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Sebastian Skatulla
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Preface

The Proceedings of the 19th International Conference on Computing in Civil and Building Engineering (ICCCBE) presents findings concerning current and future applications of computing in a wide range of civil and building engineering disciplines.

The conference was the latest in a sequence of ICCCBE International Conferences being held for the first time in Africa where it took place in Cape Town, South Africa, during 26–28 October 2022. It promoted innovation in civil engineering through digital twin technology; geometric modelling; simulation and process modelling; monitoring, information and communication technologies; big data, artificial intelligence and machine learning software; robotics, automation and control; computational structural mechanics. The conference therefore provided a forum and a unique opportunity for researchers and students from the African continent to interact with members of the civil engineering community from around the world.

ICCCBE 2022 has received excellent support by researchers and practitioners all across South Africa, with authors being drawn from numerous research and industrial organisations. The Proceedings contains scientific contributions presented at the conference, classified into a total of 16 themes split over two volumes. Only original contributions were considered for inclusion. All papers submitted were subjected to a full process of double-blind peer review. The review of manuscripts was undertaken by the members of the Scientific Advisory Board and other identified leading experts, acting independently on one or more assigned manuscripts. This invaluable assistance, which has greatly enhanced the quality of the Proceedings, is gratefully acknowledged.

Special acknowledgments are due to our supporters and partners in the industry:

- CIOB
- SSD
- SAICE

Finally, the editors wish to thank the authors for their efforts towards producing and delivering papers of high standard creating a base for discussion and providing suggestions for future development and research.

S. Skatulla
H. Beushausen

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Asset and Facility Management, Operation, and Maintenance

UAV Image-Based Defect Detection for Ancient Bridge Maintenance

Zhaolun Liang, Hao Wu, Haojia Li, Yanlin Wan, and Jack C. P. Cheng

Abstract Ancient bridges lack adequate maintenance strategies and public attention compared to modern bridges. The current bridge maintenance standards are tailored for modern bridges and cannot be directly applied to ancient bridge maintenance because of differences in structure designs and construction materials. Besides, due to the urban development and the evolution of traffic, the frequency of using the ancient bridges has tapered off; people gradually elided the maintenance of ancient bridges. Nevertheless, some ancient bridges still serve as integral hubs in the transportation network and require more inspection due to their common features of aging structures and complex damage history. Previous studies have mainly applied sensor-based analysis for structural deformation problems in ancient bridge health monitoring. The mainstream inspection technologies include sonic transmission, radiography, infrared thermography, and ground-penetrating radar (GPR). However, these methods can only partially depict the interior condition of the bridge, and are time-consuming and complicated to implement in practice; their feasibility on ancient bridge maintenance is debatable. This paper proposes an image-based detection method to provide an effective solution for the maintenance of ancient bridges using Deep Neural Networks (DNNs). A masonry arch bridge in Hong Kong, built in the 1880s, was investigated. Unmanned Aerial Vehicles (UAVs) were deployed to collect the bridge surface information, and a 3D model generated with Structure from Motion (SfM) was preserved for further bridge health monitoring. In addition,

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an assessment criterion was purposed to evaluate the ancient bridge health condition, which is beneficial for the decision-making on ancient bridge maintenance.

Keywords Ancient bridge maintenance · Deep Neural Networks (DNNs) · Unmanned Aerial Vehicles (UAVs)

1 Introduction

Bridges act as a significant role in linking one area to another, making it possible for the transportation network to expand and function. As a fundamental infrastructure of a nation, bridges are designed to carry pedestrians, road traffic, trains, or even canals for waterborne transport. Each day, thousands of cargos and people pass through the bridges; these activities create numerous economic values and keep people connected. Among the many types of bridges in the present world, beam bridges are the most general ones due to their cost-effectiveness. Cable-stayed bridges, suspension bridges, and arch bridges are also commonly built in many regions. Those bridges are mainly constructed with concrete, steel, and brick materials followed by modern standardizations, allowing them to be inspected systematically with the corresponding specifications.

Bridge inspection is pivotal in civil infrastructure maintenance, enabling engineers to discern trivial defects and potential problematic regions before they grow into irretrievable issues. Despite the difference in regulations and practices around the world, inspecting a bridge is mandated at least once every two years in most countries [1]. The inspection procedure is conventionally carried out by the bucket truck, which is also known as the "snooper truck" [2]. At its core, a man-carrying bucket is fitted at the end of the hydraulic pole on the truck, where the workers can complete their inspection jobs safely on the lifted bucket underneath the bridge. There are four mainstream bridge inspection methods: superficial, routine, principal, and special inspections [3]. Routine and principal inspections refer to periodic and detailed inspections, where special inspection is applied to investigate the specific bridge problems. During the inspection, inspectors often use four common techniques; they are visual, acoustic, thermal, and ground-penetrating radar [3].

In contrast to modern bridges, there were no consistent standards for the construction of ancient bridges. The earliest bridges were spans made of wooden planks or stones with simple supports and crossbeam arrangements. The origin of arch bridges can be traced back to the Roman Empire thousands of years ago, some of which are still standing today. In European countries, many stone arch bridges remained a crucial component of modern transportation networks. Brick and mortar bridges were later invented, and rope bridges were found to be used in South America in the 1500 s. During the eighteenth century, engineers designed timber bridges, followed by the development of steel bridges in the nineteenth century after the emergence of the Industrial Revolution. Up to now, the arch bridge is the one with the greatest number preserved by relatively intact structures amidst all ancient bridges. Two typical examples are the Pons Fabricius Bridge [4] in Italy and the Anji Bridge [5] in China, which were built in 62 B.C. and 605 A.D., respectively. Due to its distinctive design and prominent performance of resistance, the arch bridge is still considered one of the most popular solutions to span a river, valley, or gorge nowadays. However, unlike modern arch bridges built from reinforced steel and concrete, ancient arch bridges were prevailing constructed with natural materials, which limited their pliability. With repeated applied stresses and the effects of efflorescence, disintegration and cracking may occur over time between the mortar and the natural materials, leading to structural problems in ancient arch bridges. Because of its representativeness among ancient bridges, a masonry arch bridge was investigated as the research subject in this paper.

It is generally known that the longer the time, the greater the opportunity of the object being damaged, and this also applies to ancient bridges. Ancient bridges have accumulated more injuries than modern ones and undertook many circles of stresses to their surfaces and internal structures. Therefore, it is imminent to see that additional maintenance is added to prolong the lifespan of ancient bridges. Unfortunately, current specifications only focus on the inspection and maintenance of recently built bridges, while the maintenance of ancient bridges lacks explicit provisions. One reason is that variations in characteristics such as modality, material, age, and span make ancient bridges difficult to be classified. Another ground is that the use of bridges built earlier as main transport arteries is becoming less and less frequent, as the development of advanced transportation networks relied more on modern bridges in the present day. So far, many countries and regions have begun to pay more attention to the maintenance of ancient bridges, as many are still being used as the main traffic routes. However, the problem of lacking inspection remained unaddressed in the overwhelming number of ancient bridges around the world.

2 UAV-Based Ancient Bridge Inspection

2.1 Background of UAV-Based Inspection

Although traditional inspection tasks are performed by professional inspectors, it still faces the problems of low efficiency and high cost [6, 7]. One major challenge in the inspection task is the difficulty of accessing the corner and bottom of the bridge. Another challenge is the complex environment during the bridge inspection process. In some cases, the inspection work consumes considerable time to inspect all the details of the bridge. Safety is another concern, while falling from the bridge would be a fatal accident [7].

With the development of aerial robotics, UAVs (Unmanned Aerial Vehicles) offer bridge inspectors a solution to overcome the problems discussed above. UAVs, by another name, are drones and can be defined as a class of automated or remotely controlled aircrafts. Nowadays, most commercial drones are equipped with wireless transmission and camera systems. The operator can visualize and capture the images by the remote controller, which can protect the inspectors from danger. Due to the drone's highly autonomous controller and agile flying ability, it can improve its working efficiency significantly [8]. The UAV can be divided into several types, including fixed wing, airship, helicopter, and multirotor [8, 9]. Researchers have tried different platforms for the inspection task. Fixed-wing drones are suitable for long-distance and large-scale surveys, but inspecting the side of constructions is strenuous. Meanwhile, airship and helicopter drones are inappropriate for conducting civil infrastructure inspections due to their massive size. Multirotor drones can take off and land vertically in a tiny space and hover stably in the air. With the assistance of gimbals, multirotor can take images from different angles. Benefiting from these advantages, the multirotor is more suitable for bridge inspection tasks.

Today, UAVs are used in civil engineering to solve various problems with high-definition cameras. Kumar et al. [10] employed the UAV to perform the damage detection task and achieved the automatic detection pipeline. Ellenberg et al. [11] developed a monitoring system for the bridge using UAV. Costa [12] and Álvares [6] applied the UAV in the working progress monitoring and safety checking. Predictably, the use of UAVs in the construction industry will increase in recent years with the innovation of technology; this trend can further promote the application of UAVs becoming more sophisticated in civil engineering fields, such as bridge inspection.

2.2 Significance of UAV-Based Inspection for Ancient Bridges

UAVs are flexible platforms that can inspect areas inaccessible to manual inspectors. In manual inspection, regions such as corners, bearing connections, and underneath bridge regions are difficult from being viewed by inspectors due to spatial constraints. The bridge inspection truck, also named the "snooper truck", will be employed to inspect those hard-to-reach regions. For some ancient bridges, the primary issue is the difficulty of deploying the snooper truck to the work site. One reason is the concern of potential deficiencies caused by structural deterioration, where some ancient bridges may not be able to withstand the load of a truck; another is due to environmental and geometric limitations of the bridge. For example, it is challenging for a working platform on an inspection truck to pass under narrow or various ancient bridge structures. Accordingly, many ancient bridges are still not well inspected despite the massive development of today's bridge inspection technologies.

Nowadays, it is a norm to apply non-destructive testing (NDT) [13] techniques for ancient bridge inspection and monitoring. NDT methods are prevalently adopted in civil engineering surveys because they do not introduce any damage to the structure of infrastructures. NDT methods for ancient bridge inspection applications include infrared thermography [14], sonic transmission [15], seismic reflection [16], ground-penetrating radar (GPR) [17], electrical impedance tomography [18], radiography [19], and laser scanning [20]. Different NDT approaches have their unique operational principles:

- Infrared thermography discovers the subsurface defects based on the radiant energy captured by the specialized camera;
- Sonic transmission and seismic reflection can investigate the internal flaws using sound waves;
- Ground-penetrating radar detects the irregularities in the subsurface with radar pulses;
- Electrical impedance tomography allows the formation of 3D tomographic images for particular body parts by measuring the surface electrical properties;
- Radiography records the internal view of an object by penetrating it with electromagnetic radiation;
- Laser scanning describes the object surface by generating its 3D point clouds with laser beams.

However, adopting the above NDT methods for ancient bridge inspection normally requires professional knowledge and skills. Their implementation is also accompanied by excessive time consumption for equipment manipulation and data analysis. Furthermore, their application in bridge inspection is significantly restricted by the surrounding environment and equipment size. Lastly, the limited interior bridge information obtained by most sensor-based technologies during each detection can hardly be utilized to assess the health of entire ancient bridge. Hence, employing a vision-based inspection of the ancient bridges is more straightforward and efficient than using the sensor-based NDT methods.

The UAV-based inspection provides an effective solution to the ancient bridge inspection as three major advantages brought by this robotic application: access to more informative data, faster inspection speed, and safer working environment. In many cases, inaccessible areas can be inspected by adjusting the angle of the mounted camera and the aerial position of the UAVs, which provides adequate information for a comprehensive assessment of bridge health. Concurrently, UAVs allow faster inspections than human inspectors due to their inherent high maneuverability and wider field of view. Most importantly, the entire inspection was carried out using the UAVs without imposing any load on the bridge. The deployment of UAVs to inspect ancient bridges does not cause any damage to the structure, which further ensures the safety of the inspection procedure. In general, due to the various benefits offered by UAV applications, it is possible to make UAV-based inspections a universal approach for most ancient bridge inspections.

2.3 Crack Segmentation

Today, implementing deep neural networks has become a trend in engineering applications because it can solve the problems of low efficiency and impracticality faced by traditional industries. In traditional bridge inspection, detecting defects is laborious, while using deep learning models can detect bridge defects automatically with higher efficiency and accuracy. In this research, the segmentation network U-Net [21] is employed, instead of using the object detection networks. Because the bounding box given by the object detection network will contain multiple objects in the same box, the operator may be confused when detecting defects using this method. For segmentation, a pixel-wise mask is generated for each object in the image, where irrelated issues will be excluded. Two popular architectures, VGG16 and ResNet_101, are used as transfer learning architectures to enhance the model performance in this research. U-Net, known as its "U"-shaped structure, is a typical segmentation model that can be simply viewed as two parts. The first part of U-Net is used for the feature extraction, while the second part is the feature convergence network. The output of the U-Net model has the same size as the input image with high resolution, and each pixel is classified into a certain class.

2.4 Evaluation Metrics

To evaluate the performance of the proposed models, the evaluation metric is adopting IoU (Intersection over Union) and Dice, where Dice is also called "F1 score". For object detection methods, the typical evaluation metrics are precision and recall, which represent the correct prediction rate in positive samples and ground truth, respectively. It is inappropriate to use precision and recall in a segmentation problem because they cannot describe the classification of pixels. The IoU and Dice metrics are used in segmentation problems as they represent the overlapping between the predicted output and target mask. In general, the Dice coefficient often gives a higher score than the IoU. Below are the expressions of IoU and Dice:

$$IoU = \frac{TP}{TP + FN + FP} \tag{1}$$

$$Dice = \frac{2 \times TP}{(TP + FN) + (TP + FP)} \tag{2}$$

In this paper, TP (True Positive) indicates the prediction of a defect on the ancient bridge is correct; TN (Ture Negative) indicates the prediction of a non-defect object is correct; FP (False Positive) represents the prediction of a defect on the ancient bridge is wrong; FN (False Negative) represents the prediction of a non-defect object is wrong.

2.5 3D Modelling of Ancient Bridges

A 3D model of the target bridge will be generated using the images captured by UAVs, and the digital bridge information can be stored in the database for bridge health monitoring in due course. After acquiring the bridge images from UAVs, the method of Structure from Motion (SfM) [22] will be employed to reconstruct the 3D model of ancient bridge. Using techniques such as Scale-Invariant Feature Transform (SIFT) or the Speeded-Up Robust Features (SURF), correspondences between images can be determined, and a 3D model of the bridge can be generated as a result. In SIFT, the points of interest of the objects are first detected and stored in the database. Then, features extracted from new images were used to compare with the key points in the database to find the matches based on Euclidean distance. A feature enhancement approach, Difference of Gaussians (DoG), is applied to obtain the features from the images. Knowing the match information and filtering out false matches, the object location, scale, and orientation can be computed. With sufficient matches and feature trajectories, the 3D positions of the object can be determined, along with the parameters for camera pose and calibration. Eventually, two-dimensional imagery information can be converted into three-dimensional form.

2.6 Ancient Bridge Maintenance

Based on the obtained detection results and the 3D reconstruction model, successive bridge maintenance strategies can be introduced as the defect information has been revealed. However, there is no standard specification for the maintenance of ancient bridges. In this paper, an evaluation criterion of health conditions for ancient bridges and the corresponding maintenance strategies are proposed for reference. First, the health condition of the ancient bridge can be classified into 1 to 5 levels. Level 1 indicates the bridge is in good condition, and so on; level 5 indicates that the bridge has critical problems and cannot be used. The criteria of the ancient bridge health condition assessment are listed in Table 1. The assessment is referenced to the modern bridge appraisal; the difference is that each ancient bridge has a different degree of deterioration. With the assessment of the bridge health level, the corresponding measurements can be determined. Table 2 shows the possible defects and the causes for these phenomena and provides solutions for each health level of the ancient bridges.

Worth mentioning, all ancient bridges were not designed to carry the modern traffic volume, but using ancient bridges as the main transport networks is prevalent in some regions. For example, some ancient bridges were assigned traffic volumes including pedestrians, cars, and heavy trucks; some century-old bridges have been incorporated into the railway system and given the mission of rail transportation. Bridges in these conditions require particular cautiousness and extra attention, as structural deformation can easily occur when ancient bridges experience unexpected

Table 1 Definition of health condition levels of ancient and modern bridges

Health condition level	Description of ancient bridge	Description of modern bridge
1	Minimal deterioration; no major impact on bridge functions	Well condition; robust functionality
2	Mild deterioration; capable to maintain normal functions	Minor defects; no major impact on bridge functions
3	Moderate deterioration; pedestrian passage allowed; additional loading not recommended	Moderate defect; capable to maintain normal functions
4	Severe deterioration; normal use cannot be guaranteed	Severe defects on major components; normal use cannot be guaranteed
5	Critical deterioration; out of service	Critical defects on major components; out of service

Table 2 Possible defects of ancient bridges with different health condition levels and corresponding maintenance measures

Health condition level	Possible defects	Possible causes	Maintenance measures
1	A small number of cracks, plants, minor spalling, or other defects on the bridge surface	Aging process; environmental effects such as sunlight, rain, and wind, etc	Maintain regular inspection
2	Some defects such as cracks, spalling, plants, molds, and efflorescence on the bridge surface/subsurface; no structural deficiency	Aging process; environmental effects such as sunlight, rain, and wind, etc	Carry out detailed inspection on demand
3	Some deteriorations on bridge surface; mild structural deficiencies	Aging process; environmental effects; long-term loading	The bridge should not be subjected to heavy loads; restoration works need to be settled soon
4	Severe deteriorations on bridge surface; several structural deformities	Aging process; long-term loading; environmental effects; transient loading due to the modern traffic	Prohibit bridge accessibility; carry out rehabilitation work as soon as possible
5	Critical deterioration on bridge surface; severe structural deformities on bridge components	Aging process; transient loading; natural disasters such as land sliding, heavy storms, flood, etc	Restrict all access; consider demolishing the bridge or permanently banning its use

loads. In general, most ancient bridges are experiencing the slow effects of environmental problems such as sunlight and rain. It is inevitable to induce a gradual deterioration of bridge components and triggers many potential problems for the entire bridge structure.

3 Experiment

3.1 Site Condition

The experimental site was chosen the stone bridge located at Tai Tam Tuk Reservoir, Hong Kong. The Tai Tam Reservoir Stone Bridge was built in 1888 as an arch bridge with vehicular and pedestrian access. Since the bridge has constructed about 130 years, the surface has been covered with plants, mosses, and molds. Below the bridge is a reservoir, where the water level rises or falls with the seasons. Due to the water level and the limited arch space, performing traditional manual inspection for the Tai Tam Stone Bridge is not feasible. Moreover, applying other inspection technologies to the entire bridge, such as laser scanning, sonic tomography, or ground-penetrating radar is not applicable as there is no appropriate space for equipment installation and operation. Thus, conducting a UAV-based inspection is preferred in this experiment because UAVs can not only eliminate the effects caused by geometric constraints but also provide information about the bridge from different perspectives (Fig. 1).

3.2 Implementation of RTK

The DJI Phantom 4 RTK and D-RTK 2 station were used in the experiment to achieve better UAV positioning performance. RTK [23] is known as Real Time Kinematics, a technique for correcting GNSS (Global Navigation Satellite System) errors. The accuracy of RTK is measured in centimeters compared to the positioning accuracy of GPS (Global Positioning System), which is measured in meters. In general, the location of an object is computed by calculating the distance from satellites to the GNSS receiver. The distance is related to the speed of the travelling signal and is often accompanied by a delay caused by the Earth's atmosphere. These delays will induce computational errors in signal propagation, so GNSS receivers cannot provide data with better than meter-level accuracy. In RTK, there are two receivers: one is the static station fixed at a specific location, and another is the rover responsible for data collection. In this paper, rover refers to the DJI Phantom 4 drone. In addition, the RTK station can be replaced by an NTRIP (Networked Transport of RTCM via Internet Protocol) service in certain scenarios. The GNSS errors can be eliminated when two receivers in close proximity because signals observed by the two receivers

Fig. 1 Tai Tam Stone Bridge

can be treated as identical. Furthermore, to achieve centimeter-level accuracy, RTK uses carrier phase measurement to resolve the integer ambiguity problem. Carrier phase measurement is an advanced technique for calculating the phase of the signal wavelength; the distance between the satellite and the GNSS receiver can be determined accurately. In the experiment, owing to the high real-time precision of RTK, the data acquisition is relatively safe and facilitates the post-processing of data. In addition, the 3D reconstruction accuracy using SfM is further promised (Fig. 2).

