multiple use of available spaces like using school playgrounds as parks after school time.

- Proximity: It is viewed to be both temporal and spatial, and all basic services shall be available and readily accessed by residents in each neighborhood. It helps cities not only in reducing the amount of time lost in traveling but also in reducing the environmental impacts. Ultimately, it allows residents to experience better service through both commercial and public establishments since all essential services are close to each other. Also, basic infrastructure can be used for multiple purpose like using school playgrounds as parks when public is free to access after school hours.
- Diversity: It consists of two parts - (1) the necessity for mixed use neighborhoods which are important in providing a healthy combination of residential, commercial and entertaining components and (2) variety in culture and people. The first part is vital in ensuring that an optimal density and proximity of essential amenities are achieved which guarantees that residents can benefit from essentials within their residential areas without spending much time. The second part, as having a multicultural dimension in a city has positive impacts economically. Locals would enjoy a wide diversity of products such as cultural products and cultural heritage, and this will make it as an attractive urban landscape for visitors and encourage tourism and other related sectors to create new businesses in that area which would result in promoting economic vitality and lead to the creation of increased employment opportunities [24].
- Digitalization: It ensures the actualization of the above three components. Digitalization makes the city smart where factors such as inclusivity, resident participation and real-time delivery of services are encouraged through varying platforms [25, 26]. For example, it is more feasible to use digital tools to ensure that biking practices are improved, by stressing solutions such as bike sharing and the utilization of sensors to ensure the safety and security of cyclists.

Due to COVID-19 heath protocols and lockdown measures, which undermined the economic and social dimensions of cities, today's modern urban planning concepts that have created fragmented cities and communities are heavily depended on automobiles [10]. It is not effective to respond to these restrictions because this situation (COVID-19 restrictions vs a heavy reliance on automobiles) had caused bottlenecks in the service delivery to society. Therefore, having more walking and bicycle lanes/streets in the city (re-thinking the transportation system) can be considered to counter the impacts arising from vehicular movement restrictions. Transforming cities from car-driven to more walkable and cyclable provides environmentally friendly alternatives as well as benefit the physical and mental health of citizens [14]. Walking and cycling (micro-mobility) have numerous benefits on social, economic, and environmental levels such as [10]:

- On health and well-being of people by having more time and opportunities to exercise and gain social interactions with health protocol.
- In reducing congestion and pollution (noise, emissions, and others)
- In unlocking numerous potential positive outcomes such as employment, new innovations, creation of urban unique (identity) brands, helping to reduce overheads acquired from fuel costs, road maintenance, and other associated costs.

According to Eltarabily and Elghezanwy (2020), to prevent diseases to public, it is necessary to redesign streets by adding another lane for cyclists and pedestrians which will create healthier and more social-sustainable cities that affect citizens' behaviour in the time of pandemics. This is a good opportunity for urban planners to rethink streets' design by excluding cars from some streets and providing more spaces for pedestrians and cyclists which will turn the city into green and low carbon streets. Moreover, it is required to consider new standards of using sidewalks such as social distancing while queuing which results in wider sidewalks and paths, providing 1.5m safe distance along with distinguishing the individual's point with a sign on the ground, including more space to accommodate the queue at the public facilities' entrances and providing fixed seats for the elder people [8].

Moreover, having micro-markets to provide essential needs and ensure that locals can access basic commodities within their proximity can help to reduce congestion in supermarkets which will result in reducing the risk of infection and spreading virus [10].

As transportation is a key part of every city and urban environment, health safety strategies are needed in public transportation such as buses, subways, trains, and airplanes to reduce the risk of transmitting infection by touching handles, armrests, and seats. Providing social distancing, frequent purification, undertaking temperature screening, proper cleaning and sanitizing hygiene of employees and passengers are the changes that shall be done for public transportations [8].

Having digital transformations in all daily activities reduce the time wasted in traveling by automobile which will result in reducing emissions that is harmful to the environment. For example, digitalization of businesses makes employees to host online meetings and to work with new portable types of equipment for virtual communication [14]. Also, digitalization can be effective for online shopping, cashless transaction and virtual communications and interactions especially during any pandemic [10]. Moreover, smart cities are safer cities from the public health view since governments can use modern technology and digitalization to track people infected with pandemics which will help in monitoring and collecting infection data [8].

There shall be significant changes in the design of buildings include greener spaces, better air ventilation and intimacy, improved water and wastewater management, introduction of touchless technologies and antimicrobial materials, better solid-waste management, social distancing within the house, and lightweight architecture and flexible building design. The strategies for building construction in cities, shall be modular construction which allows the construction of various building types quickly with lower expenses. The future buildings shall be designed considering the chance for efficient, flexible, and speedy transformation of the building for essential needs (hospitals, medical facilities, etc.). Also, lightweight and flexible structures have benefits due to construction speed and portability. Hygienic building materials that are easy to be sanitized shall be used as a response to pandemic. Design and operation of building shall be changed in such a way to promote self-sufficient strategies and refocus on green space and low-rise buildings with better indoor air quality. Green spaces positively influence people's mental health and allows them to grow food during self-isolation time which is friendly to environment [14].

Urban planners and designers shall design the public places according to human need and to be designed as pandemic-resilient and flexible spaces since the use of public spaces can repurpose for emergency hospitals at the time of pandemics [8].

Homes shall be more than just a living place as COVID-19 suddenly disturbed professional and personal lifestyles globally, so homes shall become more resilient and sustainable for other possible upcoming pandemics. Current urban residents spend a large fraction of their time indoors where they are forced to work from home due to COVID-19. Thus, from the social behaviour aspect, their health is directly affected by housing space which resulted in negative impact of public health, if the designs of homes are poor. Designers shall go back to nature in redesigning the homes and using biophilic design approach to improve quality and performance of homes [8]. Health and safety in houses shall be improved through expanded use of touchless and automotive technologies, selection of finishing materials based on viral survivability, and green spaces expansion. Sustainable technologies shall be used as a response to environmental needs to decrease the consumption of energy and water. Also, it is required to enhance communication technologies to use better remote services and utilize motorized technologies to control better comfort parameters (e.g., air quality, light, temperature, humidity) [14].

Having outdoor parks and green areas is a human need that reduces tension and improves physical, psychological, and mental health. Designers shall create more spaces and practices for individual use in developing green areas such as expanding running tracks and giving priority to small community parks. After all, parks and green zones can inspire more people to safely walk outside their homes and keep safety simultaneously [8].

At the end, it is essential that government create an effective federal policy which can act as the driving force towards implementing the "15-Mintute City" concept including green building. Therefore, all stakeholders (owner, designer, public, etc) would be looking for development of the "15-Mintue City" concept and the adoption of "15-Minute City" in the long-term planning, would result in a higher quality of life.

4. Conclusion

It is clear to everyone that after pandemic crisis, the society will not return as before, and a new norm is established. It is the beginning of changing values, habits, homes, and cities. However, sustainable city is a complex planning and designing problem that merges with technical, environmental, social, and economic aspects, the pandemic crisis triggers the need for developing sustainable and functional cities. Also, with increasing population, it is logical and essential to change the way of thinking in planning and designing cities, to make them healthier and more stable to face any future challenges and crisis. Many research papers introduce the "15-Mintutes City" concept as a solution to pandemic response. The city shall be planned to achieve the best conditions and capabilities for the urban life of its residents and to create environments to attain an enjoyable life, and make the life smoother, comforter, and safer for the residents within it by implementing good technological and sustainable features. If all cities are going to be designed based on four dimensions identified (density, proximity, diversity, and digitalization) within a comprehensive and flexible framework, numerous issues of pandemic crisis can be avoided.

In conclusion, it is emphasized that proximity-based urban planning is key in maintaining quality of life and in delivering the basic urban functions. It is found through study that the three main aspects to have an optimal design for city are being smart, sustainable and comprehensive, considering social design. Therefore, designers, planners, government, and public health officials should cooperate to build healthier cities from now on, as a response to any future pandemic crisis. However, more research is required on enhancing the disease prevention theory through good design of contemporary cities and studying health design strategies.

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Global BIM Adoption Movements and Challenges: An Extensive Literature Review

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Abstract

Building Information Modelling is progressing and improving stakeholders' abilities to manage their projects from very basic steps to their retirement. BIM is preparing a comprehensive basis to facilitate access to all information of the elements and the whole project on the nD platform; also, it helps to provide detailed progress reports at any time. A global movement is being started to implement BIM and use its advantages. In spite of all achieved benefits due to BIM adoption and all investigations, a limited number of countries prepared approved roadmap, and related rules and regulations. In this paper, the BIM implementation state is investigated in three categories globally based on a literature review. Also, the barriers and challenges hindering the BIM adoption extracted, and the ten most frequent global impediments achieved that lack of trained personnel is the most crucial impediment in the way of BIM, and absence of awareness around the BIM advantages is second; also, heavy initial funding is hindering BIM. In addition, it is vital to compensate for the lack of needed rules and regulations; conversely, successful BIM adoption requires powerful support from the government. The additional barrier is sticking to traditional methods, and resisting change, as well as sufficient and efficient training, is a crucial activity to adopting BIM. Likewise, providing appropriate software requires considerable investment; governmental supports, as the key, driver will remove barriers and facilitate the process; also, it requires to develop investigations to generate BIM science and technology that will motivate industry.

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Keywords: adoption, BIM, building information modeling, challenge, implementation, roadmap

Introduction

Traditional management approaches put organizations in changing and missing information problems. Separate project lifecycle phases cause inefficiency. BIM, relying on a digital model, facilitates the recording, maintaining, and exchange of information [1]. BIM, in the pre-construction phase, enables accurate documentation and reliable time and cost estimation, and facilitates design problem-solving; also, accelerates high-quality engineering and team management effort reduction, and simplifies review and reengineering, as well as clash detection. Meanwhile, due to accurate estimation, resource consumption will compute precisely, which empowers project teams to manage resources on time; communication will enhance, and time and cost will be under efficient management, as-built construction will reduce material loss and eschew cost deviation. Predicted tasks help to reduce HSE risks. In the post-construction phase, assets will be managed easier, accessible documents will improve maintenance, and crisis management, and each component's life-cycle will be tracked accurately [2]–[4]. Although BIM represents different benefits, it is hindered by some barriers which should be categorized in Organizational challenges, which include opposition to change, localization obstacles, unawareness, sticking to traditional approaches, absence of cooperation, and team-building issues. Financial challenges include education costs, investment, and expert payment. Technical obstacles are immature BIM technologies, large-scale BIM adoption issues, and different stakeholder interests. Also, due to conflicts in Intellectual Property and Copyright Considerations, the responsibility of erroneous data is ambiguous, meanwhile required regulations are not approved; also, inhibitor cybercrime laws are lacking [5], [6]. To a wide BIM development, these impediments should be identified; in this paper, through a comprehensive literature review; these challenges are explored and listed.

1. Universal BIM movements and barriers

Despite the fact that BIM affects the construction industry positively, there are some barriers to adoption globally. In Table 14, these hindrances are presented. Then, to discover BIM's current state, the world is divided into three main categories. The first category includes pioneer countries with impressive movements, including roadmap and rules approval, with a mandated BIM. The second group consists of developing countries in BIM, in which some activities and progression recorded, roadmap and/or rules are approved, but BIM is not compulsory yet. The third group refers to countries at the BIM beginning stage where few reports are published or BIM is being implemented limitedly.

Table 14- Global BIM barriers

Category	Description	Ref.
Technical	Technical issues, lack of training	[7]–[9]
	Absence of contractual framework	[7]–[10]
	Lack of rules and regulations	[11]
	Non-user-friendly software formats	[11]
	Lack of trained experts	[8], [9]
	Absence of sharing the information	[8]
	Lack of knowledge	[9], [10]
	Data owning conflict	[9]
	Software data exchange incompatibility	[9]
Cultural	Change resistance	[9], [10]
	Lack of project participation	[7]
	Real BIM-based sample nonattendance	[7]
	Insufficient government support	[11]
	Lack of employer interest	[11]
	Top managers' insufficient of support	[9]
	Lack of request from the contractor side	[9]
	Sub-contractor opposition	[9]
Management	Upgrading the platform of communication	[7]
	Team building complications	[7]
	Engineering phase prolongation	[7], [9]
	Visual modeling considerations	[7]
	Need for cultural change	[8]
Financial	Initial funding	[7]–[10], [12], [13]
	Unclear ROI (Return on Investment)	[7], [9], [11], [13]
	Expensive training	[10]
	Cyber security	[7]

1.1. First Category: Pioneer Countries

In 2009, 50% of the USA industries were using BIM tools, which has grown by 75% compared to 2007 [14]. To support BIM, in 2003, General Services Administration (GSA) published the "National 3D-4D-BIM" to achieve a digital imagination during a project life-cycle [15]. In 2007, the first edition of the "National BIM standard" was published [16], revised lastly in 2015. In 2011 and 2012, the BIM adoption roadmaps were presented by The US Army [17], [18]. Since 2008, BIM has been required in public projects [19]. In 2006 and 2009, the "BIM guideline for Contractors" was published, which analyzed BIM based on practical experiences [11]. In 2018, about 72% of American firms joined the BIM movement [20]. Pilot projects and compulsory BIM have promoted the US to a pioneer country [14]. Meanwhile, multiple public and private are cooperating to develop BIM [21].

Britain allocated 3.86 million pounds to promote BIM [22], [23][23] and registered the highest speed of the BIM adoption [24]. BIM obstacles are lack of BIM familiarity, opposition to change and training, as well as, lack of knowledge, unclear cost-benefit, unmeasurable benefits, insufficient benefits, and investment [25]. In 2011, the BIM plan and requirements were published, through the BIM Strategy Working Group, which consists of standards to implement BIM in level 2 from 2016 in all public infrastructure projects, with a 5-million British pounds budget [23], BIM is mandated in Britain [22]. Cambridge University published a BIM adoption roadmap with a two-year schedule to complete in 2020 with five pillars [26]. In 2015, BIM penetration was 48%, that in 2018, which got to 54%[20].

Finland started automation in construction in the 1970s[27]. In 2001, several pilot projects were defined to develop BIM. In 2007, BIM-COBIM General Requirements was published by the Parliament State Property Agency, and updated in 2012. Since 2007, BIM has been required in ordinary projects [11]. In 2007, BIM usage was around 33%, but in 2009, with rocket change, 93% of the design firms and about 60% of architects were using BIM [28]. Finland dedicated a 21.7-million-euro fund to BIM adoption [23]. Its BIM implementation roadmap was approved in 2014, with a ten-year predicted period on five main pillars [29]. COBIM clarifies modeling and project requirements, and "InfraBIM Requirements" facilitate the digitalization was approved in 2015 [30]. In 2016, 99% of construction projects performed BIM [31].

Denmark is a leader to adopt BIM by Det Digitale Byggeri [19]. In 2006, half of the architects, 40% of engineers, and around 30% of employers partially adopted BIM [28]. In 2007, the Danish BIM guidelines were published [32], and BIM was accepted in public projects. Since 2011, BIM has been required in the projects with a value of more than 2.7 million euros [11]; also, since 2008, 3D modeling has been mandatory in projects with the more than 40 million DKK estimation and in public renovation and housing projects from 2008 and 2009, respectively. BIM implementation needs to attract the top managers' attention and enhance experts' knowledge; also, the Industry's insistence on using 2D drawings should be reduced; meanwhile, software is incapable of exchanging elements to IFC, and rules should be approved [33].

In Norway, Statsbygg Institute is leading BIM implementation [27]. In 2010, 22% of the construction industry used BIM [28]. In 2007, the first BIM instruction was published [11], SBM 1.2.1 is the latest revision of this standard that provides tips and rules for working teams [34]. Since 2010, BIM has become mandated in new buildings [19]. From 2010 to 2014, a 21.7-million-euros invested on BIM [23]. Meanwhile, since 2016, several Norwegian employers have required BIM [35].