3.3 Dataset and Operational System

In this paper, around 11,200 images from several public datasets [24–29] were used, and all images were resized to 448 × 448. A total of 271 labeled images of the Tai Tam Stone Bridge taken by UAVs were utilized to test the proposed method. In practice, the model will have good performance if the image contains only cracks and a pure background. However, detecting cracks and other defects is intricate in reality as different objects will appear in the same image. To improve the robustness of the proposed method, the images involved in the training include the categories:

- Pure cracks;
- Cracks with moss;
- Cracks with blocky surfaces;

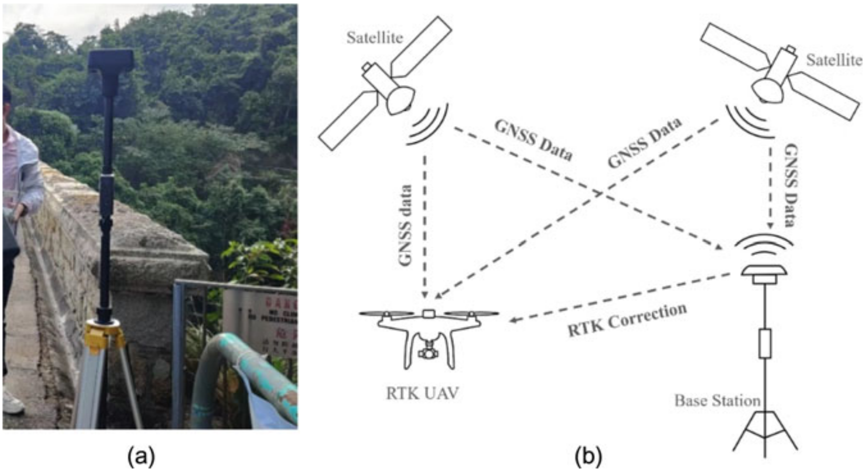

Fig. 2 **a** D-RTK 2 mobile station **b** working principle of RTK

- Cracks in a large context.

The experiment is conducted in an environment of Intel Core i7-6700 CPU @ 3.4 GHz × 8, and an NVIDIA GeForce GTX 1070 GPU. It is clear that the operating system used in this research is generic, which demonstrates the universality of the proposed approach, as its replication cost is affordable.

4 Result and Discussion

The results obtained from the two proposed models are shown in Table 3. The IoU and Dice coefficients of UNet_VGG16 are 0.4727 and 0.6012, while for UNet_ResNet_101, the values of IoU and Dice are 0.3792 and 0.5021. Apparently, the combination of U-Net with transfer learning of VGG16 is outperforming the U-Net with ResNet_101. Examples of detection results are shown in Fig. 3. The outcomes indicate that the proposed methodology can significantly localize the cracks in the images. A model based on SfM has been created to provide a comprehensive view of the Tai Tam Stone Bridge. Figure 4 shows the geometric bridge model, which is reconstructed using the software "ContextCapture" from Bentley. As shown in the figure, the reconstructed model with the aid of RTK is rich in detail. According to the detection results and the information observed from the 3D model, the health condition of the Tai Tam Stone Bridge is evaluated as level 2. The bridge has experienced mild deterioration and can still undertake loads from vehicles and pedestrians. Some cracked areas, such as the main road of the Tai Tam Stone Bridge, require to be examined in detail. The following inspection can be carried out by NDT methods, such as chain dragging and

Table 3 Performance of the proposed models

Model	IoU	Dice
UNet_VGG16	0.4727	0.6012
UNet_ResNet_101	0.3792	0.5021

hammer sounding to identify the delamination areas under the cracks by listening to the sounds produced by vibrations.

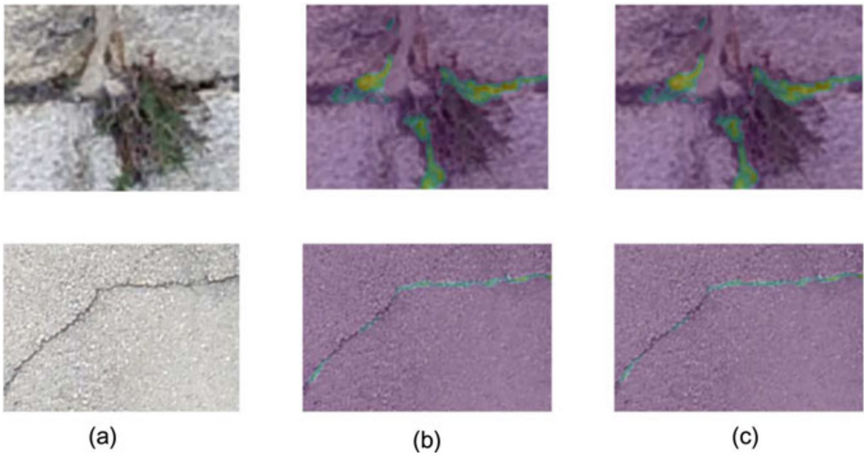

Fig. 3 Example of detection results for bridge flank wall and deck images **a** original images **b** detection results obtained by UNet_VGG16 **c** detection results obtained by UNet_ResNet_101

Fig. 4 3D model of Tai Tam Stone Bridge

Essentially, datasets in this research contain cracks in different occasions and backgrounds to achieve the goal of generalization, but the concomitant is a decline in the algorithm performance. Another concern regarding the model performance is that the cracks with different backgrounds are not evenly distributed in the training dataset. Last but not least, a problem revealed in this research is the lack of ancient bridge images for training purposes. In future studies, the research direction could be focused on developing a model capable of detecting multiple defects with higher accuracy. Correspondingly, it requires more data to facilitate more robust predictive performance to better solve the ancient bridge inspection problem. Collecting more images of ancient bridges and building relevant datasets is of great significance for the future image-based maintenance of ancient bridges.

In this experiment, it is noteworthy that UNet_VGG16 outperforms UNet_ResNet_101, which is against common cognitions. Theoretically, the deeper or more complex the network, the better the model performance. As the transfer learning part of the model, ResNet_101 is expected to conquer VGG16 because ResNet_101 has 101 layers, while VGG16 contains only 16 layers. Additionally, ResNet (Residual Network) has been proven to surpass VGG in many image detection studies because it solved the problem of gradient vanishing and exploding by introducing the shortcut connection, whereas plain networks such as VGG always suffer from such problems. However, the application of more advanced techniques does not make a model perform better to some specific problems. Most deep learning models are developed to solve problems observed in previous models, which cannot be simply inferred that it will appear to work well on other occasions. Moreover, the detection process is performed by U-Net, and the impact that transfer learning brings to the performance of the final model is elusive. Thus, it is not impossible for UNet_VGG16 to outperform UNet_ResNet_101.

5 Conclusion

This paper proposes an integrated method using UAV images for ancient bridge maintenance. A criterion for the health condition of ancient bridges is established, and corresponding measures are suggested for each health status. An ancient stone bridge in Tai Tam Tuk Reservoir was chosen for the experiment. As a reservoir surrounds the bridge and the inspection truck is not available to enter, employing UAVs has become the primary option for the inspection. Defects on the bridge were segmented using U-Net with transfer learning of VGG16 and ResNet_101. The results indicate that the performance of UNet_VGG16 is better than the combination of U-Net with ResNet101. To improve the inspection performance, RTK was introduced in the experiment to enhance the localization accuracy. Additionally, based on the SfM, a 3D model is generated using UAV images to further monitor the target bridge. With the obtained detection results and 3D model, the health condition of the ancient bridge can be eventually assessed.

In summary, the proposed methodology can provide useful guides to ancient bridge maintenance. The UAV image-based inspection is considered beneficial in ancient bridge inspection regarding automation, flexibility, and inspection deliverability. In future research, by enhancing the detection model and acquiring more ancient bridge images, UAV image detection can become more sophisticated and thus can be expected to serve as a universal solution for the maintenance of ancient bridges.

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Leveraging AI and IoT for Improved Management of Educational Buildings

Ashvin Manga and Christopher Allen

Abstract As countries around the world gradually return to life before the Covid-19 pandemic, it is important for facility management divisions across education sectors to use innovative technology and unique solutions to provide healthy and safe learning environments. This research aimed to improve the management of educational buildings by leveraging innovative technologies. The first objective was to develop a system for real-time occupancy levels within lecture venues. To achieve this, a branch of artificial intelligence known as computer vision was combined with existing CCTV cameras to count occupants in real-time. This was achieved by training a convoluted neural network on a dataset of 15 000 images of 'human bodies' extracted from Googles Open Images v6. The second objective was to measure indoor air quality. A medical grade air quality device was placed within the assessed lecture venues and real-time occupant count was correlated against real-time indoor air quality data. The results from this study demonstrate the successful use of computer vision combined with existing CCTV cameras to accurately count occupants in real-time. The study utilised open-source AI resources and provides a method for further computer vision research. Regarding indoor air quality within the assessed educational buildings, the results of this study indicate that even under significantly reduced occupancy levels, carbon dioxide accumulated within assessed venues, indicating inadequate ventilation. The Covid-19 pandemic will not be the last pandemic we encounter. However, facility management can utilise innovative technologies to ensure educational buildings are managed using data-driven strategies that ensure learning environments remain safe and accessible spaces for students.

Keywords Computer vision · Indoor air quality · Educational buildings

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1 Introduction

The Covid-19 Pandemic has emphasised that indoor air quality must be actively managed to ensure safe indoor environments [12]. Educational buildings are spaces where students and lecturers spend extended periods of time and are therefore high-risk environments for airborne transmission of SARS-CoV2 [13]. Humancentric designed and managed education buildings, that provide thermal comfort and clean air, are fundamental for providing education and promoting the learning process [14]. Education buildings are often characterised by infrequent interventions for building maintenance and environmental remediation [9].

Insufficient indoor air quality may lead to illness, student absenteeism, loss of concentration, drowsiness and tiredness, as well as adverse health symptoms, such as respiratory problems or headache, and decreased academic performance [1]. This study aimed to improve the management of educational buildings by leveraging two innovative technologies artificial intelligence and Internet of Things (IoT) devices. The study used lecture venues at Nelson Mandela University as a case study to test the effectiveness of a custom computer vision model that utilised existing CCTV cameras within lecture venues to count occupants in real-time. The study also evaluated indoor air quality of lecture venues by using a medical grade IoT device. For each assessed venue real-time occupancy and indoor quality data was correlated.

2 Literature Review

2.1 Indoor Air Quality in Learning Environments

Humancentric designed and managed education buildings, that provide thermal comfort and clean air, are fundamental for providing education and promoting the learning process [14]. Today human beings spend 90% of their lifetime in an indoor space [14]. It is estimated that students spend 70% of their daytime in classrooms making it is the second most important indoor space after their homes [15]. IAQ in schools continues to be identified as one of the most critical factors affecting students' health [3, 5] and academic performance [8].

The quality of the classroom environment a significant impact on a student's learning process and performance and affects students' physical and mental well-being [10]. Students are exposed to numerous indoor air pollutants in classrooms, the source of which can be existing outside and inside (Asif and Zeeshan 2020). Education buildings are often characterised by infrequent interventions for building maintenance and environmental remediation [9]. Indoor air quality (IAQ) in school buildings is characterised by various pollutants, such as volatile organic compounds (VOCs), aldehydes, particulate matter (PM2.5 and PM10), fungi and bacteria [9].

IAQ may lead to illness, student absenteeism, loss of concentration, drowsiness and tiredness, as well as adverse health symptoms, such as respiratory problems or headache, and decreased academic performance [1]. To ensure minimum ventilation rate to guarantee air quality conditions in educational buildings, ASHRAE Standard 62.1 (2010) sets the minimum ventilation rate for schools to 5 l/s per person, UK standards between 8 and 9 l/s per person Spanish regulation between 12.5 and 20 l/s per person, French regulation between 4.2 and 5 l/s per person; and Portuguese regulation between 6.6 and 7.7 l/s [1]. During experiments conducted by [16] carbon dioxide concentration at the beginning of classes in all analysed classrooms was below 1000 ppm, as recommended, however at the end of classes recorded CO_2 level was between 1070 and 1506 ppm.

2.2 Importance of Building Occupancy

Occupant behaviour is recognised as a key factor contributing to the amount of energy a building consumes thus making it difficult to predict building energy [7]. There are several solutions being used for occupancy detection and estimation. Motion sensors, Wi-Fi based, smart meters, camera sensors. However, the field of artificial intelligence is rapidly being explored as a technology that can enable HVAC systems to perform at optimised levels [7]. The actual energy performance of a building is significantly impacted by the building occupants. Using technology advancements to affordably collect occupant data from the building environment is crucial for the efficient use of energy in a building [17].

Energy consumption within buildings includes the following main categories heating, ventilating and air conditioning (HVAC) and lighting systems [18]. Globally, the building sector is responsible for nearly 36% of the final energy consumption and close to 40% of total direct and indirect CO_2 emissions [17]. The role of the built environment in the in preventing a climate crisis is improving the energy efficiency in buildings however, there is insufficient data on the factors that determine energy use to meaningfully improve energy efficiency in buildings [19]. Designed versus actual total energy are often significantly different and the reason for this is the poorly understood role of human behaviour rather than the building design.

Collecting data to improve building operation and occupant behaviour is said to be the next frontier in sustainable design [20]. Improvements to data collection processes, the accuracy of individual sensors, and the data obtained, has led to progress in the areas of (i) occupant movement and presence, (ii) thermal comfort, (iii) windows, shades and blinds and, (iv) lighting and electrical equipment [20]. Historically, occupants would have a direct connection to (and control of) the sources for building control, for example, heating (e.g., fireplace) and ventilation (e.g., operable window). However, for public buildings and buildings such as tertiary education buildings the control of heat and ventilation is not controlled by the occupants but by the building management system. It is therefore critical that the built environment obtain accurate occupant data to ensure healthy buildings. This widening gap between building systems and occupants can remove real or perceived control over building systems, often at the detriment of occupant satisfaction, productivity, and comfort [21].

2.3 Artificial Intelligence

In May 2017, Google unveiled AutoML, an automated machine learning system that could create an artificial intelligence solution without the assistance of a human engineer [22]. The field of artificial intelligence is improving faster than experts expected and there are calls for immediate AI regulation by the likes of Elon Musk [23]. As seen in Fig. 1, the history of AI is filled with significant milestones achieved. In 2016, a historic AI moment took place as AlphaGo, an AI by Deepmind, beat Lee Sedol 4-1 in the game Go.

AI currently encompasses a vast variety of subfields, from the general (learning and perception) to the specific, such as playing chess, proving mathematical theorems, writing poetry, driving a car on a crowded street, and diagnosing diseases [27].

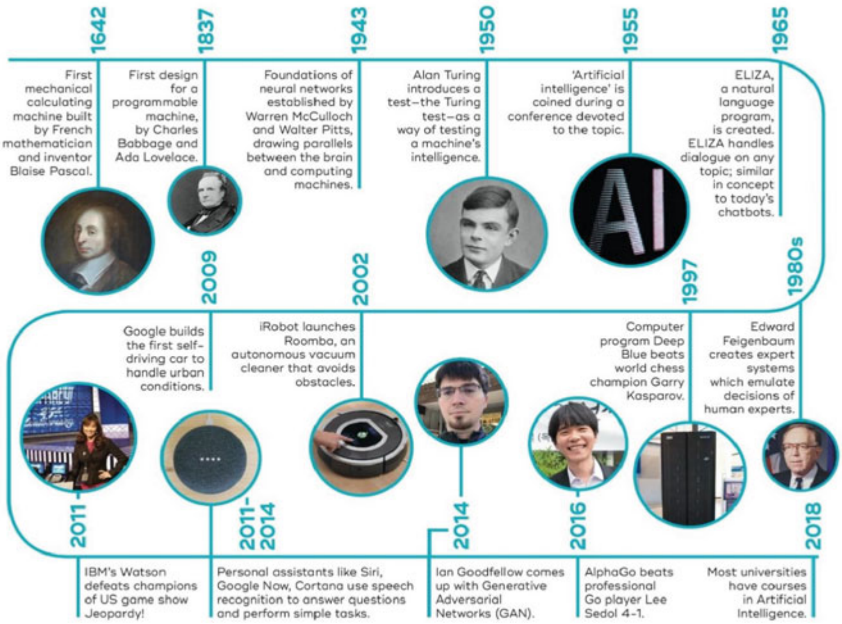

Fig. 1 A visual history of AI

2.4 Computer Vision and Construction

Computer vision is an interdisciplinary scientific field that focuses on how computers can acquire a high-level understanding from digital images or videos [11]. Object detection is fundamental to computer vision, as its aim is to identify an object's semantic features and locations contained within images. Image classification is a critical task in computer vision, as it is used to identify an object that appears in an image [24]. Computer vision can be used to transform tasks of engineering and management in construction by enabling the acquisition, processing, analysis of digital images, and the extraction of high-dimensional data from the real world to produce information to improve decision-making.

Computer vision has been used to examine specific issues in construction such as tracking people's movement, progress monitoring, productivity analysis, health and safety monitoring, and postural ergonomic assessment [11]. The cost of visual sensors has decreased significantly, together with the availability of robust visual systems, the integration of computer vision in industrial environments has grown exponentially in the last decades in a broad range of sectors, such as retail, security, automotive, healthcare, and agriculture. In the construction industry, computer vision has received attention as it can be used for the automation of critical tasks that require continuous object recognition, identification, monitoring behaviour and location estimation [25]. The cost of visual sensors has decreased significantly, together with the availability of robust visual systems, the integration of computer vision in industrial environments has grown exponentially in the last decades in a broad range of sectors, such as retail, security, automotive, healthcare, and agriculture. In the construction industry, computer vision has received attention as it can be used for the automation of critical tasks that require continuous object recognition, identification, monitoring behaviour and location estimation [25].

A journal paper by [11] provided a mapping of computer vision research within the construction industry. The conclusions from the study indicated that the use cases for computer vision in the construction industry are safety monitoring, performance monitoring, materials estimation, and defect detection. Computer vision has steadily increased within the construction research sector with a strong upward trend illustrated by Fig. 2 sourced from [11].

3 Research Methodology

The overarching aim of this research was to investigate how computer vision can be used to extract data from CCTV video data for improved management of facilities. This section outlines the experimental design that was used to investigate the relationship between indoor air quality and occupancy in lecture venues. The research used a quantitative case study methodology. Lecture venues at Nelson Mandela University

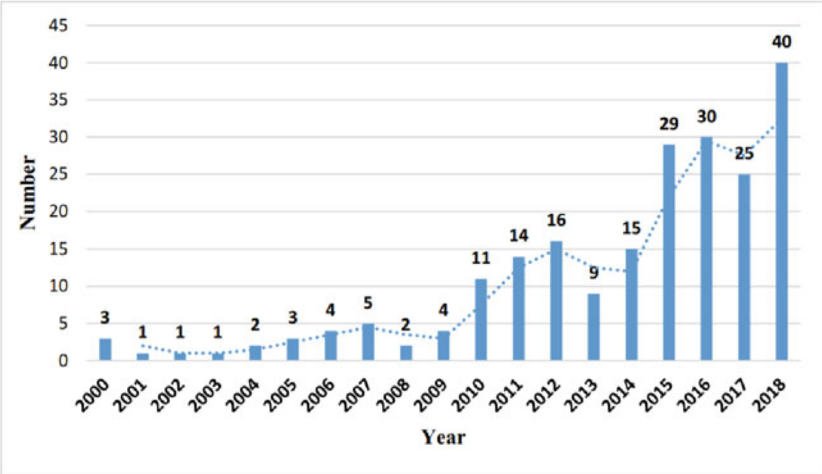

Fig. 2 Increase in Computer vision research papers over 18 years

North and South Campus were used as a case study to collect numerical data on the indoor air quality and number of occupants during lectures.

Two primary data sets were collected to achieve the research objectives and test the hypotheses stated in chapter one. The first computer vision data set was created by analysing CCTV camera images from lecture venues at Nelson Mandela University. The CCTV camera images were analysed with a computer vision model that counts the number of people in images and videos. The number of people detected in each analysed image is recorded to a.csv file. The second indoor air quality dataset was created using an indoor air quality monitor that was placed within lecture venues at Nelson Mandela University. The research methodology is summarised by Fig. 3.