In the 1990s, Singapore Building and Construction Administration (BCA) developed a model-based design approach [11]. Since 1995, the government has published several instructions and enforced the adoption of BIM [24]. In 2010, the first BIM implementation roadmap was approved to engage 80% of firms within five years [36]. The required budget was allocated in 2012, 2013, and 2015 to motivate firms through BIM [37], and half of the 24-million-SGD public BIM required budget prepared by the government [23]. Singapore BIM adoption was 65% 2014 [38]. Since 2016, BIM has been compulsory in projects with more than 50 million US dollars estimated [24]. In 2014, the second Singapore BIM adoption roadmap was approved in 5 pillars and a 4-year plan [39]. Barriers against BIM are lack of cooperation between stakeholders, foreigner BIM operators, and sticking to 2D drawings [40]. The first category BIM adoption roadmaps presented in Table 15. In Table 16, the main events of BIM movements of pioneer countries are presented.

Table 15- First category countries BIM implementation roadmap pillars

Country	pillars					Ref.
Britain	Approach	Governance	Commons	Enablers	Change	[26]
Finland	Standards and guidelines for the whole life-cycle	Comprehensive information management know-how	Collaborative model-based processes	Services created through open data	Enabling technology	[29]
Singapore	Drive BIM collaboration throughout Virtual Design and construction	BIM for Design for Manufacturing & Assembly	New Training programmes at all levels	BIM for Facility Management & Smart City	Research & Development	[39]

1.2. Second Category: BIM Developing Countries

In 2008, Australia approved national guidelines [32]. 98% of the Australian firms are small size and medium size enterprises (SMEs) [41], and only 5% of them are using, and 75% are not using BIM [42]. Barriers to implementing BIM are funding, unawareness, and lack of interest, trust shortage, and lack of rules; meanwhile, limited business information; high uncertainties, lack of experts, and opposition to change [43].

In 2012, New Zealand issued the "Building and construction productivity partnership" for 20% efficiency improvement until 2020 [11]. In 2014, its BIM handbook was published [44]. In 2017, 98% of the industry used BIM, while 38% of employers were aware of and using BIM [45]. The barriers could consider unawareness, inaccessibility of professionals, lack of demand, lack of samples, absence of standards, initial funding, cultural resistance, legal issues, technical hindrances, and lack of cooperation [46].

In 2008, Canada mandated BIM [19]. And a 6-pillar BIM implementation roadmap approved through Canada buildingSMART institute [47]. In 2018, BIM was used by 67% of Canadian enterprises [20].

In 2010 and 2011, studies revealed Brazil ranked second in publishing BIM papers [48]. In 2018, the Brazilian BIM adoption roadmap was published in 8 pillars with a 10-year plan [49]. Barriers that hinder BIM are the absence of rules and regulations, data management, deferring engineering conflicts to construction, a non-collaborative atmosphere, dispersed BIM usage, and separated design and construction [50].

In 2014, the German BIM guideline was published [19], and in 2015, "Roadmap for digital design and construction" was approved [51] In 2019, its Strategy was presented [52]. In 2018, 90% of German companies used BIM [20].

In the Netherlands, in the recent years, the BIM performance in the public sector has notably increased. In 2011, the Rijksgebouwendienst government agency required BIM in public projects with more than 10 million euro [19]. Employers demand BIM [30], although no regulation has been approved yet [53].

In 2007, BIM entered the Malaysian industry [2], and in 2010, the first BIM pilot project was performed [54]. Lack of knowledge and staff were the main barriers against BIM [55]. In 2018, only 20% of architectural firms and 10% of surveying organizations were using BIM[56].

The Hong Kong public sector has published a set of standards, manuals, and guidelines to build, manage accurate models, and communicate between users [11]. In early 2015, the Construction Industry Council (CIC) issued the Strategic BIM Implementation Roadmap with nine pillars, but the required time was postponed to industry acceptance [57].

In the 2000's South Korea intended to BIM, and since 2010 experienced a slow progression [19]. In 2010, the BIM implementation roadmap was presented [11]. In 2011, Korea Public Procurement Service released its goal: the use of BIM in projects with a value of more than 50 million dollars [15].

The Japan Federation of Construction Contractors established a committee to approve specifications [15]. In 2010, a pilot project cooperating with several firms was performed to promote BIM [58]. Although, in 2014, BIM guidelines published by MLIT (Ministry of land, infrastructure, transport and tourism), Japan's construction industry didn't become familiar with BIM. In 2014, the BIM instruction was published and was used as the legal instruction, and obstacles are the supply chain's lack of incentives and the employer's lack of knowledge [40]. The trend line of BIM implementation in developing countries are shown in Figure 17. The Second category's BIM adoption roadmaps are presented in Table 17.

Table 16- BIM movements in First category countries

Year	**Country & Event**
1970	Finland- Investment in information technology
1990	Singapore- Developing the first model-based design
2000	Norway- Widely BIM using
2002	Denmark- Investment in productivity
2003	USA- Identification the BIM abilities and establishment
2007	Finland- Mandated BIM
2010	Norway- Mandating BIM in 25% of companies
2011	USA- BIM implementation roadmap Britain- Publishing plan and requirements
2012	Denmark- Using BIM in projects
2014	Finland- BIM implementation roadmap Singapore- BIM implementation roadmap
2016	Singapore- Mandating BIM in large projects Britain- Mandating BIM
2019	Britain- BIM implementation roadmap

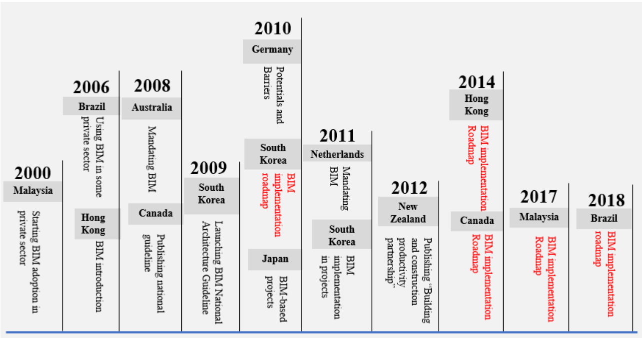

Figure 17- BIM movements in Second category countries

1.3. *Third Category: Countries at the BIM Beginning*

Europe*:* In 2014, the European parliament legislation enforced all European countries to use BIM for public projects from 2016 [27]. Some European countries like Switzerland mandated BIM implementation in public Projects [19], but they did not publish any national standard [15].

Since 2017, France mandated BIM [30] and dedicated a 20-million-euro to it [23]. In 2015, the BIM implementation penetration increased from 39% to 71% within 2 years [59]. A transition plan titled "BIM 2022" and MINnD as national strategies legislated, and some incentives are defined [60]. In 2017, the BIM adoption roadmap was approved [30].

Table 17- Second category countries BIM implementation roadmap pillars

Country	pillars									Ref.
Hong Kong	collaboration	incentive and proven benefits	standard and common practice	legal and insurance	information sharing and handover	promotion and education	sufficient digital capability and vendor support	risk management	global competitiveness	[61]
Canada	Engage	Develop	Education	Deploy	Evaluate	Sustain				[47]
Brazil	Governance	Infrastructure technology and innovation	Legal framework	Technical regulation	Investments	Capacity	Induction by the federal government	Communication		[49]
Malaysia	Standard and accreditation	Collaboration and incentives	Education and awareness	National BIM library	BIM guideline and legal issues	Special interest group	Research and development			[62]

In 2013, Sweden decided to perform BIM in the next few years[15]. In 2014, the “BIM Alliance” was founded to prepare BIM tools and regulations and execute BIM [30]. Since 2015, BIM has been mandated, but no rules are provided yet [53].

In 2017, Ireland published the BIM implementation strategy and roadmap with a 3-year perspective. Due to Covid-19 and trend toward digital approaches, the industry is ready for BIM to be mandated [63]. The Czech Republic’s BIM strategy was approved in 2017 and it is planned to mandate BIM from 2022. A plan from 2018 to 2027 is proposed and includes recommendations for an efficient outcome. In 2015, the participation rate was about 19% [30], [60], [64]. From 2020, BIM is required in Lithuanian high-value government civil projects. Despite insufficient BIM promotion, its maturity is acceptable [60], [65]. In Italy, old buildings impede widespread BIM adoption. Also, a 3-stage plan is defined to mandate BIM between 2019 and 2022 in all projects [11], [53] . In 2016, Portugal’s BIM implementation roadmap was proposed; also, It is scheduled to mandate BIM from 2020 [19]. Recently, BIM has mandated Spanish public projects with a value of more than 2 million euros. The first guideline and roadmap were published in 2014 and 2015, respectively [30], from 2015, BIM has been required in Luxembourg [53]. In 2018, 22.6% of Slovakian companies were using BIM, and BIM is required in some public projects, but no strategy has been approved yet [60], [67]. Slovenia published the BIM roadmap, but BIM is not required yet [60].

Asia: In the Middle East, only almost 10% of companies are using BIM. Barriers against BIM in this region are sticking to CAD, opposition to change, additional costs, lack of request, and lack of professionals [59].

In 2016, 28% of Iranian firms used BIM [68]. In Iran, consultants have more knowledge than employers and contractors which is due to employers’ lack of interest [69]. The BIM implementation roadmap is proposed focusing on the Iran construction industry in 6 pillars [70].

In China, BIM is not mandated and hasn’t been considered in the five-year development plan [15]. In 2016, 20% of its companies were using BIM [35], and generally, BIM is employed for clash detection [71].

In Indonesia, in 2012, the first BIM guideline was published [72]. In 2017, the BIM adoption roadmap was published, and the construction industry started to use BIM [73]. In 2020, 70% and 17% of its projects used BIM level 1 and pre-BIM, respectively [74].

In 2014, the Dubai municipality mandated BIM in towers with more than 40 floors or 300,000 square feet area and public construction. In 2015 another circular was released to encourage organizations. [75]. In 2017, 38% of UAE projects were using BIM, and it was forecasted this would get to 51% within 2 years [76]. A framework of BIM adoption in Saudi Arabia is proposed in nine pillars. In 2017, 21% of its projects implemented BIM in 60% of its tasks, and it was forecasted an increase to 38% by 2019 [76], [77]. In 2014, the Taiwanese LOD specifications were published. Since 2017, two-third of Taiwanese firms have a restricted knowledge of BIM [15], [78]. In Bangladesh, BIM is widely used in pre-construction and construction phases. The government is not interested in BIM [38]. Russia has published the BIM adoption stages [79]. Since 2017, 22% of the Russian firms have adopted BIM[80]. In 2017, in Qatar, 65% of megaprojects and 23% of large projects have been implemented BIM [59]. At present, the maturity level of the Qatari BIM is comparable to that of the United Kingdom [81]. In 2020, 39% of Bahrain construction projects were involved in BIM [82]. In 2016, Vietnam’s BIM implementation framework was published with three stages[71]. In 2019, Nepal represented a framework to speed up BIM adoption within seven pillars [83]. In 2019, 33.6% of the Philippines’ construction firms employed BIM, while 33.6% of the industry was unaware of BIM [84]. In 2015, Mongolia’s BIM adoption roadmap was approved in three pillars [71]. In 2018, 11% of Pakistan firms implemented BIM for 3D geometrical modeling. [20]. In India, BIM is used just as a design tool and virtual construction; in 2014, 26% of the construction industry were using BIM [19], [85].

Africa: North Africa has the highest level of BIM in Africa [86]; in South Africa, it is limited to 2 World Cup stadiums for3D modeling and clash-detection [87]. In 2015, in South Africa, BIM was used in 80% of the industry, concentrated on cost- and time-control and project management [88]. In 2019, the Ethiopian BIM adoption roadmap was published with nine pillars [89]. Around 57% of Kenya firms are using BIM [90].

In 2018, Nigeria's BIM penetration rate was around 22.8%. In 2020, a structure to implement BIM sustainably published to motivate SMEs [91], [92]. In Algeria, the architects have the highest BIM understanding with 35%, then engineers with 25%, and contractors with 23%. A framework is proposed based on four pillars to promote BIM [93]. In Egypt, 19% of the firms are using BIM or are striving to find the best practices. In this regard, a strategic BIM adoption roadmap presented, based on successful practices [94]. In 2016, BIM was used in 24% of Rwanda's industry [95]. In Zambia, 45% of contractors, 20% of quantity surveyors, and architects and 15% of engineers use BIM [96]. In 2017, 5% of Jordanian's firms were using BIM [97].

America*:* Since 2016, fifteen pilot projects have been constructed in Chile with BIM planning. A program is approved to adopt BIM from 2020, titled "Build 2025" to achieve the integration between the private and public sectors and academia. Also, it was planned that BIM become mandated in 2020 [98]. A BIM implementation roadmap has been suggested for Costa Rica with three pillars, and a 6- to 9-year schedule [99]. Mexico has BIM-related regulations, but BIM was not mandated yet. In 2016, a program was defined to adopt BIM in consultants, whose main goal was to attract construction companies to use BIM. The New International Airport of Mexico City which achieved the 5th AEC Excellence Awards 2017, has used BIM in designing [98]. The third group's BIM obstacles presented in Table 18.

2. Discussion

A comprehensive literature review has been employed to measure the BIM development around the world within three categories. The first category represents pioneer countries that approved related rules and regulations, mandated BIM, and published the implementation roadmap. The second category is the developing countries that published rules and regulations and/or implementation roadmap but did not mandate or accept BIM widely yet; the third category, which is the countries in the early stages, who are suffering several obstacles, as is represented in Table 18. Also, the ten significant barriers are shown in

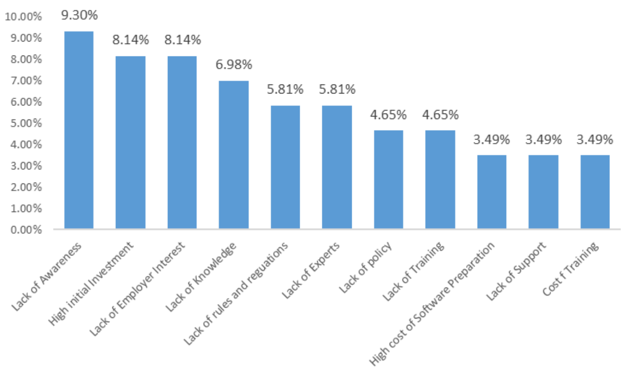

Figure 18- Major BIM barriers in Africa

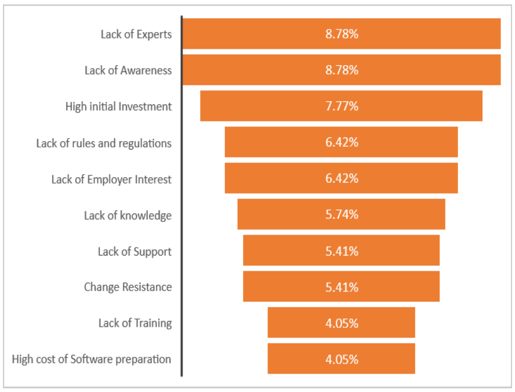

Figure 19- BIM adoption major obstacles

Figure 19.