4 The Results

4.1 Indoor Air Quality Results

The carbon dioxide results were obtained from 7 exam sessions that took place in three different lecture venues, two mechanically ventilated venues and one naturally ventilated venue. The ventilation system in the mechanically ventilated venues operated at full capacity. The duration of the air quality data collection for each exam session was one hour and thirty minutes. Table 1 indicates the type of ventilation used during the exam session, the carbon dioxide level at the start and at the end of each session, the number of occupants and the change percentage of carbon dioxide. The naturally ventilated venue performed the best, remaining at healthy carbon dioxide levels for the duration of the exam session. Session 2 and 7 had the largest change

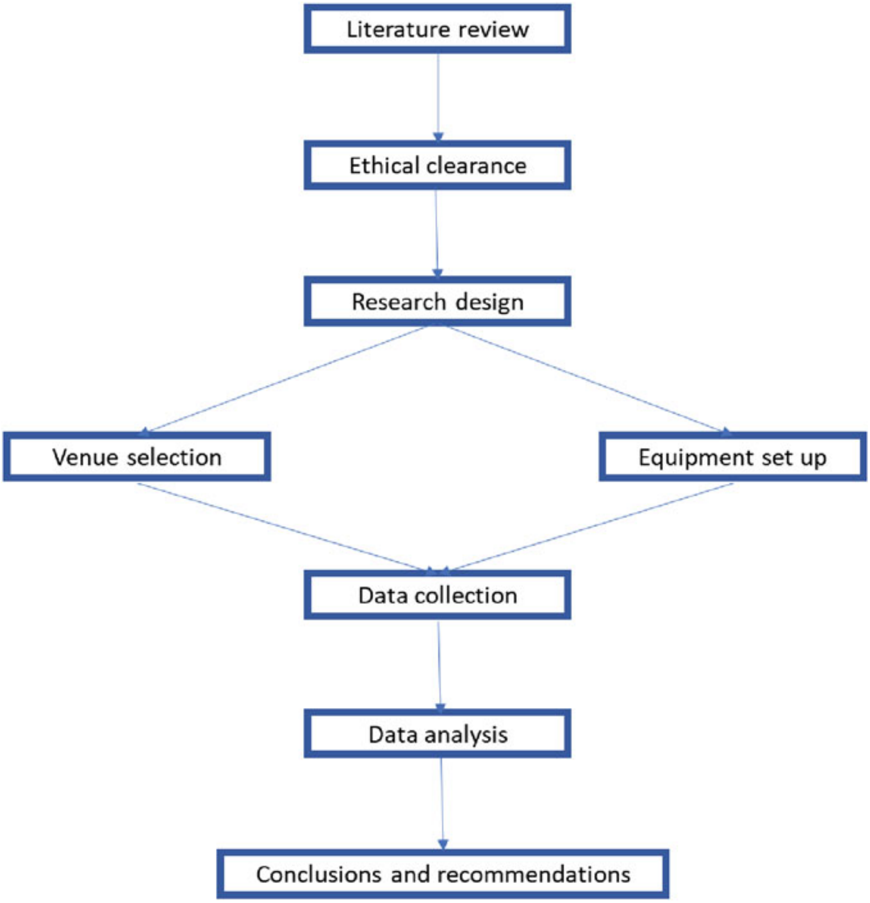

Fig. 3 Summary of the Research methodology

percentage and ended with carbon dioxide levels above 700 ppm. Session 4 took place immediately after another exam session. The venue had accumulated carbon dioxide from the preceding exam session and remained above 700 ppm for the duration of the exam session included in this study in which indoor air quality was captured.

Figure 4 provides a bar graph of the start and end carbon dioxide levels within the measured venues. Even under dramatically reduced occupancy levels 2, 4 and 7 ended exceeding 700 ppm. Exam sessions 1, 2 and 3 was held in the same venue (288 0010, North Campus, Nelson Mandela University). Each session was 1 and a half hours in length and the HVAC system operated on maximum. The only variable between the internal conditions of exam sessions 1, 2 and 3 was the number of occupants. From the actual data set a simulated data set was created that simulated carbon dioxide levels with 50 occupants. The results are indicated in Fig. 5. The simulated results indicate significant non-compliance in the performance of the ventilation

Table 1 Carbon dioxide results

Exam session	Type of ventilation	Carbon dioxide level (ppm)		No. of occupants	Change percentage in CO_2
Session 1	HVAC full	Start	430	4	26%
		End	542		
Session 2	HVAC full	Start	430	14	75%
		End	751		
Session 3	HVAC full	Start	443	4	15%
		End	509		
Session 4	HVAC full	Start	730	8	5%
		End	770		
Session 5	HVAC full	Start	485	6	20%
		End	584		
Session 6	Natural	Start	419	12	13%
		End	472		
Session 7	NO HVAC	Start	578	22	76%
		End	1020		

system with carbon dioxide levels reaching well over 1000 ppm. An indoor environment exceeding 1000 ppm places any student undertaking an examination at a physiological disadvantage.

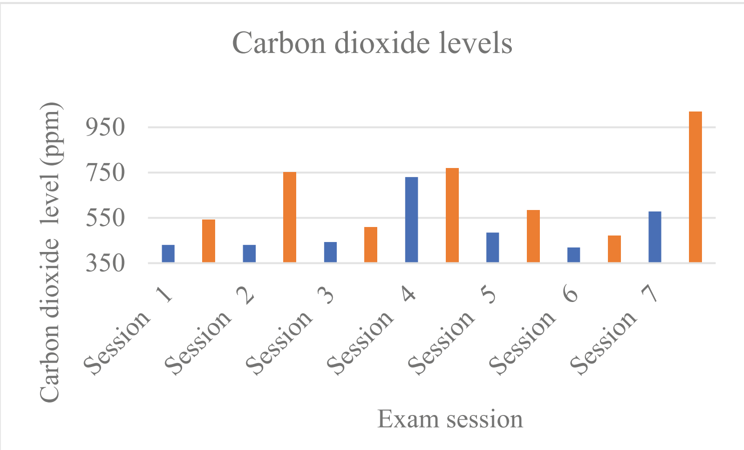

Fig. 4 Carbon dioxide results

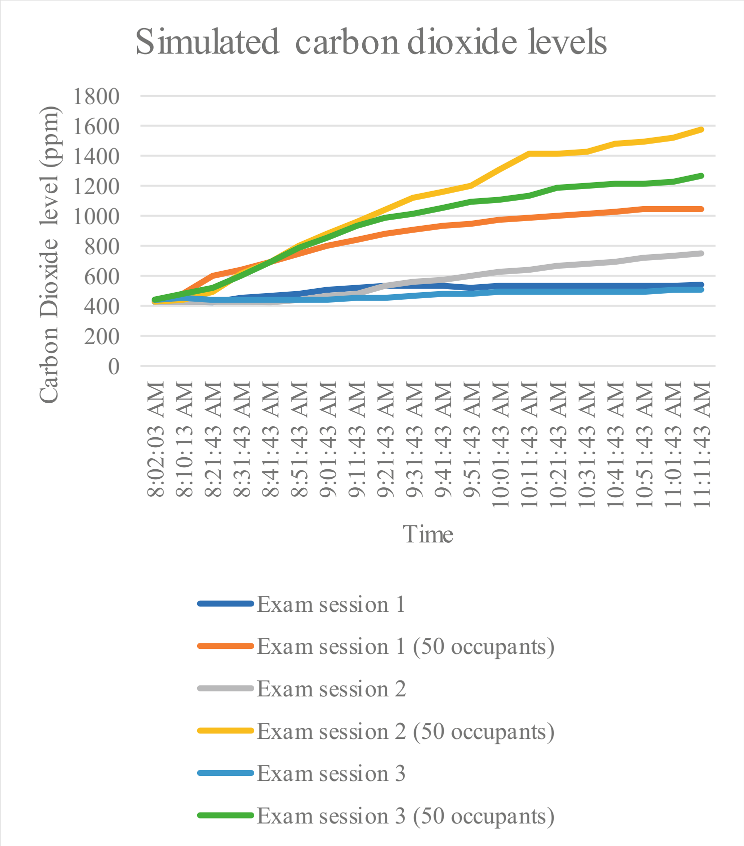

Fig. 5 Simulated carbon dioxide levels for venue 288 0010

4.2 Computer Vision Results

The purpose of this dataset was to evaluate if computer vision can be used to count occupants from existing CCTV cameras installed in lecture venues. The results in this section are from a comparison between a custom YOLOv4. weights file and the pre-trained YOLOv4.weights file available online. By comparing a custom trained model and the YOLOv4 pre-trained model a better evaluation of the CCTV data's potential to be used for occupant count was undertaken. Table 2 is an overview of the results obtained from the detections generated from the pre-trained and custom YOLOv4 weights. The pre-trained and custom detections are benchmarked against a manual counting of occupants from the test images. The average confidence for the detections is also displayed in Table 2.

The most notable findings are indicated in Fig. 6 and 7. Figure 6 indicates the impact CCTV location has on occupancy detection accuracy. Figure 7 displays the

Table 2 Overview of CV accuracy

	Image 1			Image 2		
	Pretrained	Custom	Actual	Pretrained	Custom	Actual
Number of occupants detected	18	8	33	0	1	8
Detection divided by actual	55%	24%		0%	13%	
	Image 3			Image 4		
	Pretrained	Custom	Actual	Pretrained	Custom	Actual
Number of occupants detected	18	25	26	7	5	14
Detection divided by actual	69%	96%		50%	36%	
	Image 5			Image 6		
	Pretrained	Custom	Actual	Pretrained	Custom	Actual
Number of occupants detected	8	7	11	32	17	57
Detection divided by actual	73%	64%		56%	30%	
	Image 7			Image 8		
	Pretrained	Custom	Actual	Pretrained	Custom	Actual
Number of occupants detected	19	123	125	27	19	47
Detection divided by actual	15%	98%		57%	40%	

impact changes in light level has on occupancy detection accuracy. The detection results in Fig. 7 which are generated from this study illustrate how a slight change in the light level of the venue reduced the accuracy of the computer vision model. The top image detected 11/11 (100%) occupants while the bottom image detected 2/11 (18%).

4.3 *Summary of the Results*

The results indicate that computer vision technology has a significant potential to be utilised within construction management and facility management. Although the results produced scattered results, when the computer application performed, it performed with high accuracy. The computer vision model's failings can be improved with further training.

The results from this study indicate that lecture venues do not perform as designed. This study collected air quality data under the Covid-19 level 5 lockdown. The lecture venues assessed were drastically under occupied during the air quality assessment and air quality metrics were not healthy. Furthermore, when the actual data was used to extrapolate lecture venue air quality with 50 occupants, the simulation results indicate carbon dioxide levels in venues exceed 1000 ppm in under an hour with 50 occupants, less than 50% of the lecture venues design capacity.

Fig. 6 Impact of CCTV camera location

5 Discussion

It is no secret that the built environment sector has been slow to adopt new technologies [2]. However, the potential benefit to dramatically improve the management and operation of all built environment assets has increased owners' interest in procuring technology solutions. This research thus set out to better understand the potential use of one of these new technologies, computer vision applications, to inform the body of knowledge in relation to their use for the management of facilities. Nelson Mandela University was used as a case study location for this research, with the intention to understand how computer vision can be used, in conjunction with existing lecture venue CCTV cameras, to improve indoor air quality management of these venues.

From a university facility management standpoint, autonomously counting the number of occupants within lecture rooms has two major benefits that radically improve the management of the facility's venues. The first benefit is derived from using real-time lecture venue occupancy data to optimise the HVAC system for both efficiency and to provide a healthy learning environment for students. Indoor air quality (IAQ) in learning environments continues to be identified as a critical factor affecting students' health [3, 5] and academic performance [8]. The quality of the classroom environment has a significant impact on a student's learning process and

Fig. 7 Impact of CCTV camera location

performance affecting students' physical and mental wellbeing [10]. Insufficient IAQ may lead to illness, student absenteeism, loss of concentration, drowsiness and tiredness, as well as adverse health symptoms, such as respiratory problems or headache, and decreased academic performance [1]. To ensure minimum ventilation rates that guarantee air quality conditions in educational buildings, ASHRAE Standard 62.1 (2010) sets the minimum ventilation rate for schools to 5 L/s per person, UK standards between 8 and 9 L/s per person, Spanish regulation between 12.5 and 20 L/s per person, French regulation between 4.2 and 5 L/s per person; and Portuguese regulation between 6.6 and 7.7 L/s [1].

In South Africa, SANS 10,400-O states that educational buildings must provide 7.5 L/s (litres per second) of fresh outdoor air per person (SANS 10,400-O:2011: 17). The South African national standard is well adjusted when reviewing guidelines stated by governments from around the world. Meeting the ventilation requirements stated in the SANS 10,400-O document, as highlighted in this chapter, remain a challenge due to inadequate compliance in the initial design and more importantly, during operation of the ventilation system. Notably, all the minimum ventilation rates reviewed are in litres of air per person per second. Therefore, accurate occupancy data is essential for maintaining these indoor ventilation requirements. In a lecture facility or learning facility environment, knowing the number of occupants is critical for efficient ventilation management and measuring IAQ is important to further ensure healthy indoor air quality.

This research was conducted during the Covid-19 Pandemic which resulted in the Nelson Mandela University campus being closed for most of the 2020 academic year. As a small number of examinations required an on-campus traditional assessment the researcher managed to collect lecture venue air quality data from 7 examination sessions across 3 different lecture venues. It must be noted that during the examination sessions, the venues were on average at 10% of their design capacity. With all 3 venues designed to accommodate over 100 students. Exam session 1, 3, 4, 5 and 6 had 14 or less students during the entire exam session.

With that said, the carbon dioxide levels in the venue at the start of the session were lower than the carbon dioxide levels at the end of the session with carbon dioxide levels steadily rising. Lecture venue 7 had 22 students and the increase in carbon dioxide is significantly higher than lecture venue 2 which had 14 students. In all the mechanically ventilated exam sessions the ventilation system did not respond to an increase in occupancy. The increase in CO_2 within these venues is alarming, with lecture venue 7 reaching more than 1000 ppm, at a time when less than 40% of the design capacity is present, essentially rendering lecture venue 7 an unhealthy learning environment.

There is a significant opportunity to improve the ventilation management of lecture venues. The ventilation strategy that was implemented at the time of this research was to leave the ventilation system across lecture venues in operation as staff members did not want to be held responsible for the operation of the ventilation system. One can ask the question, in the context of a university, should the staff member presenting within the venue be responsible for ensuring the lecture venue is healthy or is it the responsibility of the facility manager. Interestingly the only venue in which carbon dioxide levels remained consistently within the healthy range was the exam venue that was naturally ventilated only. Figure 8 indicates the carbon dioxide levels for the duration of the 4-h exam.

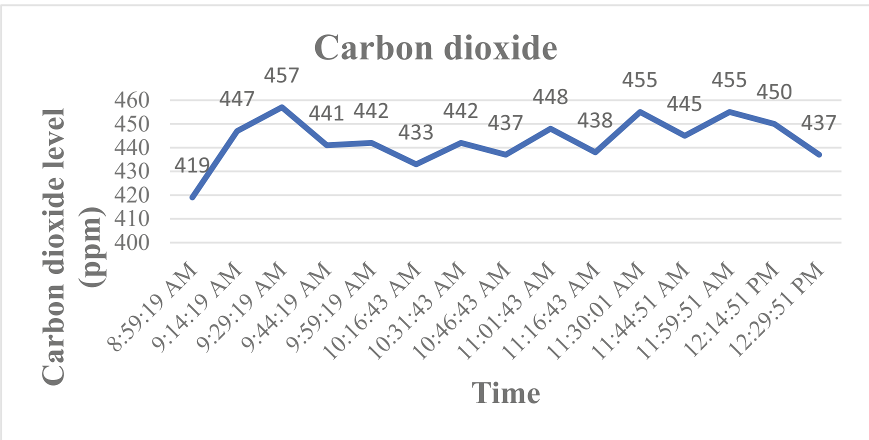

Fig. 8 Naturally ventilated venue performance over 4 hours

5.1 Carbon Dioxide Levels from Exam Session 6 (Natural Ventilation)

The effectiveness of natural ventilation within Port Elizabeth concurs with research conducted by Manga (2020) in which natural ventilation was used to improve office indoor air quality. Furthermore, during this naturally ventilated exam session, the particulate matter concentrations did not exceed 12 $\mu g/m^3$ for PM2.5 and 14 $\mu g/m^3$ for PM10. The U.S. Environmental Protection Agency states that indoor PM10 concentrations should not exceed 150 ($\mu g/m^3$) and PM2.5 should not exceed 35 ($\mu g/m^3$) [4].

There is a significant opportunity to optimise mechanical ventilation systems to be dynamic and provide fresh air based on real-time occupancy. The amount of fresh air 5 occupants and 10 occupants require is substantially different. Therefore, it makes sense that mechanical ventilation systems require real-time occupant data to function effectively, and computer vision is a promising solution.

6 Conclusions

Leveraging existing CCTV lecture venue cameras produced scattered results. The accuracy of the custom trained computer vision model ranged from detecting 98% of all occupants present within a venue to 13% of occupants detected. However, the results indicate a significant potential for an improved occupancy detection system that uses computer vision as the detection mechanism. Accurate occupancy data from a lecture venue provides unique advantages for a university. Occupancy data can be used to optimise lecture venue HVAC systems and ensure that fresh air is provided efficiently for the number of occupants. As lecture venues are used on a scheduling system, occupant count can be used along with additional existing data sets such as the number of registered students per module and which module is scheduled to use the venue. These three datasets can now be leveraged for autonomous module attendance and performance. The results from this study show real potential for computer vision to be used as a method of collecting previously inaccessible building usage data through artificial intelligence.

There is a significant need for improvement in the indoor air quality and the management of indoor air quality within lecture venues at Nelson Mandela University. The indoor air quality results from this study were obtained under the Covid-19 Pandemic and South Africa was under one of the hardest lockdowns in the world. The two mechanically ventilated lecture venues that were used in this study are recently constructed by Nelson Mandela University and were used at 30% of their design capacity. Considering the significantly reduced occupancy levels, the mechanically ventilated lecture venues did not perform as expected. The results indicate that a mechanically ventilated lecture venue which is designed for 100 students and was occupied by a mere 14 students had a carbon dioxide level above 700 ppm at the end of an hour and a half exam session. Furthermore, the simulated carbon dioxide results created with actual air quality data indicate that new lecture venues are not performing to their design capacity. This is alarming and calls for further air quality study's to be conducted at Nelson Mandela University.

A notable aspect that must be highlighted with regards to the custom computer vision application used in this study. To create a computer vision model and achieve the results presented in this study, a computer with a modern high-specification graphics processing unit is required. As this research did not receive funding and was not able to purchase the hardware required to train computer vision models, the researcher explored free resources to create the custom computer vision model. Google Colab is a cloud computer that allows users access to advanced GPUs through the internet. The computer vision model used in this research was trained on Google Colab's free online GPU. It is noteworthy that the development of advanced artificially intelligent applications is available to the public for free. There is an extraordinary amount of free AI resources available through the internet and organisations need to embark on skills development programs to train their employees to utilise this powerful resource.

Every single business in the next decade will have to implement artificial intelligence to process data and provide business insights or consumer services. This will be driven by the massive return on investment for implementing artificial intelligence (AI) and competition from businesses that leverage AI. A great example of this is the Full Self Driving (FSD) technology developed by Tesla. FSD will allow a fleet of autonomous taxis that will compete extensively with Uber and potentially disrupt the ride-sharing industry to such an extent that Uber will be made redundant [6].

It is recommended that digitally useful data is collected within your organisation. In the context of facility management, for a university to leverage AI for space utilisation and optimisation of lecture venues, a dataset generated from onsite camera data will provide the most accurate results. The data used to train any deep learning model has a direct impact on the performance of the model. In the context of this research, the computer vision applications performance would have been improved if the training dataset were produced from Nelson Mandela University's historical camera data from lecture venues and not generic images from the internet.

It seems useful for our indoor spaces to understand the needs of the occupant. Computer vision is a technology that can provide previously unobtainable building usage data for improved building management and performance. Occupant detection is only the first step in the learning process for an artificially intelligent building management system. The video data collected from a multi-tenant office building over one year is a large enough data set for a facility manager to extrapolate countless insights that will improve the performance and management of the building. Computer vision opens the door to a personalised indoor environment that changes as different occupants enter the space. Buildings are dynamic and need to perform in the interests of occupant health and happiness. Camera-based sensors and computer vision provide an opportunity to optimise lighting and ventilation requirements in a building based on real-time occupancy data. With such accurate real-time occupant data, HVAC and lighting optimisation will provide an opportunity for buildings to meet their energy requirements with onsite solar and storage.

The design of future buildings should be inclusive of the sensors deployed for the management of the building. The dynamic world of a commercial building's indoor environment makes it difficult to use a single sensor. Computer vision is software, and this allows any building management system that uses computer vision to improve over time with software updates. Based on this fundamental factor, camera-based sensors and computer vision is perhaps the best approach to a scalable artificially intelligent building management system.

7 Recommendations

For lecture venues, camera-based and computer vision occupancy detection systems are recommended. This recommendation concurs with [26] in that artificial intelligence and camera data is the best methodology for occupant detection. As indoor air quality has such a significant impact on learning. It is recommended that all learning environments have indoor air quality monitors as a key quality indicator for indoor air quality. This is especially critical for facilities that primarily provide education for children or provide care for the elderly [9].

An additional critical reason as to why camera-based and computer vision building management systems are recommended is that developments in computer vision can then be easily leveraged by your building management system. Leveraging existing lecture venue CCTV cameras must be evaluated before implementation. It is recommended that CCTV camera location and computer vision applications are considered in the design stage of a building both for the management of the internal and external environment of the building.