Table 18- Universal Barriers against BIM implementation

Lack of qualified experts and unawareness about BIM	Continent	Country name	Lack of Experts	Lack of Awareness	High initial investment	Lack of rules and regulations	Lack of Employer Interest	Lack of knowledge	Lack of Support	Change Resistance	Lack of Training	High cost of Software preparation	Unclear ROI	Lack of Incentives	Cost of Training	Lack of ICT Infrastructure	Lack of collaboration	Lack of policy	Software Complexity	Lack of Contractual framework	High price of Hardware preparation	Time-consuming process	Absence of Efficient Training	Financial limitation	Lack of legal platforms	Cultural and Organizational issues	Time Required for training	Absence of adoption plan	Imperfect BIM promotion	Changing Workflow	Absence of Evaluation	Technology Inaccessibility	power failure	Need to Change	lack of studies	Absence of Market Competition	Lack of Information about Software	Lack of stakeholders in BIM usage	absence of following after adoption	Monetary Risks	Lack of equipped Employers	Market Requirements	More Design Time	subcontractor's disaffiliation	Software Cooperative Ability	absence of functional drivers	Governmental Issues	ambiguous vision about BIM	poor Communication	poor management expertise	Technological Issues	ambiguous responsibility division	Assurance Issues	undefined property Rights	Immature Situation	Empowering Project Managers	information exchange	Fear of New Technologies	Ref
1		Turkey	✓	✓	✓	✓			✓											✓			✓					✓																✓															[100], [101]
2		Iran	✓	✓		✓		✓	✓			✓	✓	✓		✓					✓																						✓																[102] [68] [103] [69]
3		India	✓				✓								✓																✓																												[104]
4		UAE			✓				✓																																																		[83]
5		Russia	✓		✓	✓		✓																																																			[71]
6		Pakistan		✓	✓	✓	✓	✓	✓	✓					✓				✓																																								[105]
7		Egypt		✓	✓	✓	✓		✓		✓																																																[106]
8		Saudi Arabia	✓	✓	✓		✓	✓		✓			✓	✓		✓		✓																		✓				✓	✓	✓																	[107]
9		Qatar	✓		✓	✓			✓	✓		✓							✓		✓		✓																																				[108]
10		Iraq	✓	✓			✓		✓	✓	✓																																																[109]
11		Kazakhstan	✓	✓				✓		✓				✓			✓													✓		✓																											[110]
12		Jordan	✓	✓	✓	✓	✓			✓				✓									✓																																				[111]
13		Sudan	✓		✓		✓	✓	✓		✓																																																[112]
14		Yemen		✓	✓				✓			✓									✓			✓					✓																														[113]
15	Asia	Syria	✓					✓																																																			[114]
16		Palestine	✓	✓		✓		✓	✓																												✓																						[115]
17		Lebanon		✓					✓		✓						✓																						✓																				[116]
18		Kuwait					✓	✓				✓			✓												✓											✓																					[117]
19		Armenia	✓	✓				✓																																																			[118]
20		China				✓	✓				✓			✓		✓	✓														✓																												[119]
21		Taiwan			✓					✓	✓			✓								✓				✓																																	[78]
22		Indonesia	✓	✓						✓																																																	[120]
23		Bangladesh			✓						✓								✓																																								[38]
24		Philippines	✓							✓		✓																																															[84]
25		Vietnam	✓		✓					✓			✓									✓			✓				✓																	✓													[104]
26		Nepal			✓						✓																																		✓														[83]
27		Thailand									✓		✓									✓																																					[71]
28		Sri Lanka	✓	✓	✓							✓									✓						✓																																[105]
29		Cambodia	✓		✓				✓	✓					✓																																												[106]
30		Africa			✓		✓	✓							✓					✓				✓																																			[86]
31		Ghana		✓				✓										✓																																									[121]
32		Ethiopia															✓		✓	✓					✓	✓																					✓												[122]
33		Nigeria		✓	✓	✓		✓	✓						✓																	✓	✓																										[123], [124]
34		Tanzania	✓	✓	✓	✓	✓			✓			✓		✓	✓		✓		✓													✓																										[125]
35	Africa	Kenya	✓	✓	✓							✓		✓				✓																✓																									[126]
36		Algeria			✓	✓	✓	✓		✓								✓																														✓											[127]
37		Uganda															✓							✓																									✓	✓	✓								[128]
38		Cameroon					✓					✓																																															[129]
39		Libya		✓				✓			✓																																																[130]
40		Rwanda	✓	✓		✓	✓				✓					✓																			✓																	✓							[95]
41		Zambia	✓	✓								✓																																															[96]
42		EU			✓	✓	✓	✓	✓				✓			✓			✓						✓									✓																			✓	✓	✓		✓		[53]
43		Ireland	✓						✓	✓			✓																																														[54]
44		Slovakia	✓			✓																													✓																								[131]
45		Czech Republic		✓			✓					✓																																															[64]
46	Europe	Poland	✓			✓			✓																																																		[132]
47		Latvia					✓	✓				✓																✓		✓																										✓			[133]
48		Estonia		✓		✓											✓																																										[134]
49		Romania				✓	✓				✓							✓		✓																																							[135]
50		Spain	✓				✓					✓										✓																																					[136]
51		Luxembourg		✓																																																							[137]
52		Colombia								✓																																																	[138]
53	America	Chile		✓		✓																																																					[139]
54		Trinidad and Tobago		✓	✓					✓			✓																																													✓	[140]
Sum			26	26	23	19	19	17	16	16	12	12	8	7	7	6	6	6	5	5	4	4	3	3	3	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Percentage			8.7%	8.7%	7.8%	6.4%	6.4%	5.7%	5.4%	5.4%	4.0%	4.0%	2.7%	2.4%	2.4%	2.0%	2.0%	2.0%	1.7%	1.7%	1.4%	1.4%	1.0%	1.0%	1.0%	0.7%	0.7%	0.7%	0.7%	0.7%	0.7%	0.7%	0.7%	0.7%	0.7%	0.7%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	

Lack of training and education and software cost is in the sixth. Providing software and employing professionals requires high investment, which could be resolved through some incentives or policies, for instance, tax exemption or considering organizational BIM adoption in tender qualification. Also, governments should robustly support BIM to break the opposition and motivate participants, as well as employer requests will force firms to apply BIM. Likewise, approving rules and regulations will accelerate BIM adoption and satisfy needs to attain a reliable level of adoption.

3. Conclusion

In this paper, the BIM progress around the world was reviewed. A wide range of articles, reports, as well as thesis were reviewed, which resulted in three categories of pioneer countries, developing countries, and countries at the BIM beginning. Ten significant barriers identified. It proposed to overcome the challenges, a concentration required on preparing high-quality training and education to train professional experts and to improve the awareness about BIM benefits and its impacts, as well as BIM technical knowledge; also, it will authorize the industry to overcome the opposition against cultural and workflow changes.

On the other hand, governments' support is required to remove obstacles. Financial barriers slow down the process, so it proposed to approve some incentives to facilitate the movement; subsequently, acceptance will accelerate, and ease off providing related software.

In addition, related rules and regulations should legislate to lead BIM adoption and clarify requirements. Likewise, employers should increasingly request BIM to enforce and energize firms to apply BIM.

While a lot of effort has been performed, the lack of information and study about BIM in different countries hindered the collection of BIM states in all countries. Key drivers to implement BIM widely can enumerate as government support which is the most critical character to accelerate approving the rules and regulations; also, requiring BIM is another crucial driver toward BIM. Fast-pace BIM implementation needs to approve a realistic roadmap with an executive schedule and financial aids.

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Measuring The Spacing of Formwork System Members Using 3D Point Clouds

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Abstract

Formwork systems significantly impact the safety risk, construction productivity, and capital investment of infrastructure projects. Ensuring that formwork systems are properly installed is fundamental to avoid those adverse impacts. To do that, quality inspection during installation is important. The traditional spacing inspection process of different members of the formwork system is time-consuming and labordemanding, and it is easily affected by the inspector's knowledge and skills. This study proposes a methodology for the spacing measurement of formwork system members using 3D point clouds to overcome these shortcomings. The feasibility and effectiveness of the proposed methodology were tested on a formwork system mockup. The mean absolute percentage error (MAPE) of the eight spacing measurements compared to those using a measuring tape was 1.05%. The experimental test demonstrates that the 3D point cloud approach is promising, and it has the potential to be an alternative solution to measure the spacing of formwork system members.

Keywords: concrete construction, construction automation, data processing and analysis, dimensional measurement, laser scanning.

1. Introduction

In infrastructure projects, the formwork system is a set of temporary structures for molding fresh concrete into the desired appearance, dimension, shape, and position [1]. The formwork system is a critical element in concrete construction. It can easily cause safety risks during concrete placement and seriously affect the quality of concrete after the placement. Formwork systems occupy a significant proportion of the investment in concrete construction. A report shows that it usually accounts for something between 40% to 60% of the total cost of a building's structural concrete frame [2]. Consequently, formwork systems can significantly impact the smooth progress and successful completion of infrastructure projects.

Compared to permanent structures, temporary formwork systems are more fragile and require sufficient strength, stiffness, and stability [3]. The quality inspection of formwork systems is an essential construction management procedure that examines, measures, and gauges whether the characteristics (e.g., number, size, and spacing) of installed formwork systems properly meet specific design requirements. On the one hand, if the installed formwork systems do not satisfy the design requirements, they could be not firm enough and may cause severe damage or deficiencies to the infrastructure project being constructed, even fatalities in the case of a collapse. On the other hand, if the installed formwork systems exceed the design requirements, they might result in unnecessary waste such as more work hours and materials. For these reasons, the quality inspection of formwork systems is of great practical significance in infrastructure projects.

The formwork system typically comprises different members such as panels, studs, wales, ties, and braces (Fig. 1). To ensure its strength, stiffness, and stability, the spacing of different members of the formwork system needs to be specifically designed according to the force determined by the properties of concrete (e.g., density, initial setting time, slump) and the means and methods of construction (e.g., placement approach, speed) and the object determined by the features of formwork system members (e.g., material, size, shape). Traditionally, the spacing inspection of different members of the formwork system is conducted through eye observation or simple measuring tools (e.g., measuring tapes). This process is time-consuming and labor-demanding. In addition, it is easily affected by the inspector's knowledge and skills, making the collection of data subjective and inconsistent [4].

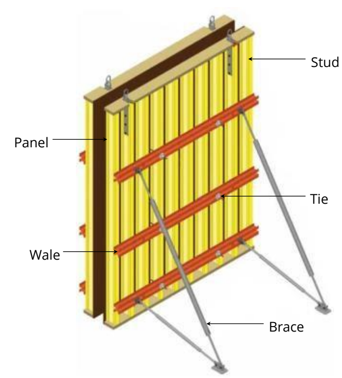


Fig. 1. A typical formwork system [5].

A 3D point cloud is a set of data points containing three-dimensional coordinates and other information such as reflectance, color, etc. It provides a promising solution to overcome the above shortcomings because 3D point clouds can effectively represent the external surface of objects. Currently, 3D point clouds have been successfully applied to various dimensional quality inspections in infrastructure projects. In the field of precast components, a technique was presented to detect slab sizes and shear pocket sizes and positions to ensure the quality of precast concrete slabs [6]; and a framework was developed to examine slab sizes, girder sizes, shear pocket sizes and positions, and shear connector orientations and positions to guarantee the proper connection between precast bridge deck slabs and precast girders [7]. Since irregular precast components and precast components with holes increase the complexity of detection, a technique was presented to determine the panel depth, shear key sizes and positions, and flat duct positions of a precast bridge deck slab with geometric irregularities [8]; and a method was proposed to estimate panel sizes and squareness and hole sizes and positions for accelerating the measurement of precast concrete panels with holes [9]. Considering the difficulty of scanning the side surface of precast concrete components, a mirror-aided system was developed to check the outer sizes and shear key sizes of a precast bridge deck slab [10]. In the field of steel reinforcement bars (rebars), a methodology was proposed to assess rebar spacings, concrete covers, and formwork inner sizes to control the placement of rebars in formwork [11]; and a colored point cloudbased technique was proposed to estimate rebar positions that are important for the overall structural performance [12]. In the field of steel structures, an approach was presented to determine the bottom and top center point positions and altitudes of steel columns for the dimensional compliance control of the steel structure of an industrial building [13]. In the field of temporary structures, a method was designed to detect toe-board heights and guard-rail positions for complying with scaffolding safety regulations [14]. So far, there has been some beneficial research on applying 3D point clouds for dimensional quality inspections; however, formwork systems have not received much attention yet. Unlike other elements, the formwork system has its specific members and layouts, so it is necessary and meaningful to conduct specialized research according to the characteristics of the formwork system.

With that in mind, this research focuses on the spacing measurement of formwork system members using 3D point clouds. The remainder of this paper is organized as follows. Section 2 elaborates on the steps of the proposed methodology. In Section 3, a formwork system mockup is tested for validation. Section 4 summarizes conclusions and outlook.

2. Methodology

The proposed methodology consists of five steps: 1) remove surroundings, 2) remove outliers, 3) transform the coordinate system, 4) recognize formwork system members, and 5) measure spacing between members (Fig. 2). Each step is detailed below.

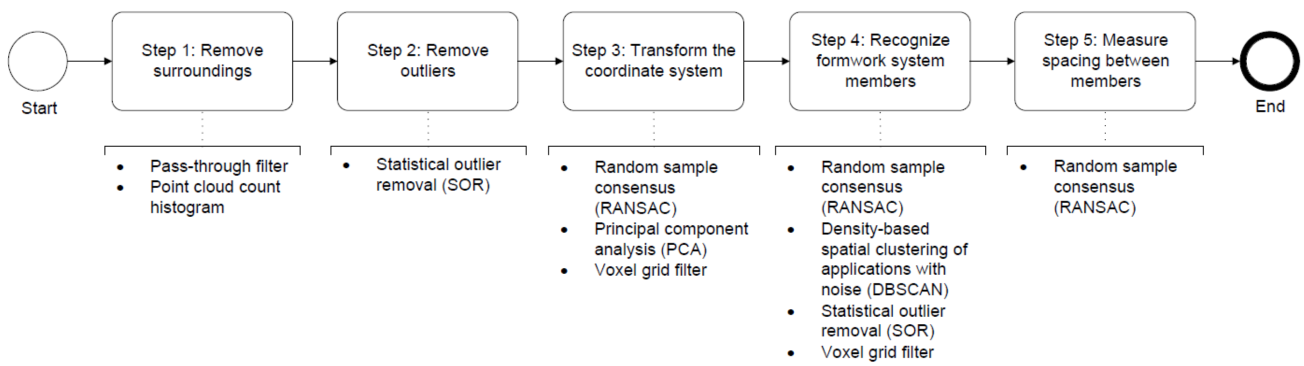


Fig. 2. Five steps of the proposed methodology.

2.1. Step 1: Remove surroundings

The point clouds acquired by the laser scanner include the formwork system and its surroundings. To avoid the interference of surroundings, Step 1 removes surroundings with the pass-through filter and the point cloud count histogram. By setting thresholds, the pass-through filter retains and filters the point clouds inside and outside the threshold range, respectively, to perform the preliminary filtering of surroundings. The thresholds are determined according to the three-dimensional coordinates of the formwork system, and this process needs to be done manually. In some cases, the ground is close to the formwork system, which makes it difficult to be completely removed by the pass-through filter. Hence, the point cloud count histogram is applied to filter the ground. Taking the normal direction of the ground as a coordinate axis direction, the point cloud count of the ground is significantly more than that of the formwork system along the coordinate axis. In other words, there is one highest peak representing the ground in the histogram, which can facilitate the division from the lower peaks representing the formwork system.

2.2. Step 2: Remove outliers

Laser scanning often produces outliers due to random noises, especially when scanning reflective surfaces. The information from outliers is of no use and should be ignored. Outliers are featured by being sparsely distributed in space. Considering this feature, Step 2 removes outliers using the statistical outlier removal (SOR) [15]. SOR computes the distances of each point to its set nearest *k* points and assumes that the resulting distances follow a Gaussian distribution. If the mean distance of a point is outside the interval defined by the mean and the set *n* times the standard deviation, it is considered an outlier.