It is recommended that facility management firms that wish to leverage artificial intelligence begin collecting and creating labelled visual datasets that can be used to train computer vision models. This recommendation concurs with a research paper presented by [11] that mapped computer vision research over 18 years and concluded that there is a lack of adequately sized databases for training computer vision models and noted that issues associated with data privacy were a concern. The final recommendation from this research is that there is an extraordinary amount of open-source and free artificial intelligence resources available on the internet. This powerful resource should be leveraged by organisations. There is no reason to wait, AI skills development must occur today within organisations.

In terms of future research, this master's dissertation provides alarming air quality data that indicate a need for air quality studies to be conducted at Nelson Mandela University to ensure lecture venues are safe. Teaching and learning are changing dramatically with Covid-19 restrictions. However, Nelson Mandela University and all Universities have a significant investment in spaces designed for teaching and learning. There is no reason these spaces cannot be used safely, however is a need for real time data both for air quality and occupancy.

Natural ventilation can be used to provide healthy indoor environments, especially in Port Elizabeth with our favourable climatic conditions. There is need for research in the development of retrofitted actuators that turn manual existing windows into self-actuating smart windows that leverage automation and sensors to improve energy efficiency and occupant satisfaction in lecture venues.

There is a need for further computer vision applications to be developed both in the fields of construction management and facility management. Computer vision is growing rapidly and requires significant further research to ensure the built environment sector leverages artificial intelligence.

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Factors Affecting Maintenance Management of Public Buildings in South Africa

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Abstract Government buildings, similar to any other structure, require regular maintenance to retain the original and ensure that they perform their functions. Building maintenance is separated into two areas building maintenance management and building maintenance technology. Building maintenance management must be looked at precisely as unfolding how a system of maintenance initiative might be planned to deal with a building maintenance problem. There are a few factors that influence the decision to accomplish the maintenance work. The study focused on assessing a few selected factors affecting public building maintenance based on user perspective in order to develop an effective public building maintenance strategy.

A survey will be undertaken based on previous literature among building maintenance professionals. The research will enhance the body of knowledge about factors affecting maintenance management of public buildings.

Keywords Maintenance · Management · Strategies · Buildings

1 Introduction

Building maintenance is an important program for ensuring the long-term suitability of infrastructure development [12]. Maintenance is defined as "any actions taken to keep an item in, or restore it to, an acceptable condition". [7] defines maintenance as "the methods and procedures used to maintain, restore, prevent, and care for a building fabric and engineering services after finalisation, restore, renovating, or

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renewal to current standards to allow it to represent its desired purpose throughout its entire lifespan without drastically upsetting its basic features and use."

It is public knowledge that the main objective of building maintenance is to keep buildings in their original functional, structural, and aesthetic states [2]. The absence of proper building maintenance policies affects the early aging of component durability performance, as well as the impact of global costs and maintenance operations, which may lead to significant malfunction consequences and a reduction in life span [8]. The goal of maintenance is to extend the life of the building, reduce costs, and increase its value (Masengesho et al. [9]). The goal of maintenance is to extend the life of the building, reduce costs, and increase its value.

The service life of any building is affected by many factors including the appropriateness of the design, construction details, and construction methods. It also varies based on how the building is utilized as well as the maintenance policies and procedures in place throughout its life span (Masengesho et al. [9]).

Given the importance of maintenance on new and old buildings, South Africa in particular, there are still some alarming factors encountered towards maintenance development. If these barriers are not resolved quicker, the buildings will begin to deteriorate.

As a result, the utmost goal of this study is to thoroughly and comprehensively evaluate factors affecting the maintenance management of public buildings in South African.

2 Factors Affecting Maintenance Management of Public Buildings in South Africa

South Africa's public buildings are facing numerous challenges that have a direct impact on the state of the buildings. Existing research has discovered that there are factors that are said to affect the performance of maintenance of the South African construction industry. Thus, the factors affecting the performance of the South African construction industry will be extensively outlined and discussed in this study.

According to [13], these five major factors affecting public building maintenance are: a lack of preventive maintenance, insufficient funds allocated for building maintenance, a lack of a building maintenance standard, a lack of spare parts and components, and a lack of response to maintenance requests. [12], wrote that the most influential factor in residential building maintenance is a lack of building maintenance funding. In a study by [4] it was discovered that some of the factors causing poor public building maintenance are building age, lack of funding, a lack of a maintenance culture, high maintenance costs, pressure from a number of users on the building, and poor construction and maintenance work performed by maintenance personnel in the organization.

Meanwhile [2] discovered 12 factors influencing building maintenance strength, including design decision, structural strength, material strength, maintenance manual, safety measures, environmental factors, maintenance stations, quality control factors, usage factors, skill maintenance personnel, and post-construction strength protection. Understanding the factors that influence maintenance procedures and identifying which are the most significant influence is critical for managing such factors as a preliminary move toward improving maintenance procedures.

2.1 Lack of Preventive Maintenance

Preventive maintenance is defined as action based on a specific timetable that identifies, avoids or mitigates the decay of component or framework state so in order to maintain or expand its life by means of controlled corruption to an adequate level. According to preventive maintenance is maintenance that is carried out regularly. A lack of preventive building maintenance usually causes buildings to deteriorate to the point of breakdown or demolition. According to the building owner claims that the maintenance strategies used are unproductive and that they have ceased to enhance the building purpose and system installed.

On the other hand, according to South African National Roads Agency Limited (Sanral) engineering executive Louw Kannemeyer, the most notable contribution to the worsening of the South African road network is a lack of preventive maintenance.

While [1] stated that preventive maintenance does not carry out according to a schedule where it does requires, daily, weekly, monthly and yearly inspection as the maintenance team are busy performing the emergency breakdown maintenance. As the facility or building ages, preventive maintenance and emergency repair requirements are expected to emerge, so preventive maintenance is critical. (Szuba [11]) argue that a good maintenance plan is established on preventive maintenance.

2.2 Insufficient Funds Allocated for Building Maintenance

Stated that there is a need to increase the maintenance budget because the allocation of maintenance work is always below the needs and requirements. Further stated that an inadequate budget for maintenance works will cause a delay in performing the maintenance works because covering the needs for maintenance requires high costs. Lack of funds can lead to inefficient, ineffective, or even dangerous maintenance practices, such as keeping parts in service far beyond their service life, utilizing lower priced suppliers, making temporary repairs, or asking inappropriately skilled tradespeople to make repairs. According to the budget allocation for maintenance works influences the quality of maintenance work performed.

2.3 Lack of a Building Maintenance Standard

Maintenance standards are heavily influenced by available maintenance resources, as well as common factors such as building, tenant, technical, administrative, and political factors. According [14] organizations have different understandings of the appropriate maintenance standard, that could be higher or lower than the original standard, depending on how much maintenance resources are accepted. The baseline objective is to meet the minimum standards. An argument has been made by different organisations on the acceptance of standards.

The dispute stems from maintenance policies, and the allocation of maintenance resources varies by organization. When compared to the original standard, organizations with adequate maintenance resources have a higher maintenance standard [14]. On the other hand, organizations with narrow or even insufficient maintenance resources face challenges in restoring a building facility to its original condition while still meeting minimum standards.

2.4 Lack of Spare Parts and Components

Maintenance personnel make decisions as to which maintenance strategies to apply in a building based on the availability of maintenance resources. According to [14], although the maintenance strategies implemented are intended to improve a building's sustainability, they have been neglected due to limited spare parts. Furthermore, according to [1], it is difficult to find suitable spare parts in the local market, particularly for an old system or machine.

This exacerbates the maintenance process because spare parts must be acquired from the external market. The practice of buying spares from the outside market raises cost of maintenance while also delaying the maintenance process [1]. Furthermore, the worst-case scenario is that the entire maintenance and building operation will be halted due to a lack of spare parts.

2.5 Lack of Response to Maintenance Requests

In maintenance operations, it is critical for the maintenance worker to comprehend the maintenance requirement in order to guarantee the building occupants' ability to carry out their activities and business continuity [1]. According to the research conducted, most maintenance departments do not have an appropriate framework to strengthening maintenance operations. According to [10] this issue arose as a consequence of a lack of coordination between the executive team and the operational team.

2.6 Lack of a Maintenance Culture

(Suwaibatul et al. [5]) define maintenance culture as “the values, way of thinking, behaviour, perception, and underlying assumptions of any person, group, or society that regards maintenance as a matter of importance (priority) and practices it in their daily lives.” The concept of maintenance culture, according to is the innermost layer between management and staff in providing adequate maintenance through the exchange of ideas, beliefs, and values of each member in an organization. Establishing and adopting a maintenance culture through effective leadership, sound policy, and attitudinal development, among other things, would not only boost national development but also place our country among the developed nations [3].

2.7 Skilled Maintenance Personnel

According to the majority of maintenance personnel don’t really comprehend the operational and management framework in the maintenance program and depend excessively on technology. [1] discover that the most of maintenance workers employed by maintenance contractors are immigrant workers with varying levels of maintenance experience ranging from unskilled to skilled workers, with the majority being unskilled workers.

3 Conclusion

This study assess the factors affecting maintenance management of public buildings in South Africa. This study revealed that lack of preventive maintenance on public buildings has not been carried out as scheduled as a result, building start to deteriorate and breakdown. Whilest buildings are breaking down the is little hope of restoring them due to the fact that maintenance contractors employ unskilled personnel’s to conduct maintenance with foreign knowledge of maintenance. Furthermore, the is no proper framework to strengthen that respond to maintenance request. Buildings are left unattended as a result of lack of spare parts and lack of funding to maintain the building causing a serious deterioration and degenerating the standard of the building.

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Technological Innovation for Improving Energy and Water Consumption Efficiency and Sustainability on Government Buildings in South Africa: A Comprehensive Review of Literature

Evans Magaisa, Kathy Michell, and Alireza Moghayedi

Abstract Low operational efficiency and sustainability characterise South African government buildings, which partly emanates from lack of innovation in the South African public sector. As a result, inefficiency and lack of sustainability in the use of energy and water are major challenges, consequently affecting sustainability in buildings and causing detrimental effects to the environment. It is therefore imminent that the South African government adopts innovative technologies that ameliorate the public built environment. The goal of this paper is therefore to understand, from a critical review of literature, how harnessing technological innovation can improve operational efficiency and sustainability in energy use and water consumption in government buildings in South Africa. Careful selection of the most appropriate scholarly sources was done, which were then appraised to understand how the different latest technologies can be utilised and how they can be helpful in improving efficiency and sustainability in energy use and water consumption in buildings. The internet of things, digital twin, big data analytics and smart meters, were identified to be useful in improving efficiency and sustainability in energy and water consumption in buildings, whilst also improving indoor environmental quality. The result would be reducing the cost of energy and water management in South African Government buildings, and elimination of the energy and water crisis in South Africa, as well as minimisation of harm to the environment.

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Keywords Government buildings · Operational efficiency · South Africa · Sustainability · Technology

1 Introduction

South Africa is facing a water crisis that is caused by insufficient water infrastructure and its maintenance, recurrent droughts, which is negatively impacting economic growth as well as the wellbeing of South Africans [31]. Further, South Africa is also in the grip of an unprecedented energy crisis, characterised by inadequate electric power supply capacity by the ageing power stations, and low investment in new generating capacity [20]. Climate change and the ever-increasing population are also contributing to rising water and energy shortages in South Africa, resulting in rising pressure on the electricity and water grids, and therefore a need to adopt measures that minimise the energy required to meet the functional requirements and save energy significantly. In buildings, water and energy are the world's two most important resources [7]. Water is used for drinking, landscaping, in restrooms, heating and cooling. Buildings use electricity as a source of energy to provide thermal comfort, lighting, communication and entertainment to building occupants [16]. [19] and [5] concur that the operation and maintenance of buildings is characterized by massive consumption of energy and water, which are the most critical natural resources in the world, thereby consequently significantly contributing to harm to the environment. The increase in energy and water demand in buildings partly emanates from a continuous rise in the number of people occupying buildings, which consequently results in overexploitation of natural resources and damage to the environment, depletion of the ozone layer and global warming [27]. [2] agree that population growth and economic development are driving the demand for energy and freshwater globally, which tends to outstrip the accessible supply capacity in the near future. [11] further note that demographic growth in a context marked by urbanisation and economic development strain conventional energy and water resources in the world, leading to energy and water scarcity, which are the most important challenges to human health and environmental integrity in the world. There should therefore be emphasis on the adoption of measures that negate the detrimental effects of increasing demand for energy and water, and climate change.

The challenges to energy and water expenditure in buildings are also existent in the South African government buildings, in which the building stock is old and at the same time poorly operated and maintained [10]. Despite the fact that the South African government owns the largest property management portfolio in the country, [9] notes a backlog in sustainability and green building, and operational efficiency, resulting in major problems of energy and water consumption efficiency. The Department of Public Works and Infrastructure therefore aims to reduce water consumption in government buildings, which will resultantly see significant savings in government expenditure [10]. For the South African government buildings, it is therefore also necessary to propose the implementation of efforts to conserve energy and water, and to improve sustainable performance of energy and water consumption systems [21]. Beyond the traditional pattern of building operations, [28] note that massive numbers of technologies are blooming to satisfy the requirements of building owners and occupants sustainably. In spite of being a key driver for competitive management of buildings [1], technological innovation has not yet been sufficiently adopted in the context of South African buildings, making it one of the reasons for the need for transformation in the management of government buildings South Africa. However, while it is imperative to improve on the energy and water efficiency of buildings, it is important to do so whilst preserving thermal comfort conditions and therefore sustainability of buildings. This paper therefore seeks to understand, through a comprehensive review of literature, how latest technologies can sustainably improve efficiency and sustainability in energy and water consumption in South African government buildings.

2 Methodology

In this study, the literature review was used as an end in itself, to inform practice and provide a comprehensive understanding of energy and water consumption efficiency and sustainability in buildings. While year of publication, language and type of article are among the criteria that was used to determine the relevance of the primary, secondary and tertiary sources for inclusion and exclusion in the study, more emphasis was put on logical and valid motives to answer the research question. A problem centered approach was used to carefully select primary and secondary data sources that are most suitable in proffering a solution to the problem of inefficient and unsustainable energy and water consumption systems in South African Government buildings [18]. A constructivist orientation was adopted, in which the researchers sought to accommodate new trends and insights from what is known, in a bid to improve energy and water efficiency and sustainability in buildings. A total of 24 reports and peer reviewed publications by recognized journals that discuss the use of innovative technologies in buildings were searched and accessed from relevant research websites using the internet.

3 Discussion

Literature emphasises the importance of the role played by technology on improving energy and water efficiency in buildings. From the existing literature, the role of the following, carefully selected, latest technologies in improving energy and water efficiency and sustainability in buildings are discussed as follows:

The Internet of Things. The internet of things is a network of physical devices and objects embedded with electronics, software, sensors, and network connectivity which enable these objects to collect and exchange data and communicate with one another in order to determine the health and status of things [13]. The emergence of IoT has brought dramatic changes to the management of buildings to enhance operational efficiency and sustainability. IoT helps in collecting real time information for tracking the location of users and objects, processing and analysing the conditions of facilities and suggesting specific solutions as well as predicting the risk status of facilities [3]. Employees of government buildings can obtain real time information on the conditions of facilities transmitted wirelessly to their devices such as smartphones, personal computers and laptops to improve work performance, enhance the management of facilities and improve the quality of life among employees and citizens [3]. IoT is a key component in improving efficiency and sustainability in energy and water management in buildings. It is leading the physical and digital world of technology to converge. Sensors with batteries are installed in buildings, which relay the information to building energy management systems thereby allowing the deployment of solutions to control energy and identify actions that would introduce savings and reduce costs [16].

Applications of IoT are rapidly being utilised in buildings and cities to improve efficiency and sustainability in energy consumption [4]. The internet of things provides an energy consumption monitoring system that allows the understanding of energy and water consumption patterns, thereby allowing the identification of energy equipment with the most consumption rates [16]. IoT can monitor the indoor environment and activate energy building services to respond to user needs thereby saving energy and maintaining good indoor environmental conditions [4]. IoT sensors provide feedback which provides information about energy consumption in a certain period of time, thereby resulting in energy savings [16].

Big Data Analytics. Big data and big data analytics are critical for future competitive advantage and success in many organisations [21]. Big data generally refers to the data that exceeds the typical storage, processing and computing capacity of conventional databases and data analysis techniques [23]. Big data is high-volume, high-velocity and high-variety information assets that are collected using social media platforms or existing unclassified data that demand cost-effective, innovative forms of information processing for enhanced insight and decision making. Big Data includes petabytes (1024 terabytes) or exabytes (1024 petabytes) of information that make up billions or trillions of records of millions of people and all from different sources (Internet, sales, contact center, social networks, mobile devices). As a rule, information is poorly structured and often incomplete and inaccessible. The availability of data in large amounts is important in making right decisions and supporting the making of useful strategies [23]. Big data analytics enable automation of maintenance activities and energy management and offers remote monitoring of a facility's condition [15]. Continuous monitoring and recording of asset information through sensors and prediction engines provides a solid database and digital trail that can be used as evidence of performance of energy and water equipment in buildings [15]. A truly smart building should incorporate systems that safe energy saving and environmental friendliness and also incorporate situational awareness to proactively respond to the presence of people and adapt to changing circumstances using actuators and devices that control engineering systems such as ventilation, air-conditioning, heating and lighting. It is imperative to ensure that the sensors and actuators that collect the data from the many rooms of the building are accurate in order to ensure integrity and reliability of the system. Real time and massive scale connections produce large, versatile amounts of data, which are diverse sets of information with dimensions that go beyond the capabilities of widely used database management systems. Big data enables the leveraging of the huge amounts of data provided by the internet of things-based ecosystems in order to reveal insights to be able to explain, expose and predict knowledge from them.

In energy and water management in buildings, big data analytics is used to adjust and control energy and water supply into the building according to the number of people in the building at any given moment. Big data analytics is an intelligent energy saving system that enables building systems to operate flexibly based on the user comfort preferences and performance changing features. Big data analytics combines the architectural management system with intelligent data analysis software that provides useful information for repair, service and operational opportunities. Big data also aids in making the right decisions on the type and model of equipment to buy on the reliability, performance and operational efficiency perspectives.

Digital Twin. A digital twin is a set of computer-generated models that representing physical objects [27]. Digital twin is a virtual representation of construction objects, built and civil engineering assets, a portfolio of assets and the physical environment within which these entities interact and the synchronisation between the virtual and the physical [26]. It is a connected, virtual replica of the physical, built assets. Digital twins are an important component of building assets, which transform the physical world of building assets into an intelligent, virtual form of data elements [32]. A digital twin is a system in which a representation of a physical system is used continuously by being fed with data and deriving outputs in the form of decisions [24]. Using a digital twin, facility managers are able to grasp the status of the whole building and receive timely facility diagnosis and operation suggestions that are automatically sent back from the digital building to reality [22].

Digital twins provide an opportunity to monitor existing buildings and monitor existing buildings and further their energy efficiency [14]. Models are used which are integrated into a generic control algorithm that uses data on whether forecasts, current and planned occupancy as well as current state of the controlled environment to control energy efficiency and occupant comfort basing on predictions [8]. Dedicated and pervasive sensors are used to gather information on the occupancy behaviour in buildings, on the occupancy presence, counts and location [8]. The information from the sensors is then fed into the digital twin system for processing. Using the zone control application, energy efficiency that is greater than that achieved using default operation is achieved [8].

Smart Meters. Smart meters provide instantaneous, accumulative metering information to the service providers on for the purposes of reduction of costs, energy and water consumption and emission of carbon dioxide [33]. Smart water meters result in water and cost savings, and also assist in detection of leaks and rapid water consumption [2]. Smart energy meters are designed for online data collection and the measuring of energy consumption behaviours of users.

Smart water meters are an essential component of clean water management, which is also an essential element of healthy and sustainable development [6]. While traditional water meters read manually in monthly or yearly intervals, smart water meters read consumption in real time or near real time and communicate the information to the utility and the customer [2]. Smart water meters are compatible with the internet of things through flow sensors to offer a cost effective solution for water resource management [6]. Smart water meters increase time efficiency and adequacy since bills are delivered timeously and more accurately [18].

4 Discussion

There is no literature that provides evidence of any significant, positive adoption of above discussed technologies in South African government buildings. While all the technologies can improve sustainability and efficiency in energy and water consumption in buildings, however, in South Africa, it can be deduced that they have not as yet been sufficiently utilised. [18] note that South Africa still relies on analogue and manual meter reading systems to manage energy and water usage and supply, which are labour intensive and often inaccurate since they lag in time and/or are estimates based on historical data. However, the interest and need for increasing the role of the above technologies in the built environment is undoubted [12]. [19] concur that the benefits of adopting technological innovation in buildings surely outweigh the barriers facing the pending adoption, being one of the sustainability issues facing the twenty-first century. The adoption of technological innovation can enable more efficient and sustainable facilities management and help support a safe and healthy environment [25]. The role of the above technologies in South African Government buildings is summarised in the Table 1:

Table 1 The technological innovations for energy and water efficiency and sustainability in buildings

Technology	Main purposes	Benefits
Internet of Things	1.To effectively monitor energy and water consumption in buildings 2.Information on energy and water consumption patterns 3.Monitoring of indoor environment and adjusting energy consumption	1.Real time information on water consumption will aid in timely decision making 2.Energy saving 3.Maintenance of quality indoor environment
Big data analytics	1.Large amounts of data to remotely monitor the building 2.Control energy and water supply to the building 3.Information on repair and service	1.Energy saving 2.Maintenance of building user comfort 3.Adequate repair and maintenance
Digital twin	1.Default control of energy efficiency 2.Forecasting building occupancy and adjusting water and energy use accordingly	1.Energy saving 2.Improving energy efficiency
Smart meters	1.Smart, centralised, real-time energy and water management solutions	1.Cost-effectiveness and time efficiency in energy and water management

5 Conclusions and Recommendations

The selected technological innovations from the literature are effective in improving water and energy efficiency and sustainability in buildings. The internet of things, digital twin, big data analytics and smart water meters are useful technologies in improving energy and water consumption in buildings. While they all improve efficiency and savings in use, they are also sustainable, being able to do so whilst maintaining building user comfort. Revamping South African government buildings with the above technologies is imminent so as to improve the efficiency in the use of energy and water in building. Combining the technologies will be more considerate to optimise the efficiency and sustainability in public buildings as they complement each other. The result will be savings in cost of maintenance of the building stock as well as improvement in the indoor environmental quality. The technologies will therefore go a long way in addressing the energy and crisis in South Africa. While this study was only reliant on existing literature, an in-depth case study approach is recommended in order to better understand the extent of the benefits that accrue from the use of the technologies in buildings.

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Big Data, Sensing, and Machine Learning

Lumped Approach to Recognize Types of Construction Defect from Text with Hand-Drawn Circles

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Abstract This study aims to improve the performance of optical character recognition (OCR), particularly in identifying printed Korean text marked by hand-drawn circles from images of construction defect tags. Despite advancements in mobile technologies, marking text on paper remains a prevalent practice. The typical approach for recognition in this context is to first detect the circles from the images and then identify the text entity within the region using OCR. Numerous OCR models have been developed to automatically identify various text types, but even a competition-winning multilingual model by Baek et al. does not perform well in recognizing circled Korean text, yielding a weighted F1 score of just 69%. The core idea of the lumped approach proposed in this study is to recognize circles and named entities as one instance. For this purpose, the YOLOv5 is fine tuned to detect 65 types of named entity overlapped with hand-drawn circles and yields a weighted F1 score of 94%, 25% higher than a typical approach using YOLOv5 for circle detection and a model by Baek et al. for subsequent OCR. This work thereby introduces a novel approach for developing advanced text information extraction methods and processing paper-based marked text in the construction industry.

Keywords Optical character recognition (OCR) · Circled text · Object detection · Information extraction

1 Introduction

Since paper-based communication is effective and affordable, it is still commonly used in daily life despite the advancements in mobile technologies and making marks on printed text is also a widespread practice. In the architecture, engineering, and construction (AEC) industry, this approach is often applied to highlight the status of

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a construction defect using a paper tag. Such paper tags are called defect tags, small sticky pieces of paper on which several named entities related to defects are printed. They are widely used on Korean construction sites, and circles are often drawn on them to quickly provide details about identified defects. Defect inspectors are employed to examine and pinpoint a volume of defects efficiently before occupants move in attaching and then taking pictures of these tags to send to site managers. Currently, managers manually check the circled entities in the collected images to process defect information. Since manual approaches are time consuming, labor intensive, and error prone, automating the extraction of these circled entities from the defect tag images is necessary. The goal of this research is to efficiently extract defect information from the tag images by recognizing named entities in Korean when marked by hand-drawn circles.

One possible solution is to use optical character recognition (OCR) technology which aims to automatically read text data from various images [1]. Although numerous OCR models have been developed, even a competition-winning approach by Baek et al. [2] failed to highlight and extract the printed Korean entities marked by hand-drawn circles from the defect tag images in the experiments, as shown in Fig. 1. Since no previous studies have looked at this specific task, a new approach needs to be developed to recognize Korean text with hand-drawn circles more accurately.

This study therefore proposes a lumped approach to improve the recognition of this kind of circled text. The method is ‘lumped’ approach because it recognizes the circles and named entities simultaneously. To validate the performance of the lumped approach, it is compared to a typical OCR approach that reflects the conventional concept of circled text recognition which isolates the circled text and identifies the characters within the detected region sequentially. In this study, the lumped approach

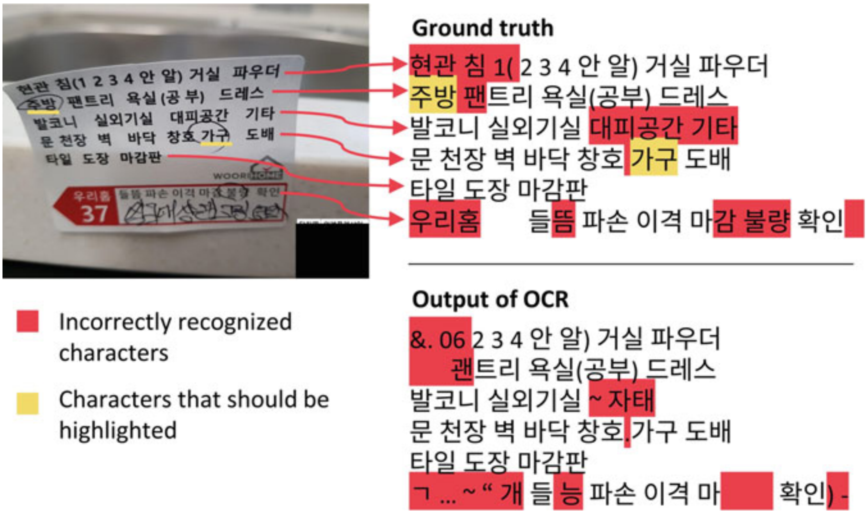

Fig. 1 Circled text recognition output using an existing OCR model

alternatively uses an object detection model to recognize the circled text while the typical OCR approach utilizes object detection and an existing OCR model for circle detection and text identification, respectively. Experiments are conducted to compare the weighted F1 scores of the two approaches with images of Korean defect tags.

The rest of the paper is organized as follows. Section 2 reviews the literature related to the topic of OCR, and the study's methods are introduced in Sect. 3. Section 4 provides detailed descriptions of the experiments, and Sect. 5 summarizes the results. Conclusions and future work are presented in Sect. 6.

2 Literature Review on Optical Character Recognition

Optical character recognition (OCR) models extract characters from images and convert them into computer-readable text. A typical OCR process consists of four key stages: image pre-processing, feature extraction, prediction, and post-processing. In pre-processing, the image quality is adjusted to improve the accuracy of recognition, and the skewed input images are transformed into a predefined rectangular shape. Subsequently, networks segment the characters in the normalized images and extract features from each one, with some models adding sequence features to consider contextual information. The prediction stage classifies the type of character and outputs a summation of the predictions. In the post-correction stage, natural language processing techniques based on context or lexicon are applied to maximize performance [2–4].

OCR models have been used in a wide range of applications, including invoice processing, legal and clinical document digitization, cyber security reinforcement using CAPTCHA [5], handwriting recognition, and so on [1]. The global market size of OCR technology was estimated at USD 8.93 billion in 2021 and is expected to grow rapidly until 2030 with a compound annual growth rate of 15% [6]. This shows that OCR technology is being both used and studied actively and, at the same time, is a promising area for further research.

Numerous OCR models have been developed that leverage various techniques, such as image thresholding, text line detection, character-level text segmentation, and chopping, to improve performance. Still, there are several challenges blocking OCR technology from achieving 100% accuracy, and existing OCR studies therefore aim to solve variations in language, poor image quality, and scene complexity [7]. To our knowledge, however, no research has yet explored the recognition of text intersected by marks that could confuse the OCR process.

A 'named entity' is a rigidly designated unit of information within a domain [8]. From this perspective, there is little previous research about extracting named entities from non-digitized documents [9–11], and what does exist focuses on filtering entities from messy OCR output rather than on improving the performance of the OCR model itself. The models employed recognize text by character, not entity. Therefore, this research proposes to recognize text with a specific graphical characteristic, namely overlapping hand-drawn circles, based on named entities.

3 Research Method

Figure 2 illustrates the concept of each approach, to be compared by weighted F1 score. The first approach, a typical OCR method, is set as the baseline, with the lumped approach second. Weighted F1 scores are deployed as the performance evaluation metric because the distribution of named entities is significantly imbalanced. To offset this, the weighted F1 score is calculated by multiplying the F1 value by the number of instances of the class [12]. The proposed method aims to yield high performance by recognizing the majority of the circled text.

3.1 Typical OCR Approach

The typical OCR approach consists of two stages. First, any hand-drawn circles are detected by a fine-tuned YOLOv5 (you-only-look-once) [13]. YOLOv5 is selected because it has shown great performance in various studies [14–16], although it is focused on real-time detection [17]. The identified regions include not only the circles but also overlapped text so that enough text image data can be provided to the OCR model. To make YOLOv5 achieve this, training dataset should be annotated to include both circles and the corresponding named entities. Once hand-drawn circles are detected, the regions are cropped and saved as separate images.

In the second stage, the cropped images are fed into Naver Corporation OCR model by Baek et al. [2]. This model is chosen for this study primarily regarding Korean text because it won the multilingual competition at the authoritative ICDAR 2019 [18]. This model predicts text at character level and references contextual information, with a final output of sequences of characters. Here, the OCR model is fine tuned to recognize text in the cropped region.

3.2 Lumped Approach

The lumped approach detects circled named entities at once. It identifies entities within hand-drawn circles from the whole image, instead of just the named entities, the circles, or the circled characters. As previously outlined, a named entity is the unit of recognition in the lumped approach, unlike typical OCR models which recognize text at character level. In this study, a named entity is semantic text printed on defect tags around which inspectors draw circles and is confined to a pre-defined set. Since the possible combinations of characters are limited to named entities, absurd sequences of characters are removed and interference of markers can be mitigated. YOLOv5 is fine tuned for circled entity detection in the lumped approach, and each circled named entity is labelled as its type, for example, ‘bedroom’ or ‘floor’ and not just ‘circle’.

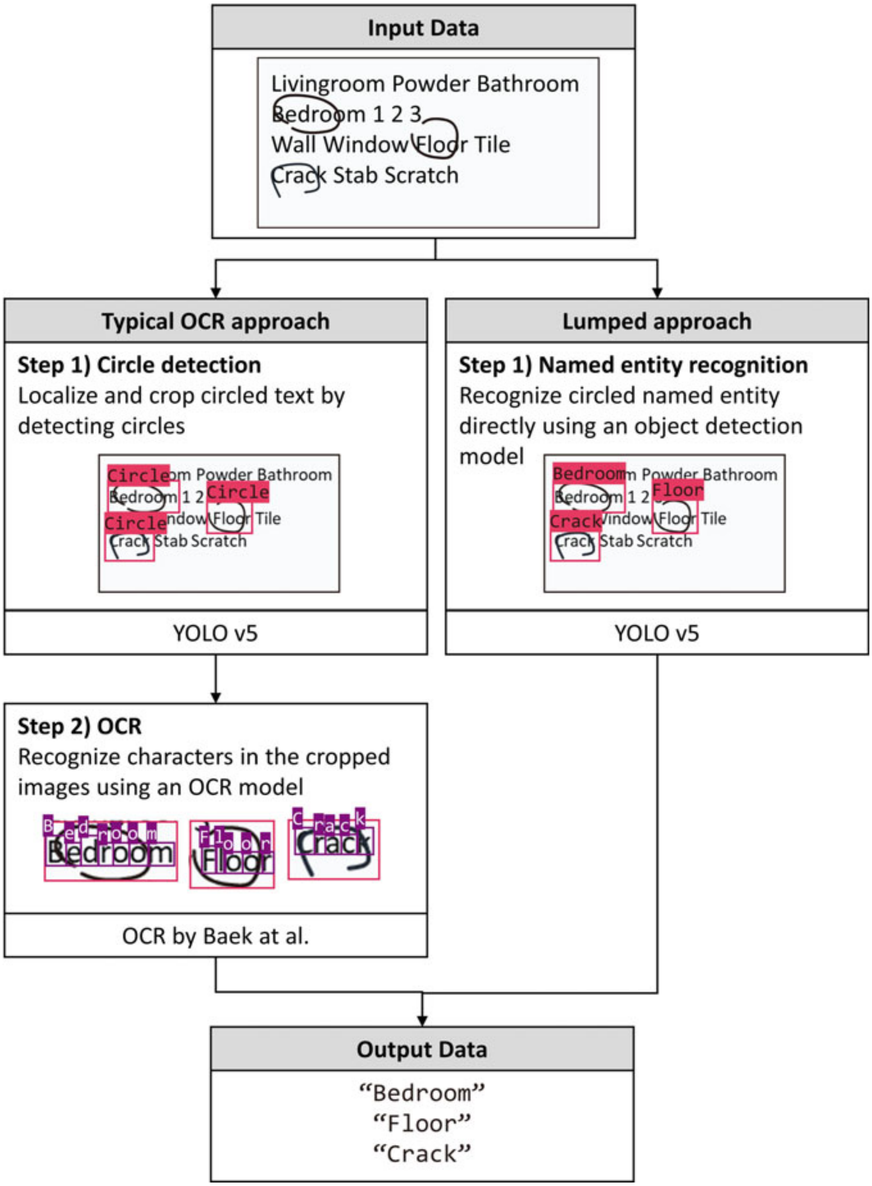

Fig. 2 The concept of each approach

4 Experiments

4.1 Datasets

The composition of the experimental data is shown in Table 1, with three types used: Korean defect tag images; cropped named entity images; and cropped book cover images. Examples of actual data are shown in Fig. 3.

The defect tag images are cluttered and skewed photos of the tags. In the collected 2,006 defect tags for training and validation, there are eleven types of defect tag, and each image can have none, one, or multiple circled named entities which comprise 65 classes. These images are used for both circle detection in the typical OCR approach and for circled named entity detection in the lumped method. Although the same data is used for the two tasks, the annotation method differs in that the circled text will be labelled 'circle' in the first but annotated as the corresponding named entity in the second. Following this rule, the whole images for training and validation are manually annotated by the authors.

For the typical OCR approach, the cropped named entity images are derived from the defect tag images. Once the original images are annotated, bounding box

Table 1 The compositions of data

Approach	Task	Data type	Train	Validation	Test	Total
Typical OCR	Circle detection	Korean defect tag images	1,577	429	40	2,046
	OCR	Cropped named entity images	5,243	1,527	158	6,928
		Cropped book cover images	20,620	3,782	0	24,402
		Total cropped images	25,863	5,309	158	31,330
Lumped	Circled named entity detection	Korean defect tag images	1,577	429	40	2,046

(a) Korean defect tag image (b) Cropped named entity image (c) Cropped book cover image

Fig. 3 Example of actual data

information of each circled named entity is obtained. When the defect tag images are cropped to this box, a cropped named entity image is generated.

Cropped Korean book cover images are also used to train the OCR model. Since the OCR model by Baek et al. opened in public only supports English [19], it needs to be additionally trained for Korean. For training, Korean book cover image dataset provided by AI HUB [20] is used. The dataset includes original book cover images and their Korean word annotation information. Following the annotation information, original book cover images are cropped. 24,402 cropped book cover images are used to train the OCR model.

4.2 Model Evaluation Details

YOLOv5 and the OCR model for three tasks are fine tuned in the same way: the whole layers are unfrozen and their parameters updated without adding any fully connected layers. Two models with the same YOLOv5 structure are trained for circle detection task and circled named entity detection task separately. For the YOLO models, batch size, image size, and number of epochs are set as 32, 416, and 300, respectively. The confidence threshold value is set as 0.45 for prediction. The OCR model is trained according to the following options: thin-place spline (TPS) transformation, residual neural network (ResNet), bidirectional long short-term memory (BiLSTM), and connectionist temporal classification (CTC). This combination of options is selected in consideration of performance and time costs, and 80,000 training iterations are used.

5 Results and Analysis

Precision, recall, F1 score, and weighted F1 score are obtained for each approach. In the typical OCR approach, the final score is a multiplication of performance of circle detection and OCR.

The results of the experiments are shown in Table 2. The lumped approach yields a higher weighted F1 score of 0.94 compared to the typical OCR method's score of 0.69, indicating the validity of the proposed approach. The poor performance of the typical OCR approach is mainly due to the exceptionally low weighted F1 score of the OCR at 0.70, while the circle detection phase obtains a weighted F1 score of 0.98. These results show that the proposed lumped approach can adapt to text that is overlapped with markers more effectively than the typical character-level approach of the OCR model.

Moreover, the weighted F1 score of the lumped approach shows significant improvement from its F1 score of 0.78. This implies that the proposed method is more effective at recognizing named entities with higher frequency. Although the F1 score of the lumped approach is lower than the weighted F1 score, the gap is only

Table 2 A comparison of the typical OCR and lumped approaches

	Typical OCR approach			Lumped approach	
	Circle detection	OCR	Final	Circled named entity detection	Final
Precision	0.97	0.31	0.30	0.94	0.94
Recall	0.99	0.26	0.26	0.77	0.77
F1 score	0.98	0.28	0.27	0.78	0.78
Weighted F1 score	0.98	0.70	0.69	0.94	0.94

about a third of that for the typical OCR approach. The gaps are 0.16 and 0.42 for the lumped and the typical OCR approach, respectively.

6 Conclusions

The study aimed to improve the efficiency of recognizing Korean text overlapped with hand-drawn circles in construction defect tags. Since an existing OCR model could not successfully handle circled text identification, a lumped approach was proposed that identifies the circled named entity at once. To evaluate the validity of the proposed method, experiments were conducted using Korean defect tag images with hand-drawn circles. The results showed that the lumped approach recognizes circled text more effectively, with a weighted F1 score of 0.94, than the typical OCR technique which yields a weighted F1 score of 0.69.

The proposed lumped approach overcomes the limitations of the typical OCR model by introducing a novel named entity-based marked text detection approach. The lumped approach may be especially effective in domain-specific projects given that the number of named entities in a single type of document would often be limited in that context. In addition, the proposed approach is expected to be useful in various applications closely connected to everyday life, such as health questionnaires and safety checklists. The lumped method is specifically advantageous to the AEC industry since its predominant small and medium-sized enterprises cannot quickly transform their work practices into up-to-date information technologies [21].

Although the proposed lumped approach achieved a high weighted Fl score, the method also has limitations as demonstrated in its relatively low F1 score. Moreover, this study only employed Korean character images with circles to evaluate the performance of the typical OCR model, and only YOLOv5 was tested for the object detection phase. Nevertheless, the experiments are valid given that recognizing Korean characters is known to have a lower accuracy than English. In future work, additional measures should be added to complement the F1 scores, and further experiments using other languages, mark shapes, and object detection models are necessary to verify the proposed approach.

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Requirements of Machine Learning and Semantic Enrichment for BIM-Based Automated Code Compliance Checking: A Focus Group Study

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Abstract Several regulations, standards, and requirements govern the lifecycle of the built environment. Such instances include legislations, government development control rules, environmental compliances, project and contractual requirements, and performance standards to be followed during construction. Compliance checking is a complex task that is often conducted manually, making it a resource-intensive, error-prone, and time-consuming affair. Past researchers have worked on methods and processes of automated compliance checking systems (ACCS); however, there has been a negligible adaptation in the industry. To this end, this study tries to recognize the reasons for the gap in the implementation of the pre-construction permit compliance systems in the Indian construction industry. The study understands the reasons from the end-user's perspective through the means of a focus group study. Key findings indicate manual pre-processing of data is a significant hurdle in Building Information Models (BIM) for application in ACCS. ACCS applications developed are restricted in their area of usage due to the limitation in applicability beyond explicit building code clauses. Rule-based validation of regulation requires enriched structured data, which is generally absent from the models developed by architects in the design phase. The study indicates the necessity of automated data pre-processing step that includes intelligent model filling suggestions and semantic enrichment to increase the adoption of ACCS. This study points out that automatic semantic enrichment (SE) can be achieved by applying machine learning (ML). Areas of application of SE in ACCS are identified in the study, which can enhance the industry's user experience and adaptation of ACCS.