2.3. Step 3: Transform the coordinate system

The coordinate system of the point clouds acquired by the laser scanner usually does not adapt to the formwork system, which is not conducive to the segmentation of formwork system members. To facilitate the recognition of formwork system members, Step 3 transforms the coordinate system utilizing the random sample consensus (RANSAC) [16], the principal component analysis (PCA) [17], and the voxel grid filter. For the segmentation of formwork system members, the panel is the best reference object because other members are all installed based on it. PCA projects the point clouds of the panel identified by RANSAC onto a surface to find the main directions, and they are determined according to the distribution variances of the point clouds. To accelerate this process, the voxel grid filter is used to reduce the density of points. By setting voxel sizes, the voxel grid filter replaces points within a voxel with the centroid point. Considering the uncertainty of the positions of formwork system members on the plane of the panel and the certainty of the relative positions of formwork system members along the normal direction of the panel, it is not necessary to deterministically place the new coordinate system.

2.4. Step 4: Recognize formwork system members

The formwork system comprises different members (e.g., panels, studs, wales, ties, braces). To recognize the different formwork system members, RANSAC, the density-based spatial clustering of applications with noise (DBSCAN) [18], SOR, and the voxel grid filter are applied in Step 4. The recognition of members is divided into two parts. The first part segments members along the determined coordinate axis perpendicular to the plane of the panel according to the existing size data of members.

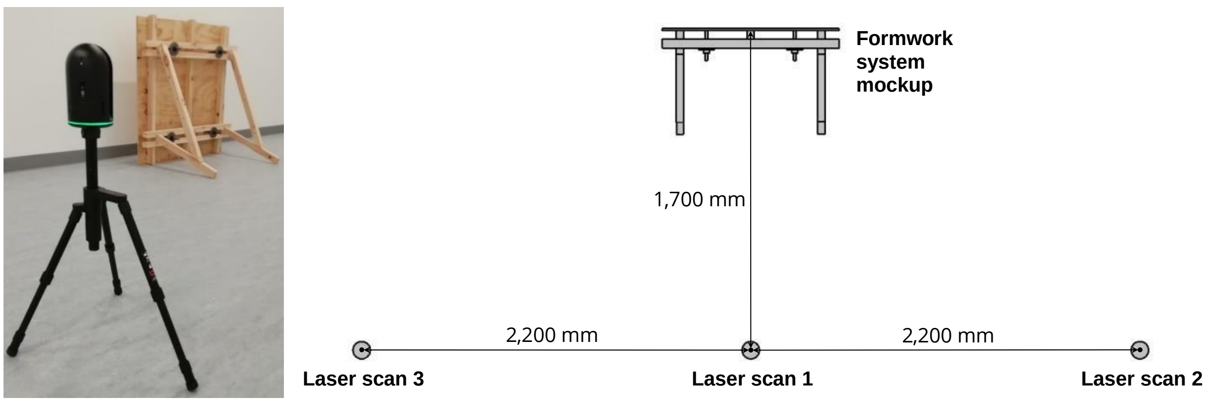
The second part further segments members using RANSAC and DBSCAN. These two approaches are used together to deal with cases such as different clusters corresponding to different members on the same plane. Regarding RANSAC, the points that can form a desired mathematical model are randomly selected, then these points are utilized to calculate the parameters of the model, and finally, the points that fit the resulting model within the set threshold are checked. This process is repeated until a set number of iterations is reached. With respect to DBSCAN, in each cluster, the points that meet the set minimum number of points within the set distance are identified as core points, then the points that are connected to the core points are identified as border points, and finally, the points that are not connected to any core points are identified as outliers. During the recognition of members, SOR is used to remove outliers, and the voxel grid filter is used for downsampling. It is worth mentioning that each recognized member is stored separately and numbered accordingly so that it can be retrieved directly without manual intervention.

2.5. Step 5: Measure spacing between members

The spacing between the members being inspected includes the horizontal spacing between studs, the vertical spacing between wales, the horizontal and vertical spacings between ties, and the horizontal spacing between braces. Step 5 measures spacing between members with RANSAC. The points of each recognized member are fitted as a straight line to calculate the mean of the corresponding coordinates of the points within the set threshold of the fitted line, and the spacing between two members is the difference between their means. For studs and braces, means are derived from coordinates of the horizontal direction. For wales, means are derived from coordinates of the vertical direction. For ties, means are derived from coordinates of the horizontal and vertical directions. The same category of members is measured sequentially according to the coordinate magnitude of the corresponding direction to achieve automation.

3. Experimental test

To test the feasibility and effectiveness of the proposed methodology, an experiment was conducted using a formwork system mockup and a Leica BLK360 3D laser scanner (Fig. 3 (a)). The formwork system mockup comprises one wooden panel, three wooden studs, four wooden wales, four iron ties, and two wooden braces. The laser scanner has a field of view of 360° (horizontal) and 300° (vertical), a scanning range of 0.6 to 60 m, a point measurement rate of up to 360,000 pts/sec, and a 3D point accuracy of 6 mm@10m and 8 mm@20m [19]. Because the layout of the formwork system mockup is complex and the spacings between the members are small, three scans with different distances and angles were taken to avoid as much occlusion as possible. The distance between the formwork system mockup and laser scan 1 was 1,700 mm, and the spacing between the laser scans was 2,200 mm (Fig. 3 (b)).



(a) (b)

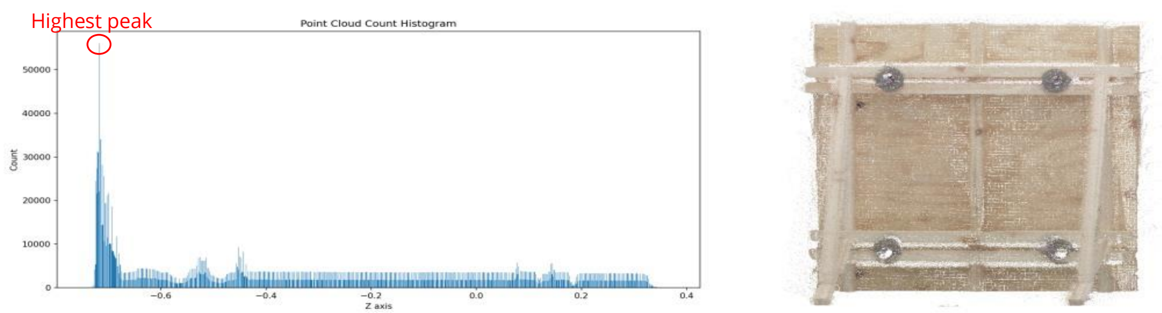
Fig. 3. Experimental test: (a) real scene and (b) schematic plan.

The raw point clouds from the three laser scan positions were registered, as shown in Fig. 4 (a). The experimental test was conducted following the five steps of the proposed methodology (Fig. 2), and the algorithm was developed using Open3D [20], a library for 3D data processing in Python. In Step 1, the surroundings were removed with the pass-through filter and the point cloud count histogram (Fig. 4 (b) and (c)). Regarding the pass-through filter, the thresholds were determined according to the threedimensional coordinates of the formwork system, and the coordinates were viewed on CloudCompare [21]. With respect to the point cloud count histogram, the point clouds were counted along the Z-axis, and the highest peak representing the ground was found in the histogram. In Step 2, the outliers were removed using SOR, and the removed outliers are highlighted in red (Fig. 4 (d)). In Step 3, the coordinate system was transformed utilizing RANSAC, PCA, and the voxel grid filter, with the Z-axis being perpendicular to the plane of the panel (Fig. 4 (e)). In Step 4, the different formwork system members were recognized by applying RANSAC, DBSCAN, SOR, and the voxel grid filter. The recognized studs, wales, ties, and braces are highlighted in red, green, black, and blue, respectively (Fig. 4 (f)). In Step 5, the spacings between the recognized formwork system members were measured with RANSAC. For example, in Fig. 4 (g), the points of the left and middle studs highlighted in red were fitted as two center lines, and the spacing between them was the difference between the means of the X-axis coordinates of the points within the set threshold of the lines. A total of eight spacing measurements were taken (Fig. 4 (h)): two for the horizontal spacing between the studs (i.e., Spacings 1 and 2), one for the vertical spacing between the wales (i.e., Spacing 3), four for the horizontal and vertical spacings between the ties (i.e., Spacings 4, 5, 6, and 7), and one for the spacing between the braces (i.e., Spacing 8).