Keywords Automated Code Compliance Checking · Semantic Enrichment · Machine Learning · Building Information Modeling · Focus Group Study

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1 Introduction

A construction project is controlled by various regulations and standards such as government development control regulations (DCR), legislations, contractual and project requirements, environmental compliances, and performance standards [1]. The verification of satisfactory performance of a project depends on compliance checking across phases. These processes require a plethora of data to be presented in a structured way for inspection. In a country like India, where more than 75 permits are required, the manual checking process is a time-consuming, error-prone affair [2]. Conventionally, at the pre-construction stage, an architect submits multiple, multi-domain CAD drawings to the urban local body (ULB) for scrutiny of the reviewers. A surge in usage of 2D drawing at this stage fails the idea of robustness to changes in the design stage itself. Further, If the drawings have failed to pass a particular permit, the cycle restarts from the architect redrafting all the drawings. Further, the construction industry involves multiple stakeholders throughout its project lifecycle. The information transfer across multiple phases and participants remains an area of concern. These problems establish the requirement of an object-oriented modeling approach like Building Information Modeling (BIM), where relations among building objects can be determined programmatically, and data can be stored in a virtual replica of a real-life project.

The process of verifying the regulatory requirements programmatically without manual intervention is termed an automatic compliance checking system (ACCS). Standardized information transfer models such as the industry foundation class (IFC), provide a structured data template for the application of ACCS [3]. Past researchers have developed several applications; however, there has been a negligible adaptation of the same in the industry. As an exception, Singapore's CORENET project is the sole ACCS that has been used in the official compliance process [1]. In the construction industry, where time and cost overruns are the major issues, it is critically important to analyze the gap between development and implementation. To achieve this, a focus group study was conducted with industry experts to understand the end user's perspective. The study outcomes indicate the areas of improvement and future research scopes in this domain to drive the ACCS adaptation in the Indian construction industry.

2 Literature Review

The idea of automated rule checking was first conceptualized by Fenves for structural design checks through the logic table in 1966 [4]. The next revolution in the ACCS domain came with the introduction of IFC as a bridge between CAD tools in DesignCheck [5]. Eastman envisioned the rule-based code compliance checking where manual interventions were required for improvement [6]. However, the manual scrutiny of permit compliance is a time-consuming and error-prone process [7]. In addition, the increase in the number of building codes and design complexity has significantly amplified the rules to be checked [8].

The guidelines for applying ACCS suggest using rule bases for compliance with standard open BIM formats. Further, the recommendation of aiding model authoring tools with model checking tools for identifying missing data implanted the requirement of semantic enrichment (SE) in the system [9]. SE in engineering is defined as a process of improving the existing information by adding another layer of data [10]. The real-world building problem can be represented in virtual rich representation by BIM. It provides element properties, attributes, relationships, and geometry through object-oriented classification [11]. However, lack of continuity and consistency across the codes and terminologies are prominent barriers to digitization. If regulation-specific object models are created depending on the existing rules, more than three hundred and fifty semantic classes will be required in IFC [12]. Therefore, a pre-processing layer is a must to make a BIM/IFC model sufficiently enriched with data for machine readability. When models are prepared for visualization and designing, enrichment levels are generally lower than regulation requirements [13].

There are three kinds of possible data types in BIM. Explicit data indicates the concepts of properties readily available in the model when exported [14]. However, a considerable amount of the information is inaccessible to other platforms as topological relationships of building elements are often kept implicit in the model. Humans can interpret these data by looking at drawings through their years of expertise; however, it is prone to subjectivity. Due to human error or ignorance, missing data can also be acknowledged in the same category. This implicit type of data restricts downstream analyses for ACCS and is required to be semantically enriched [15]. Lastly, Design data indicates concepts and properties that must be present but cannot be enriched. Changing or supplementing this kind of data will potentially impact the design's integrity [13]. However, these data can be supported through a generative design-based decision support system. This decision support system can work based on the architect's previous design decisions historically made in similar situations.

The semantic enrichment tasks can comprise creation, association, calculation, and classification depending on the requirement of clauses and regulations. These different tasks are solved through automation by applying different methods of artificial intelligence (AI) [16]. According to researchers, the learning, problem-solving, thinking, and decision-making aspect of automation can be termed AI [17]. The approaches of AI can be mainly classified into two categories, i.e., the behavioral aspect and the thought process. SE of the calculation tasks can be addressed through rule-based interpretation. On the other hand, the classification tasks are better suited for machine learning (ML)-based applications. Object-oriented modeling in BIM deals with AI's behavioral perspective, considering the objects' relations and properties. Since SE uses existing information to analyze, predict and draw new conclusions, it can be associated with the thought process [18]. Even though SE applications attain new facts through rule-interference unless the model starts learning problem-solving and decision-making, it is not entirely using AI's potential [17]. Expanding the full potential of ACCS through AI should be a layered approach. The research directions should be driven by end-user's requirements to generate higher applicability

Fig. 1 The steps involved in getting pre-construction permits from development authorities

and adaptability of the system in the industry. Such research directions of ACCS are explored in this study through brainstorming with domain experts in focus groups.

3 Methodology

According to Krueger [19], a focus group study is a planned discussion with a group of individuals unique in terms of purpose, composition, and size. It is conducted to gather data on a specific topic in a non-threatening, friendly environment, encouraging the participants to share perceptions and opinions without reaching a consensus. For this research on compliance checking for building permits, the focus group study was conducted with a group of twenty-seven architects and industry experts. The participants represented various age groups. Professional experience varied from 2 to 30 years with expertise in building, commercial, and industrial projects. All the participants had experience working with the ULBs, Mumbai Municipal Corporation, regarding building permits. Four focus groups were created with seven experts in three groups and six members in the fourth group. The study duration was two hours, including a final discussion session with all participants.

Figure 1 shows the steps involved in the pre-construction permit approval process. After the design is completed, the architect submits drawings for verification. However, the verification process requires standardized structured data, which is achieved through data pre-processing. Next, the proposed design is verified at the reviewer's end, and the plan gets approved on successful compliance with the government regulations. The focus group study contained three broad questions followed by sub-questions. The first question was designed to address the overall problem of the system as a whole. The following question focused on the two intermediate steps shown in Fig. 1. Figure 2 depicts the focus group questions that were asked to the participants, with the motives behind these questions.

4 Focus Group Study on Requirements of BIM-Based ACCS

In the first question, the participants were asked to identify the issues frequently encountered in the pre-construction permit process. The feedback gathered is illustrated in Table 1. The percentage occurrences column shows the number of times

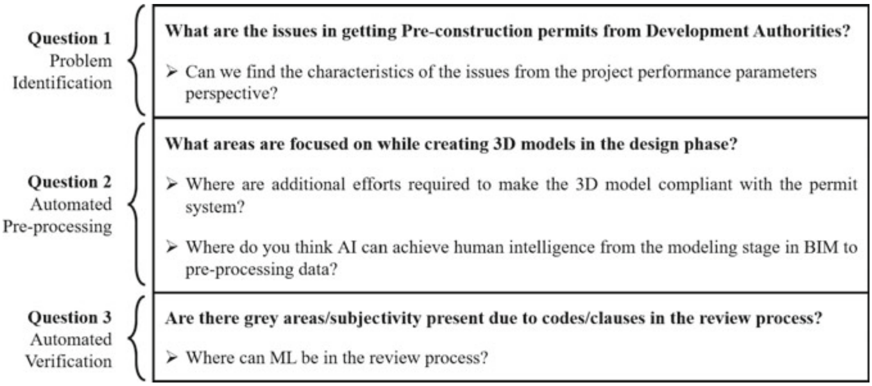

Fig. 2 The focus group study questions along with the theme of the questions

one issue appeared in the discussion across four focus groups. The results indicate maximum participants faced problems due to multiple no objection certificates (NOCs) in various departments. This practice delays the approval process, which consumes up to two months even for initial NOCs like Tree, Traffic, and Aviation. Further, there is no standardized documentation template, summing up a complicated approval process. The other indicated issues are regarding the variation of existing structures, roads, and city title survey (CTS) numbers surrounding the plot. Half of the participants also pointed out subjectivity present in the DCR clauses about deficiency calculation of floor-space index (FSI) and heights of open spaces. These pain points deduced reinforce the requirement of ACCS in the pre-construction permit approval. ACCS can help remove the non-transparent behavior of people through process development with the aid of technology.

The characteristics of issues were classified concerning the people, process, and technologies (PPT) framework [20] along with its impact on the project performance parameters (time, cost, and quality). Table 2 depicts the classification of issues by its Sr. No. from Table 1. The analysis demonstrates a significant impact of the issues on time and cost overruns.

The responses to the first question established the requirement of ACCS in the industry. However, to understand the bottlenecks of the current system, the second and third questions were targeted to understand the present workflow and the possible opportunities for automation in that system. The second question focused on the micro-level investigation of the current 3D modeling practice of the architects. The intentions behind the usage of BIM were summarized as visualization, presentation, understanding of obstacles, and design options. Therefore, it was evident that it is not a practice in the industry to prepare a model from the permit compliance standpoint. This difference in ideology in the development stage of the model increases the requirement of semantic enrichment before the application of automatic verification. The additional efforts required by architects for pre-processing data are listed in Table 3. The tasks identified by experts can be classified into four broad categories i.e., (i)

Table 1 Issues faced in the current pre-construction permit approval process

Sr. No	Issues	% Occurrences
1	Too many approvals and required NOCs	100
2	Multiple points of contact for NOCs make it a hassle	75
3	The manual scrutiny process, along with the online process, is time-consuming. Also, multiple follow-ups are required	100
4	Many documentations are required, and they are of different formats for different departments	75
5	A not user-friendly, complicated approval process	50
6	The submission and documentation procedures are not clear	50
7	The process is non-transparent	25
8	Scrutiny fees are not pre-decided	25
9	The submitted files are rejected without any proper comments	50
10	Open spaces deficiency and required height calculations	50
11	GIS does not work properly	25
12	Variation in CTS and the survey plan	50
13	The authenticity of the existing building, encroachment area, and road setback lines	25

Table 2 Characteristics of issues concerning people, process, and technologies framework

Issues	Time	Cost	Quality
People	2, 3, 4	2, 3, 4	
Process	1, 5, 6, 12	1, 5, 6, 7, 8	6, 7, 12
Technology	9, 10, 11	9, 10	11, 13

space detailing, tagging and area calculations, (ii) creation of surrounding elements, setback calculations, and plot boundaries, (iii) façade detailing and architectural projections, and (iv) the gap in BIM knowledge and implementation.

Once the additional pre-processing tasks were identified, the participants were asked where the SE process could be automated with aid from AI to ease the end-user's efforts. The ideas shared by experts can be classified into four directions, as illustrated in Fig. 3. The government system should produce a BIM-compliant site model with all easements marked, i.e., ease of access, services, sewage, and site surrounding restrictions. The surrounding 3D context, including the height and orientation of the existing building, should also be integrated through GIS-based digital twins to help the architects make design decisions. In another direction, the BIM model authoring tools can be supplemented with AI-aided add-ins, which can guide the designer with regulatory laws. Further, the system should be able to predict the impact of deviation made in the model in the verification stage. For example, the premium changes can be calculated depending on the basic FSI, and ancillary FSI used. However, if the design has crossed the permissible limits of ancillary FSI, the system can warn the designer about a potential rejection of the plan. The automated

Table 3 Manual SE tasks done to make model compliant with automatic design verification

Sr. No	Manual Semantic Enrichment Challenges	Classification of Challenges
1	Parking system and parking space detailing (i.e., mechanical pit parking, rotary parking, puzzle parking, etc.)	space detailing, tagging, and area calculations
2	Additional area diagrams for FSI calculation	
3	Manually tagging every habitable room on every floor as per DCR	
4	3D staircase and Ramp slope detailing	
5	A sloping site or contoured site needs 3D GIS integration	creation of surrounding elements, setback calculations, and plot boundaries
6	Plot boundaries and road setback lines	
7	Making of common amenities, trees of the exact size and exact location	
8	Creation of surrounding elements, existing and temporary structures	
9	Architectural projection, elevation treatments, and service ducts creation	façade detailing and architectural projections
10	Creating façade design, lighting, and claddings	
11	Handling overlapping clashes and warnings is difficult due to the unavailability of proper modeling guides	the gap in BIM knowledge and implementation
12	Detailing and drawings preparation according to each department's requirements	

tagging of spaces and computation of plinth area, FSI including double-height spaces, would further reduce the time consumed during the modeling stage leading to higher acceptance of the BIM technology to the users. The discussion also suggested that only models should be enough for verification purposes at the ULBs as it removes the requirement of various drawings. Finally, it was recommended that decision-support systems (DSS) like the location of refuge spaces and the height of open spaces with regards to adjacent road width should be included in the ACCS. As a future prospect of the DSS, green building compliance guides according to Indian rating systems can also be integrated.

For the third and final question, the study targeted the automatic verification stage of the ACCS. A few subjective regulations for the permit were identified through this question. The subjectivity of such clauses can be tackled by ML-based prediction of the expected review outcome for these grey areas. An ML model can remove ambiguity by analyzing the historical review data of a given clause for a given locality. The acknowledged areas of subjectivity are shown in Table 4. This table also directs to the possible areas where the end-user thinks ML can help in solving these issues.

Fig. 3 The directions where AI can aid end-users in the SE process

Table 4 Subjectivity-driven grey areas in the pre-construction permit process

Sr. No	Grey Areas	Can ML aid?
1	Open space deficiencies and clearances with respect to Narrow Plots	Yes
2	Free of FSI deductions	Yes
3	No rules or guidelines for parking towers	Yes
4	Deduction of encroachment, margins, and setbacks	Yes
5	Staircase to staircase distance	-
6	Refuge area and deduction for fire staircases	-
7	Mechanical or natural ventilation requirements of basement	-

From this qualitative study, it can be concluded that the end-user understands the requirement of ACC in the pre-construction permit process. The experts also directed toward the necessity of AI in SE and ML in the automatic verification stages. Successful implementation of this process can improve the productivity and transparency of the industry. Prior prediction of the possible outcome would assist the architects in iterating and revising the plan in the design stage leading to the elimination of rejections and rework loops across stakeholders and different stages of the permit compliance process. Figure 4 illustrates the possible improvements in the regulatory compliance checking process through the application of ACCS.

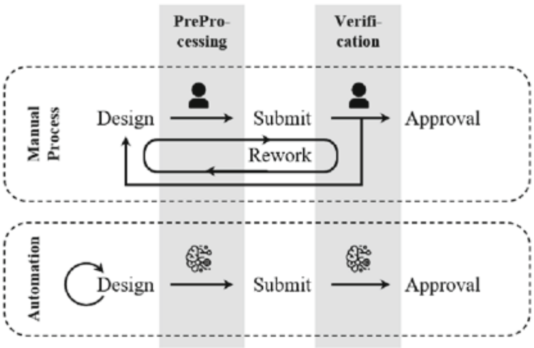

Fig. 4 Potential improvements in the compliance checking process through the application of ACCS

5 Conclusion

Despite a trust toward developing smart cities and digital twins, the construction industry lacks digital transformation. Innovative technologies and government initiatives can inject this transformation into the system. The construction lifecycle is controlled through standards and regulations by the government. It was ideated from the study that automation and digitization of permit compliance systems can improve the construction industry's productivity. Emerging technologies such as BIM can reinforce the paradigm shift. To drive the growth of the ACCS in end-users, SE must be aided through AI/ML. The current study highlighted dimensions for future integration of AI, brainstormed by industry experts. Applying such technologies in ULBs for compliance checking brings transparency and pace. Further, such an initiative from the government in implementing BIM-based ACCS will reduce ambiguity and enhance the seamless flow of information in the system.

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An Alternative Approach to Automated Code Checking – Application of Graph Neural Networks Trained on Synthetic Data for an Accessibility Check Case Study

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Abstract Automated Code Checking (ACC) can be defined as a classification task aiming to classify building objects as compliant or not compliant to a code provision at hand. While Machine Learning (ML) is a useful tool to perform such classification tasks, it presents several drawbacks and limitations. Buildings are complex compositions of instances that are related to each other by functional and topological relationships. This type of data can be easily supported by property graphs that provide a flexible representation of attributes for every instance as well as the relationships between the instances. This, together with the recent developments in the field of graph-based learning led the authors to explore a novel approach for ACC supported by Graph Neural Networks (GNN). This paper presents a new workflow that implements GNNs for ACC to leverage the advantages of ML but alleviate the limitations. We illustrate the suggested workflow by training a GNN model on a synthetic data set and using the trained classifier to check compliance of a real BIM model to accessibility requirements. The accuracy of the classifier on a test set is 86% and the accuracy of obtained results during the accessibility check is 82%. This suggests that GNNs are applicable to ACC and that classifiers trained on synthetic data can be used to classify building design provided by the industry. While the results are encouraging, they also point to the need for further research to establish the scope and boundary conditions of applying GNNs to ACC.

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Keywords Automated Code Checking (ACC) · Machine Learning (ML) · Graph Neural Networks (GNN) · Building Information Modeling (BIM) · Accessibility

1 Introduction

In current practice, Automated Code Checking (ACC) is performed by qualified experts manually and it is a costly, cumbersome, error prone and time consuming process [1]. As our digital design capabilities increase, our buildings become more complex making it even more difficult to check their compliance to all codes, regulations and standards to ensure safety and usability of the designed building. Automating the process can be of great benefit for the construction industry in many aspects. For example, as design review is one of the stages for construction permit approval in many countries [2], automating that stage can lead directly to shortening the time needed for construction permitting. Due to these potential benefits and the ability to represent building information in a computer readable manner using Building Information Modeling (BIM), the subject of ACC received much attention in the scientific community for the past 50 years [3]. Although there has been much progress in the field, even the most advanced commercial platforms for ACC (such as Solibri for example [4]) fail to provide a comprehensive and fully automated tool for code checking.

Majority of research into the subject focus on a rule based approach as described in [1]. This consists of representing the regulations in a computer readable format and enhancing computer readability of the BIM model to be checked, either manually or by automated processes such as semantic enrichment [5]. The design review process is eventually a matching of concepts represented in the regulations to those represented in the BIM model. This consists of mapping between the two and interpretation of meaning and intent, which usually requires considerable amount of manual work.

In this work, we propose to look at ACC in a different manner and define code checking as a classification task, where the goal is to assign the building (or a building element) with a “pass” label if it satisfies all relevant design requirements and a “fail” label if it violates one or more of the requirements. We therefore propose an alternative workflow for ACC that relies on a novel Machine Learning (ML) approach applied directly to a graph representation of the building information. In this paper we illustrate the proposed workflow on a simple test case of accessibility check in single family homes. Through the test case, we are able to illustrate the initial feasibility of applying novel ML techniques to ACC, but also to explore more general issues such as the core differences between the existing approaches for ACC, their advantages, limitations, use of synthetic data and direction for future research.

2 Background

Automated Code Checking is usually considered as a four-stage process that consists of translating the code requirements to logical statements, preprocessing of the BIM model, rule execution and report [1]. The need to translate codes written in natural language to logical statements, and the need to preprocess the BIM model to supplement all the semantically rich information required for checking, are the main challenges that hinder the development of a fully automated ACC platform that covers a wide range of requirements [1, 3, 6]. In this work, we suggest to reevaluate the general approach to ACC. The underlying assumption of this work is that application of novel Machine Learning techniques for design review can overcome some of the existing challenges (such as compiling rules for performance based regulations [7]), thus allowing a breakthrough in the field. Since ML relies on learning from past experience, it does not require to translate the codes and regulations into computable rules. A ML model is trained using a set of labeled examples where the labels are provided by experts in the field. In the case of code checking, these labels express the conformance of a proposed design to a specific code clause [8]. Namely, the regulations are implicitly captured in the set of labeled examples used to train the ML model. Thus, implementing ML as the checking mechanism eliminates the need to engage in the challenging task of converting natural language in to computable rules [9].

Although the idea of using Machine Learning (ML) techniques as the checking regime has been presented before [8, 10], the existing research is focused on very simple test cases and presents several drawbacks of the process. One is the lack of data for training, and the other is the difficulty in representing building information in a structured tabular form. Therefore, in this work we present and illustrate a workflow in which a Graph Neural Network (GNN) is implemented as the checking mechanism for automated code checking. Switching to a checking regime that is based on learning instead of hard-coded rules will eliminate the need to process the written documents. In addition, since graph structures are very suitable for representing building information in a complete and detailed form [11, 12], we expect to be able to overcome some of the drawbacks of using "classic" ML tools for code checking.

2.1 Application of Graph Neural Networks to Building Information

Buildings are complex structural systems composed of many elements that are related to each other by functional and topological relationships. Buildings, even of the same type, are designed with diverse shapes, functions and other characteristics, making it difficult to identify fixed data structures to represent them, as usually required by the classic ML applications. Graphs, on the other hand, due to their flexibility are extremely useful for describing such complex systems by representing building elements as nodes and the relationships as edges [13]. A Labeled Property Graph (LPG) is able to represent both the geometry of the building elements, through a set of values (features) assigned to each node in the graph, as well as the spatial relationships amongst them, through the edges connecting the nodes [14]. With the development of graph based learning methods and recent advances in graph data science [15], we are now able to better leverage the capabilities of ML techniques by applying them directly to the graph structures representing the building information.

Graph-based learning is useful for dealing with data that cannot be appropriately structured in a tabular or hierarchical form [16]. Graph Neural Networks (GNN) operate directly on the graph. The goal is to learn a d-dimensional vectorized representation (node embedding) of every node in the graph, that represents the attribute information assigned to each node and preserves the topological information described in the graph [17]. To do so, every node defines a computational graph, which consists of the node's neighbors up until k hops away from the node (denoting the number of layers). Each such neighborhood graph is used to propagate the information from all neighboring nodes across all the graph layers to compute a node embedding [18], a process called message passing. The node embeddings are generated based on the local neighborhoods while every node aggregates the information from its neighbors using neural networks.

For example, every node in the input graph illustrated in Fig. 1 defines its own neighborhood graph. Looking at the immediate neighbors of every node is equivalent to a GNN with a single layer ($k = 1$). To learn the node embedding of node A in a single GNN layer for example, we transform the representations (messages) of all immediate neighbors of node A and aggregate them. This is parametrized and sent through a Neural Network to introduce non-linearity. The result is a d-dimensional vector that encapsulates information about the attributes assigned to node A, as well as information about its position in the graph.

Many GNN architectures have been developed and demonstrated for various applications over the years [19]. The use of GNNs was recently proved useful for the construction domain as well. For example, in the work of [20] a Graph Convolutional Network (GCN) [21] model was applied for node classification to support point cloud data processing. In the work of [22] a SAGE-E model (an enhancement of the SAGE model [23]) was applied to classify room types in residential buildings for semantic enrichment purposes. In this work we define the task of code compliance checking as a classification task and aim to explore the applicability of GNNs for that task. We implement the Graph Attention Network (GAT) model [24] in the StellarGraph library [25] to perform the classification task. The main difference between GAT to other GNN models is that not all messages propagated from neighboring nodes are considered equally important. The assumption is that information from some nodes might be more significant for computing node embedding than others. Hence, in GAT every message is normalized by an attention factor that is learned for every neighbor separately.

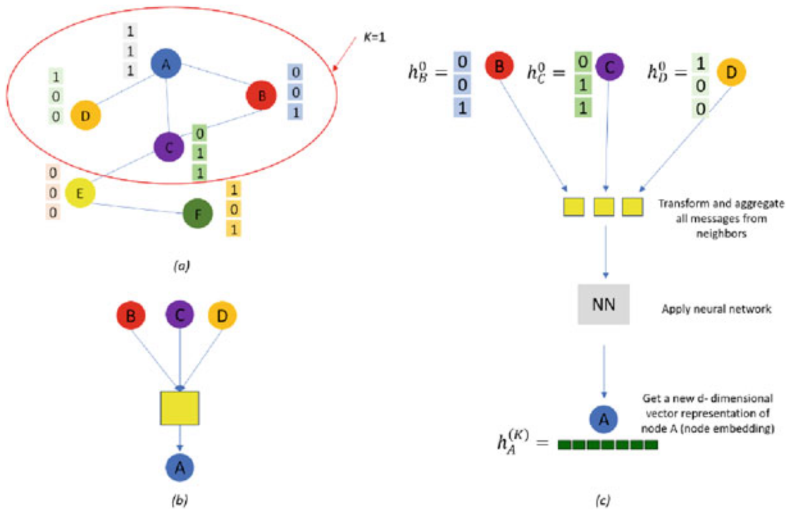


Fig. 1 Message passing in a single GNN layer. **a** illustrates an example input graph **b** is the computational graph defined by node A, and **c** is the message passing process computing the embedding of node A in a single layer GNN

2.2 The Use of Synthetic Data for Machine Learning

Graph-based learning, as any supervised ML algorithm, is reliant on a large data set of examples for training. In this case, the data set should consist of building design information, structured in a form of an LPG, labeled as compliant or not compliant to the specific code requirement at hand. Since such large data set is not available, we explore the possibility of generating a synthetic data set to be used during the training stage of the process.

The use of synthetic data to allow application of machine learning techniques is not a new idea and has been applied as early as 2004 to supplement survey data from non-respondents [26]. Since then, synthetic data generation methods have been developed for various domains, like the healthcare system [27]. The need for synthetic data sets for the construction domain has also been recognized in previous work. For example, [28] enhances a small existing data set with synthetic data to train a computer vision based system for monitoring the movement of construction workers on site. Based on the results of their work, the predictive model trained on the enhanced data set performed better than the model trained on only real data.

Although the construction domain produces vast amount of data, this data is currently compartmentalized and not accessible, or accessible but not complete making it unsuitable for ML applications for specific tasks. Furthermore, when dealing with ACC, the majority of available design documents are of buildings that have already received permit approval thus they are all code compliant and not sufficient to train a supervised ML algorithm. We assume that the lack of data is often a barrier to explore the potential of implementing ML for various purposes. To overcome this barrier, the training stage of the suggested process relies only on a synthetically generated data set. Fully synthetic data sets for training ML models are becoming increasingly popular for dealing with lack of data, especially in domains where privacy and data protection issues are dominant [29]. As data sharing is a problem in the AEC domain as well, we aim to investigate the capabilities of completely synthetic data sets to serve as starting points for training ML models for the use of the AEC industry. Similarly to the approach for generating synthetic data based on unprocessed "real" data [30], we rely on real floor plans of buildings that are publically available as a baseline for the data generation procedure as described in Sect. 4. We then focus on examining the performance of a GNN model that has been trained on a synthetic data set for classifying BIM models received from the industry as compliant or not compliant to a specific code requirement.

3 Research Aims and Method

The main purpose of this research is to demonstrate the initial feasibility of applying GNNs to ACC. We do that by illustrating the proposed workflow of ACC supported by application of a Graph Attention Network (GAT) model on a small-scale problem from the world of design review. Within that, the presented test case will also illustrate the applicability of ML models that have been trained on completely synthetic data sets for predictive analytics tasks performed on real design received from the industry. The overall suggested workflow for implementing GNNs trained on synthetic data as the checking mechanism for ACC is illustrated in Fig. 2. The training stage in the proposed workflow is implemented using the synthetically generated data set, which produces a trained classifier to be used for prediction. A "prediction" in this case is the result of code compliance checking of a new "real world" design.

We demonstrate the process through a small scale test case of checking the compliance of single family houses to several accessibility requirements based on the International Building Code [31]. The requirements to be checked are the minimal width of spaces, doors and ramps, the allowed slope of ramps and the general "ability to access". Since the chosen regulations address both geometric and topological aspects of the design, the strength of implementing graph based learning instead of "classic" ML approach can be explored.

4 GNN for ACC – Test Case

To illustrate the suggested workflow, we choose a small but representative test case of checking single family houses for some basic accessibility regulations. The checked requirements are the minimum width of doors, corridors, ramps and ramp slope, and the general ability to access each of the spaces. Although residential houses are

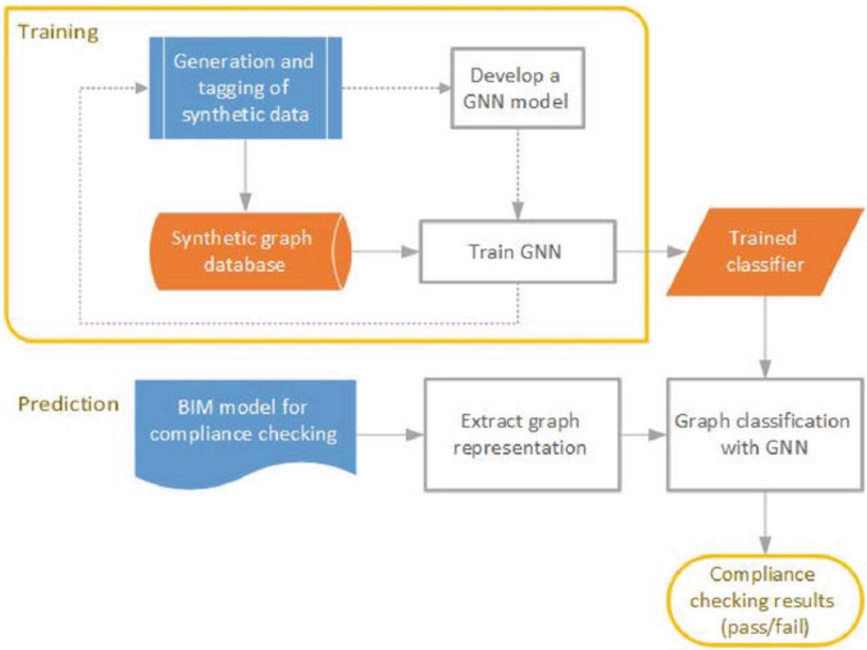


Fig. 2 Suggested process for GNN based ACC

usually not required to be accessible, unless in some special situations, this test case was chosen due to the simplicity on one hand and the ability to demonstrate the influence of geometry and topology together on the other hand. In addition, since the data for training is synthetically generated, it is important that the task is such that allows the use of a fully automated routine for labeling the entire generated data set.

While some construction regulations deal with simple geometric requirements that are concerned with specific building elements (the size of a window, the slope of a ramp etc.), others describe restrictions based on topologically complex dependencies between various building elements. Accessibility, or “the ability to access” is a requirement that encapsulates both geometric and topological aspects. Namely, for a room to be considered accessible, it is not sufficient that the room complies to all the geometric requirements, as we must also provide the ability to access the space meaning that all the spaces, doors, ramps that lead to that space must be accessible as well. The fact that we must look at the room in the context of the entire building to decide whether it is accessible or not, aligns with graph based learning models where we look at every node in the context of the graph to learn the class of the node.

4.1 Train, Validate and Test – Synthetic Data

Following the suggested workflow, as illustrated in Fig. 2, a set of 1,000 graphs representing single family houses were generated and labeled. As it is often believed that synthetic data sets must be based on real data, we begin the data generation process by collecting 10 floor plans of single family homes that are publically available on the web. The floor plans are manually translated to graph representations and serve as a baseline for generating floor plan variations. Information represented in the graphs includes only objects and attributes that are relevant to accessibility checking, i.e. spaces and their size, doors and their width, ramps and the slope of ramps, stairs. The Labeled Property Graphs therefore contain nodes that represent building elements which are assigned with properties such as element type, size etc. Edges between nodes represent navigable connections between the aforementioned objects, linking a door and its adjacent spaces, for example. By implementing a random number generator in a predefined restricted range for each of the properties, we create floor plan variations based on the baseline. Each baseline floor plan is modified 100 times which leads to 100 graphs that represent geometrically different floor plans. The topologies on the other hand remain unchanged in each of the 10 baseline floor plans, in order to ensure that we maintain topological integrity and generate graphs that represent feasible buildings. Applying the random number generators to each of the baseline floor plans we generate 1,000 graphs each representing one variation of a single-family house.

In order to train a GNN model, we label each of the nodes in the graphs based on their conformance to the chosen code provision. Labeling is performed in two stages, where the first stage is a deterministic check of the geometric requirements for each of the individual objects. For example, based on the code requirements the slopes of ramps must be within the range of 5–8.3% [31]. The results of this first stage are initial labels for each node of "pass" if the geometric requirements are met, and "fail" otherwise. In the second stage, we search for all possible paths leading from the entrance to the house to every space to check the "general ability to access". Namely, a space will be considered accessible only if there is a path leading to it which consists of other geometrically accessible elements. Eventually, the labeling routine aims to classify each node in the graph to three classes:

a) Compliant and accessible – for elements that satisfy the geometric requirements of the accessibility code and can be reached through a path that consists of other compliant elements.
b) Compliant but not accessible – for elements that satisfy the geometric requirements of the accessibility code but cannot be reached through a path that consists of other compliant elements.
c) Not compliant – for elements that do not satisfy the geometric requirements of the accessibility code.

Once the data set was generated and labeled, Graph Attention Network (GAT) model was trained in a full batch mode using the generated 1,000 graphs containing

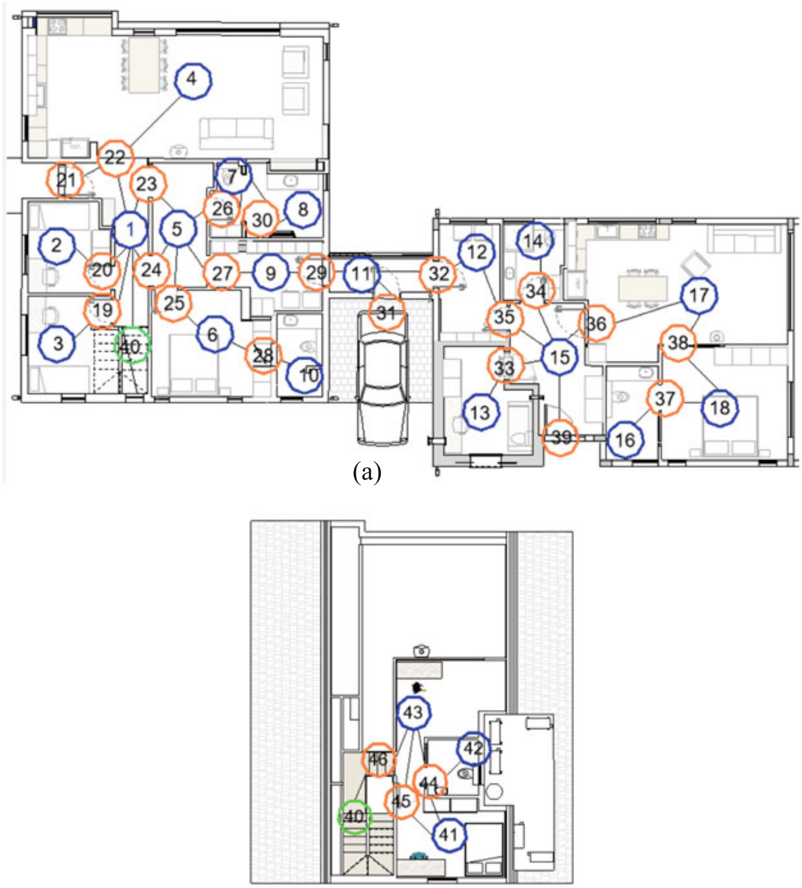
28,400 nodes and 27,900 edges. The final model for training contained four layers and 5 attention heads implemented in each layer. The rectified linear function (Relu) was used as the activation function for all hidden layers. Learning rate was set to 0.01 and the dropout value to 0.1. Evaluating the performance of the model, the data set was randomly split to data for training, data for validation and data for testing. Performance of the model was evaluated using the F1 score calculated based on the test set. The obtained F1 score was 0.86 which indicates the obtained classifier performs well on unseen data. As the validation and testing data sets are portions of the generated synthetic data set, to validate the results we must test the performance of the obtained classifier on "real world" data. The focus of the rest of the paper is the application of the trained classifier to check the compliance of design documents obtained from the industry to the accessibility code requirements.

4.2 Check Compliance – Real Design Data

To evaluate the feasibility of the entire workflow (Fig. 2), the obtained trained classifier must be applied to make predictions (classifications) based on design data provided from the industry. The following section describes the application of the trained classifier to check compliance of a BIM model that was obtained from a local architectural firm is Israel. The floor plans of the house, overlaid with their graph representation, are illustrated in Fig. 3. This design contains a main house which has two levels, and it is connected to an independent rental unit, which is very common in Israel. Note that this is a slightly different topology than in most of the houses used in the training set. The entire training set was defined based on the topologies of single-family houses mostly with a single level. While there is a minority of graphs representing houses with more than one level, there is no representation in the training data of houses connected to an independent unit that is also accessible from the main house. ML models are designed to generalize to new entities that are not present in the training data. Using this test case, we can begin to explore the flexibility that graph based learning models provide in terms of being able to generalize and provide classifications for buildings with various topologies.

The graph representation of the house (both levels) is given in Fig. 4. It contains all the rooms, doors and stairs represented as nodes, and the topological relationships between them are represented as edges. The only topological relationships represented in the graph are "access" relationships, meaning there is an edge between two nodes only if they represent elements with direct accessibility between them. The goal of this stage is to classify each building element represented in the graph as 'Not compliant', 'Compliant and accessible', 'Compliant but not accessible'. It is important to note that residential buildings built for the private sector usually do not have to be accessible. Hence, the ground truth contains elements of all three possible labels.

The nodes in the graph are assigned with a list of features to describe the elements which they represent, using the same data structure as for the training stage. Overall,



(b)

Fig. 3 Floor plan of the ground level of a house used as validation for accessibility check (design by Arch. Odelya Bar-Yehuda). **a** the ground level including the main house and the independent dwelling unit, **b** is the second storey of the main house

nine categorical features are assigned to each node as listed in Table 1. Features F1, F2, F3 and F4 determine the function of the node (space, door, stairs or ramp). F5, F6, F7 determine the minimal width of the component. For example, F5 will be assigned with the value 1 if the minimal width is greater than 170 cm, and the value 0 otherwise. F8 determines whether a space is a functional room such as kitchen, bathroom, bedroom, etc. or it is part of the circulation area within the house, such as a corridor. F9 determines the slope of ramps, such as that it is assigned with the value 1 if the slope is between 5–8.3%, and 0 otherwise. The list of features was determined based on key values from the accessibility code that were mapped into categories with numeric values. An example of a feature vector assigned to node 11

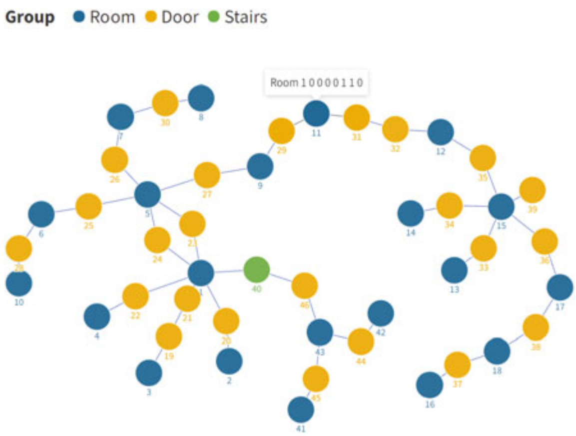


Fig. 4 The graph representation of the house plans used for validation. Each node in the graph is assigned with a vector of features (illustrated only for node 11)

Table 1 List of features assigned to each node in the graph

Feature	0	1
F1	If the element is a space	For all other elements
F2	If the element is a door	For all other elements
F3	If the element is a stair	For all other elements
F4	If the element is a ramp	For all other elements
F5	If the width of the element is greater than 170 cm	Otherwise
F6	If the width of the element is greater than 91.5 cm	Otherwise
F7	If the width of the element is greater than 81.5 cm	Otherwise
F8	If the element is a space that is part of the circulation path	For all other elements
F9	If the element is a ramp and its slope is within the range of 5–8.3%	Otherwise

is illustrated in Fig. 4. The final graph representing this house contains total of 46 nodes and 46 edges.

5 Results

In this work we implement the inductive learning setting [32], meaning that during the training only the training data is available (synthetic data) and we apply the trained classifier on a dataset which the model has never encountered before (real design documents). Overall, out of 46 entities in the graph that represents the real test case, 8 entities were misclassified resulting in an accuracy of classification of 82%. Comparing these results to the performance metrics of the trained model, we see a small deviation as the accuracy of the test set during training was 86%. Table 2 presents the misclassified nodes, their location in the floor plan, the predicted label and the result of a manual compliance check (ground truth).

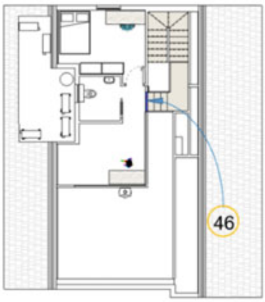
We can clearly see that most of the misclassified nodes in this case represent entities in the rental unit portion of the floor plan and not the main house. We can also see that most misclassified nodes are classified correctly in terms of geometry but not in terms of topology. In other words, spaces or doors that are compliant to the geometric requirements were indeed classified as such, but instead of being labeled "Compliant and accessible" they were classified "Compliant but not accessible", suggesting there is a problem with the path leading to those elements but not the elements themselves. We can also see that 100% of the mistakes are false negatives, meaning that relying on these results would lead to a reevaluation of the floor plan by the designers and not cause problems in later stages of the project.

The misclassified elements are marked in Fig. 5 a and b below. Although we can assume that the major cause for the misclassification is the fact that this type of topology is not well represented in the training set, the results obtained with GNN are unexplainable, just like results of the classic ML approach.