The comparison of the spacing measurement results using a measuring tape and the 3D point clouds is summarized in Table 1. The maximum error (13 mm) was the vertical spacing between the two ties on the right (Spacing 7), and the maximum percentage error (2.14%) was the horizontal spacing between the two ties on the bottom (Spacing 5). The minimum error (0 mm) was the vertical spacing between the two wales (Spacing 3), and it was also the minimum percentage error (0.00%). It was found that the errors and percentage errors of the ties were significantly larger than the studs, wales, and braces. The mean absolute error and percentage error of the ties were 9.50 mm and 1.64%, respectively. They were 3.45 and 3.49 times more than those of all the studs, wales, and braces, respectively. Some of the reasons for that could be attributed to the smaller sizes of the ties and their positions, which were obstructed by other members, making the quality of the point clouds of the ties relatively worse since only a small part of them was recognized.

(a)

(b)



(c)

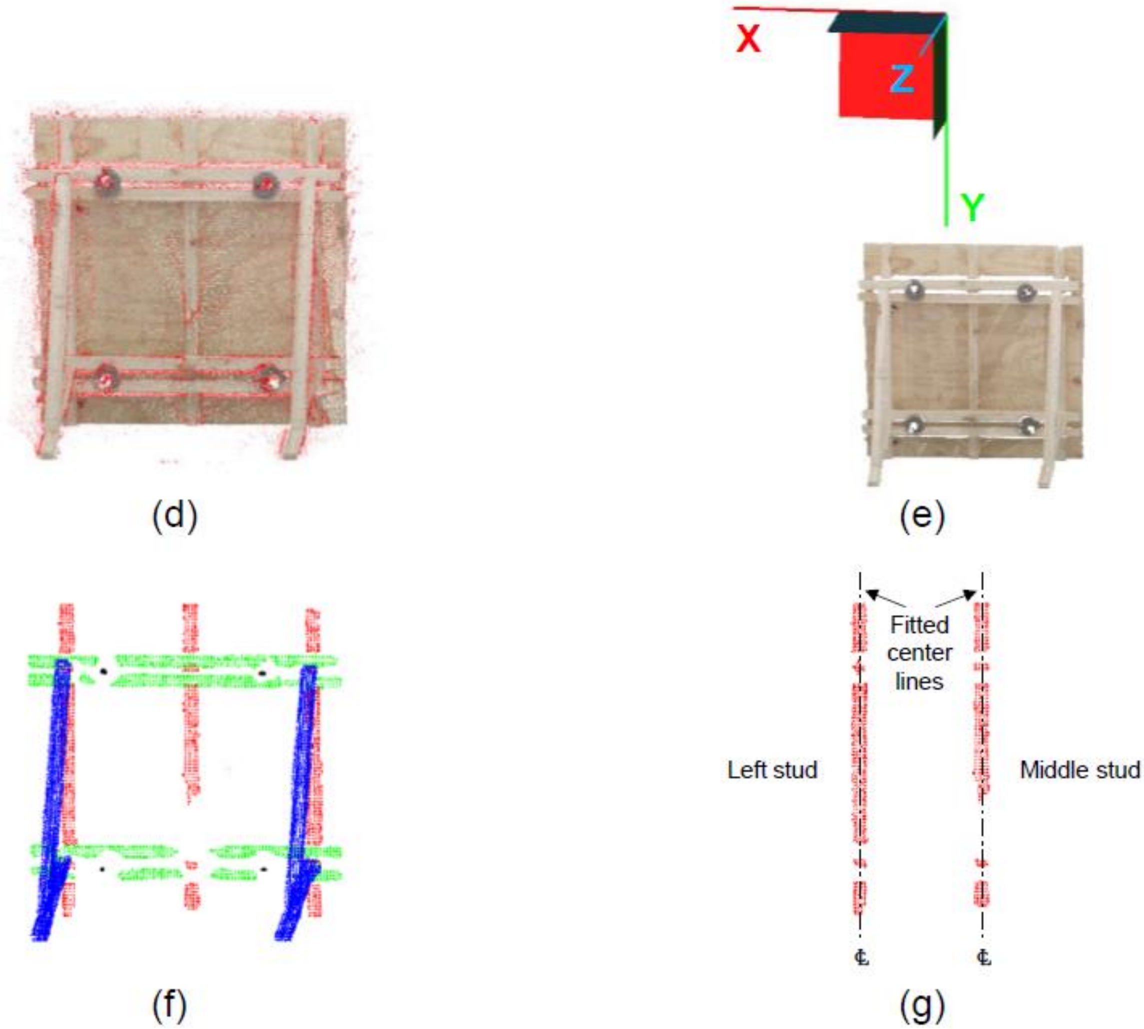


Fig. 4. Experimental test details: (a) raw point clouds, (b) point clouds after removing the surroundings except the ground, (c) point clouds after removing the ground, (d) point clouds after removing the outliers, (e) point clouds after transforming the coordinate system, (f) recognized formwork system members, (g) recognized left and middle studs with the fitted center lines, and (h) eight measured spacings.

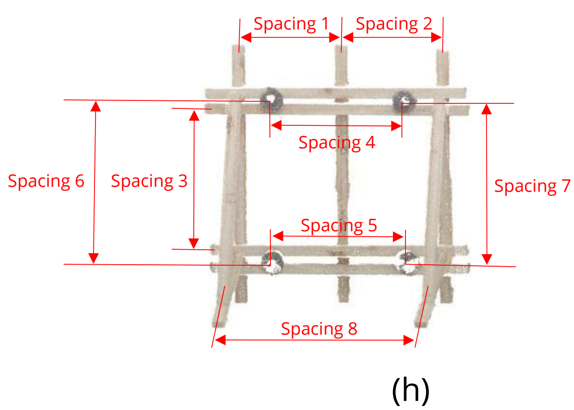


Fig. 4. Continued.

Table 1. Comparison of the spacing measurement results using a measuring tape and the 3D point clouds.

Spacing	Measuring tape (mm) (S_{mt})	3D point cloud (mm) (S_{pc})	Error (mm) (S_{pc} - S_{mt})	Percentage error (%) ((S_{pc} - S_{mt}) / S_{mt})
1	403	402	-1	-0.25
2	403	400	-3	-0.74
3	549	549	0	0.00
4	516	518	2	0.39
5	514	525	11	2.14
6	623	635	12	1.93
7	617	630	13	2.11
8	801	808	7	0.87
			Mean absolute percentage error (MAPE)	1.05

4. Conclusions and outlook

With the progress and development of point cloud-related technologies and equipment, some researchers have started to focus on applying 3D point clouds for various dimensional quality inspections in infrastructure projects. The traditional spacing inspection of formwork system members is mainly performed by manpower, and this process is tedious and error-prone. This study proposes a methodology for the spacing measurement of formwork system members using 3D point clouds to address these challenges. The proposed methodology consists of five steps: 1) remove surroundings, 2) remove outliers, 3) transform the coordinate system, 4) recognize formwork system members, and 5) measure spacing between members. An experimental test to measure eight spacings was conducted on a formwork system mockup with one wooden panel, three wooden studs, four wooden wales, four iron ties, and two wooden braces. When comparing the measurements using the measuring tape and 3D point cloud approaches, the mean absolute percentage error (MAPE) of the eight spacings was 1.05%. It is expected that this difference will be reduced by optimizing the number of scans and the position of the scanner, and the accuracy/resolution of the laser scanner. The results obtained showed that the 3D point cloud approach were comparable to the measuring tape approach; however, since the formwork system mockup comprised a small number of members, the 3D point cloud approach did not show a clear advantage with respect to the time taken during the experimental test. Considering the proposed methodology has only a few manual operations (i.e., the determination of the threedimensional coordinates of the formwork system), it can be foreseeable that the time advantage of the

3D point cloud approach will become obvious with the increase of members. In general, the 3D point cloud approach is promising, and it has the potential to be an alternative solution to measure the spacing of formwork system members.

In future work, the spacing measurement of formwork system members performed by an autonomous robot will be investigated to make such an inspection fully automatic; meanwhile, the testing will be extended to real environments (i.e., ongoing construction sites).

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