Table 2 List of misclassified entities as result from using the classifier trained on synthetic data

Room/Door	Location	Node number	Predicted label	True label
Door	Main house	27	Compliant but not accessible	Compliant and accessible
Door	Main house – second floor	46	Not compliant	Compliant but not accessible
Room – Security room	Rental unit	13	Compliant but not accessible	Compliant and accessible
Room - Foyer	Rental unit	15	Compliant but not accessible	Compliant and accessible
Room – Living room	Rental unit	17	Compliant but not accessible	Compliant and accessible
Door- exit door	Rental unit	39	Compliant but not accessible	Compliant and accessible
Door	Rental unit	36	Compliant but not accessible	Compliant and accessible
Door	Rental unit	38	Compliant but not accessible	Compliant and accessible

a) Ground level



b) Second level

Fig. 5 Floor plans of the checked building with marked misclassifications

6 Discussion

Automated Code Checking has been a subject of interest for many researchers over the years. Moving to BIM technology, we were able to make significant progress in the field, and lead to the development of advanced and sophisticated platforms with the ability to automatically check the compliance of a given design to several regulatory documents or user requirements. Despite the sophistication of the existing tools and workflows, an automated platform that provides a checking routine for a wide range of regulations in a completely automated manner remains a distant goal.

As the majority of work on the subject is focused on further development of the ACC following the well-established rule-based approach, we are constantly making progress but do not reach major breakthroughs. The broad applicability of ML techniques led to various breakthroughs in many different domains. The potential of using ML and leveraging data in the construction domain has been long recognized as well. However, the idea of applying ML techniques for ACC has not been sufficiently examined. We cannot expect for ML based ACC to reach the same accuracy as rule-based checking since results obtained with ML are probabilistic. However, while the rule-based approach provides very reliable results, it is limited in scope and requires much manual processing for rule compilation and for building information extraction.

There are some major differences between the rule-based approaches for ACC to the ML based approach for ACC. One of them is that the rule-based approach requires to process the regulations and the building design to bring them to a common environment as depicted in the left side of Fig. 6. Still, usually that representation of the regulatory documents and the design concepts do not overlap sufficiently, which causes difficulties in development of ACC platforms that cover a wide range of regulations. As described in [5], checking of a given design requires the user to "correct" the model to match the requirements of the checking routine in a process commonly called 'normalization'.

In the ML based approach, we still look for a common data representation, in the case of GNN it is LPG, but the regulations are encapsulated within that representation by the labels assigned to the nodes during the training (right side of Fig. 6). In other words, there are no two separate ontologies or vocabularies, instead both the design and the regulations are represented on the same graph which can be a great benefit of the approach.

On the other hand, representing the regulations and the design on a single data structure can also be a drawback. Regulations are often revised and changed, although the changes are not usually drastic, they have to be integrated correctly with the training process. This means that changes in the regulations will require re training, and possibly relabeling of the training set to obtain new classifiers. The complexity of a process for relabeling and retraining has not been evaluated yet. Similarly, the

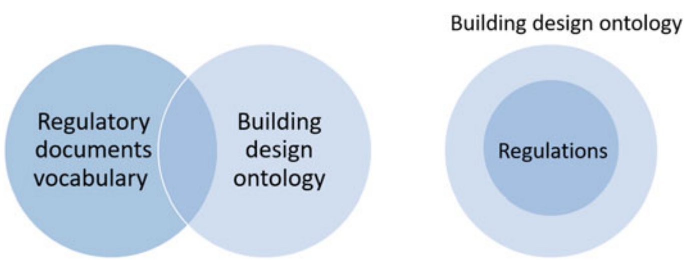


Fig. 6 Two approaches for ACC: on the left-hand side representation of the regulations and the design as separate ontologies. On the right-hand side representation of design and regulation using the same data structure

ability to group regulations into a single classifier is also an issue that needs to be investigated. In the presented work, several geometric requirements for doors, spaces and ramps were checked simultaneously in addition to the “general ability to access”. This suggests that not every code clause will require developments of its own trained classifier. A wider analysis of the regulations is needed to identify the clauses that can benefit from the GNN approach and to develop strategies for grouping code requirements that can be dealt with by the same classifier.

One of the barriers for implementing classic ML techniques or graph-based learning techniques is that both require large data sets for training. Although the construction industry produces vast amounts of data in all stages of construction projects, most of this data is not public. In addition, data that is available is not always complete, represented in a compatible format and labeled. Although the idea of generating synthetic data for training of ML models is not a new concept, this work illustrates that it can be useful for ACC. Furthermore, this work demonstrates that a graph-based learning model that was trained solely on synthetic data is applicable for checking the compliance of design documents obtained from the industry to check several accessibility requirements.

This work is focused on validating the suggested process of a GNN based ACC. Demonstration of the process for accessibility checking in a residential building leads to very encouraging results, but also reveals numerous directions for needed research. The GAT model developed in this case, and the routine for data generation and labeling are goal driven. This means that it might be difficult to generalize the created data set to be used for other purposes. In this case, we only represent the building elements relevant to the specific code requirement we want to check, but we assume it is possible to use more detailed graph representations of buildings to be able to check a larger set of regulations. This will of course influence the labeling method as well since we aim at providing labels that indicate what the design issue is instead of simple ‘compliant’ or ‘not compliant’. We can also assume that variations in the GNN model architecture, the data representation and the attributes assigned to every node will significantly influence the performance of the model. Although a rule-based approach can reach 100% accuracy in checking the same requirements, we cannot expect the same performance from a ML based approach. However, the obtained results demonstrate that GNNs can be applied to problems from the code checking domain, and they have the potential to provide a possible solution for regulations that cannot be checked deterministically. For example, vaguely written regulations or performance-based regulations that are difficult to represent as rigid rules. In conclusion, this work illustrates that GNNs are applicable for ACC, and that determining their scope and boundary conditions is a valid and important direction for future research.

7 Conclusions

This paper demonstrates a suggested workflow for implementing GNNs for ACC while relying on a synthetic data set for training and making prediction on BIM models received from the industry. The workflow is illustrated through a small- scale problem of checking compliance to accessibility requirements. The accuracy of the trained model applied to a test set achieved 86%, suggesting the classifier performs well on unseen data. Using the trained model to classify building elements presented in a BIM model received from the industry achieved accuracy of 82%.

This work has two main contributions, one is the feasibility check for using GNNs to automate compliance checking of code requirements that incapsulate both geometric aspects and topological aspects of the design. The other is a demonstration that in fact, synthetic data sets can be useful for training models that will later be used for classification of real design information.

The possible potential of using ML (whether classic ML algorithms or graph-based algorithms) has been long recognized. However, one of the main drawbacks is usually the unavailable data set for training. The construction industry produces large amounts of data in every construction project, but it is unfortunately not always available for researchers. Relying on synthetic data, we are able to illustrate the potential use and benefit of data driven approaches for ACC.

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Segmentation Tool for Images of Cracks

Andrii Kompanets, Remco Duits, Davide Leonetti, Nicky van den Berg, and H. H. Snijder

Abstract Safety-critical infrastructures, such as bridges, are periodically inspected to check for existing damage, such as fatigue cracks and corrosion, and to guarantee the safe use of the infrastructure. Visual inspection is the most frequent type of general inspection, despite the fact that its detection capability is rather limited, especially for fatigue cracks. Machine learning algorithms can be used for augmenting the capability of classical visual inspection of bridge structures, however, the implementation of such an algorithm requires a massive annotated training dataset, which is time-consuming to produce. This paper proposes a semi-automatic crack segmentation tool that eases the manual segmentation of cracks on images needed to create a training dataset for machine learning algorithm. Also it can be used to measure the geometry of the crack. This tool makes use of an image processing algorithm, which was initially developed for the analysis of vascular systems on retinal images. The algorithm relies on a multi-orientation wavelet transform, which is applied to the image to construct the so-called 'orientation scores', i.e. a modified version of the image. Afterwards, the filtered orientation scores are used to formulate an optimal path problem that identifies the crack. The globally optimal path between manually selected crack endpoints is computed, using a state-of-the-art geometric tracking method. The pixel-wise segmentation is done afterwards using the obtained crack path. The proposed method outperforms fully automatic methods and shows potential to be an adequate alternative to the manual data annotation.

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Keywords Image segmentation · Crack detection · Computer vision · Image processing · Fatigue crack measurement · Steel bridge inspection

1 Introduction

There are more than a million bridges in Europe and the USA, according to [1, 2] and every bridge structure is subjected to gradual deterioration which may lead to its collapse. In order to prevent tragic events and to detect critical structure deterioration in time, periodic inspections of bridges have to be conducted [3]. Visual inspections are the most frequent type of bridge inspection, during which, trained personnel visually examines the surface of the structure [4]. This procedure may be costly and time-consuming. Apart from the obvious expenses for inspector training and work, in some cases, there are implicit financial consequences to the regional economy related to the necessity to temporary restrict or fully shut down traffic across a bridge.

In a recent paper from Campbell et al. [5], it has been highlighted that the variability of the outcome of visual inspections is substantial, and that the detection rate of fatigue cracks strongly depends on the inspection conditions and the proneness of the inspector to report potential damage. The authors concluded that, by using the current techniques and procedures, visual inspection should not be regarded as a reliable method for bridge inspection.

The substantial cost and the low reliability of manual bridge inspections explain recent efforts directed at the designing of automatic systems for bridge inspections [6]. This is because automated visual inspection systems have the potential to augment the efficiency of existing inspection practices and to reduce its cost. In recent works, special attention was paid to automatic fatigue crack detection, since fatigue is one of the most frequent and dangerous types of bridge damage [7].

Many computer vision algorithms have been developed for crack detection and measurement in different structures and materials, see for example overviews of this topic in [8, 9]. These algorithms can be divided into two major groups, namely a) geometric image processing algorithms, and b) machine learning algorithms. Crack segmentation is a common approach extensively used in earlier works on automatic visual inspections, that besides crack detection, also allows measurement of the detected crack geometry. Image segmentation is the process of partitioning a digital image into multiple image segments, where each pixel is assigned to one of the segments. In the case of crack segmentation, two types of segments are considered: the segment of the image background type, and one or more segments of the crack type. Images of critical locations in bridge structures normally contain several elements that complicate the crack segmentation task. This may be surface corrosion, paint peeling, dirt on the surface, fasteners, and other bridge parts and joints. The performance of a fully automatic image processing algorithm dealing with such images is potentially affected by these aspects, e.g. it may result in a high false call rate by labeling a gap between adjoint elements of the considered structure as a crack, as mentioned in [10, 11]. In contrast, computer vision machine learning algorithms not only can recognize geometrical patterns of cracks but can also distinguish them from other crack-like-looking parts of the image. However, the main drawback of machine learning algorithms is that they require a labeled dataset for training and testing. A large number of researchers developing machine learning algorithms for crack segmentation uses labeled datasets created by manual labeling. In this case, the annotation consists of a manual draw of the contour of the crack, most often made with a hand-held mouse [12, 13]. Clearly, such a procedure may take a lot of time, especially in the case of a large number of high-resolution images.

Taking this into consideration, a manual annotation procedure forms a bottleneck in the process of development of a state-of-the-art machine learning algorithm for crack segmentation. In this paper, it is proposed to make use of image processing techniques to develop a semi-automatic crack segmentation tool. The developed tool has the advantage of making the process of labeling cracks on images simpler and faster, which is needed to train a machine learning algorithm for crack segmentation. Moreover, the proposed tool may also be used to extract the geometrical parameters (length, width, curvature, etc.) of a crack needed for either research or more accurate inspection. Unlike the fully automatic image processing technique for crack segmentation, the developed method requires manual input, i.e. the crack end-points. By adding such a manual input it is possible to significantly increase the accuracy of the crack segmentation algorithm, potentially allowing it to be used as a data labelling tool for machine learning algorithms. Implementation of the developed algorithm is available at https://github.com/akomp22/crack-segmentation-tool

2 Methods

Datasets to train a machine learning algorithm for crack segmentation are often manually labeled, since it is the most reliable method for pixel-wise image labeling. However, it is time consuming, because it requires a human expert to manually indicate the contours of the crack.

Fully automatic image processing algorithms do a crack segmentation much faster and without human involvement. A wide range of different image processing techniques have been created aiming at the development of a fully automatic crack segmentation algorithm. Commonly used techniques include thresholding [14–18], filtering [19, 20], and image texture analysis [21–23].

A major drawback of these fully automatic algorithms is that they are often designed to mark dark elongated structures of the image as a crack. On complex images, for example the image of a steel bridge presented in the Fig. 1, these algorithms will suffer from the significant amount of false crack detections. Hence, these algorithms can not be used as an image pixel-wise labeling tool.

The semi-automatic algorithm described in this section uses an image processing technique, where the false call rate is minimized thanks to additional information about the crack location provided by a human annotator.

The first major step of the proposed method is crack path tracking, described in Sect. 2.1 of this paper. The algorithm aims at finding the path of a crack between two manually selected crack endpoints. The retrieved crack path allows to distinguish a particular elongated dark structure of the image (which is a crack) form other elements in the image that look like a crack (e.g. shading, paint, structure edge etc.). Few earlier works considering crack tracking having selected points as input. For instance, in [24], a crack path was identified by a step-by-step movement from one of the crack points in the direction that has a locally minimal pixel intensity. A disadvantage of this tracking method is that it is not able to find a globally optimal path. It can easily be mislead by dark image regions near the crack and follow a locally optimal wrong path.

Fig. 1 Example of a steel bridge structure image where common crack detection algorithms tend to have a high false call rate.

In [25] the crack path was found using only one internal crack point as input. A fast marching algorithm was used to find a distance map relative to the selected internal point. The lowest gradient ascent path was chosen as a crack path.

Crack minimal path selection approaches was also used in [26, 27]. In these articles, Dijkstra's algorithm was used to find a crack path between multiple points inside crack contour. However, points inside crack contour were selected automatically, using the threshold method, so the problem of the high amount of false detections that is inherent to fully automatic image processing algorithms is also present in these methods.

The proposed crack tracking method uses an anisotropic fast marching algorithm to find a crack path as a globally optimal path (minimizing geodesic) in an orientation score (a multi-orientation wavelet transform) and is described in Sect. 2.1 of this paper.

To obtain a crack segmentation, the width of the crack along the retrieved path needs to be measured. One way to do this is to get an intensity profile perpendicular to the crack path, and determine crack edges based on this profile, as was done in [24]. However, the crack edges retrieved with this method have irregular shapes and may deviate significantly from the actual edges. A width expansion approach was used in [26–28], and is also used in the proposed algorithm and explained in Sect. 2.2. An alternative width measurement method is also proposed (tracking algorithm for edges as described in Sect. 2.2) which works better on images of cracks in steel bridges.

2.1 Crack Path Tracking

In [29] a general image processing method was proposed for line tracking in 2D images via 3D multi-orientation distributions (so-called 'orientation scores'). Such an orientation score [30] lifts the image-domain from a 2D position space to a 3D space $\mathbb{M}_2$ of 2D-positions and orientations, as can be seen in Fig. 2. Where a 2D image $f : \mathbb{R}^2 \to \mathbb{R}$ assigns a greyvalue $f(x_1, x_2)$ to a position (x_1, x_2), an orientation score $U_f : \mathbb{M}_2 \to \mathbb{C}$ assigns a complex value $U_f(x_1, x_2, \theta)$ to a 'local orientation' $p = (x_1, x_2, \theta)$. The real part of U_f gives the measure of alignment of the image local line structures with the specific orientation, whereas the imaginary part can be interpreted as the measure of alignment of image local edge structures with the specific orientation.

In [31] the tracking in the orientation scores (TOS) is done by formal optimal curve algorithms. The curve extraction is done with a single optimal control problem, allowing to include local contextual alignment models of oriented image features. In other words, optimality of the curve is determined not only by the intensity of pixels it lies on, but also by the alignment of this curve with the image's local anisotropic structures.

These contextual geometric models in $\mathbb{M}_2$ improve tracking when cracks are partly visible, which is often the case. Furthermore, cracks often have sudden changes in local orientation, and do not have cusps like in [31]. Therefore, the used algorithm relies on the improved forward motion model also applied in [32] for blood vessel tracking. For efficient sufficiently accurate computation anisotropic fast marching algorithm [33] is used to compute distance maps in $\mathbb{M}_2$. A subsequent steepest descent provides the optimal paths, i.e. optimal geodesics being paths with minimal data-driven length.

Such geometric TOS [32] gives a few advantages in the application of tracking cracks in steel bridges:

– When a crack is only partly visible in the image as in Fig. 3 the aforementioned contextual image processing models are needed to still recognize the crack
– Crossing structures (e.g. a crack and a sub-surface due to shading/paint) are disentangled in the orientation score (e.g. Fig. 4a and Fig. 5b). The crack and the edge/line crossing are separated because they align with different orientations, thus being on different "θ levels" in the orientation score. Thereby a tracking algorithm will stay on a true crack trail.
– Cracks can suddenly change orientation and the model based on [34] automatically accounts for that.

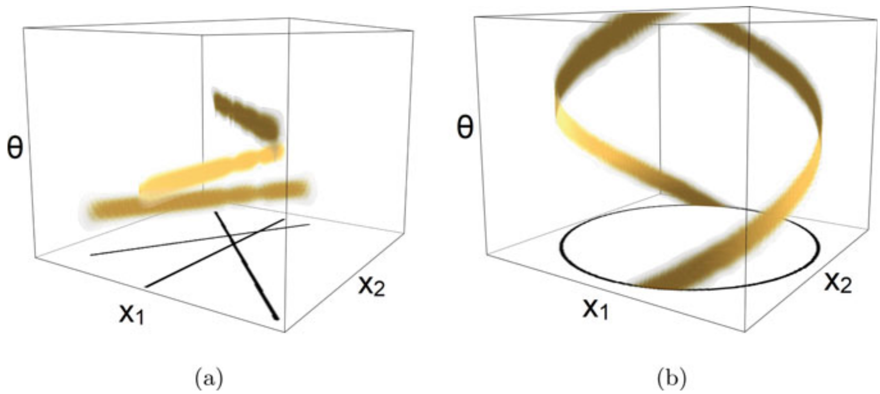

Fig. 2 Examples of the orientation scores: **a** Orientation score of an image with lines; **b** Orientation score of an image with a circle.

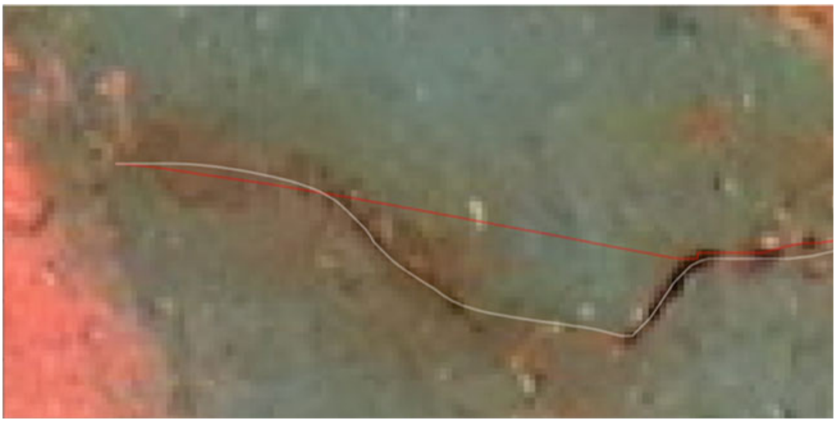

Fig. 3 Close up view of a crack with their calculated crack path retrieved by two methods: The red line shows the track obtained by tracking in $\mathbb{R}^2$ while the white line shows the spatially projected track obtained by tracking in $\mathbb{M}_2 = \mathbb{R}^2 \times S^1$.

Construction of the Orientation Score. In the orientation score, the image domain of positions $\mathbf{x} := (x_1, x_2) \in \mathbb{R}^2$ is extended to the domain of positions and orientations $(\mathbf{x}, \theta)$, where $\theta \in [0, 2\pi]$ denotes the orientation. The orientation score can be built from the initial image using the anisotropic cake wavelets shown in Fig. 4b (which thank their name to their shape in the Fourier domain [29, 30]). The convolution of an image with a cake wavelet that has a specific orientation θ will filter the local line elements, giving high response in positions where the line structures are aligned with the applied wavelet orientation. For example, the responses in Fig. 5a are obtained by applying the wavelet filters shown in Fig. 4b to the image shown in Fig. 4a.

A grayscale image can be considered as a (square integrable) function $f : \mathbb{R}^2 \to \mathbb{R}$ that maps a position $\mathbf{x} \in \mathbb{R}^2$ to a grayscale value $f(\mathbf{x})$. Similarly, the orientation score U_f is represented by the function $U_f : \mathbb{M}_2 \to \mathbb{C}$, where $\mathbb{M}_2 = \mathbb{R}^2 \times S^1$ and $S^1 := \{\mathbf{n}(\theta) = (\cos\theta, \sin\theta) \mid \theta \in [0, 2\pi)\}$. The used cake wavelets ψ are complex-valued (their real part detects lines whereas their imaginary part detects edges). The orientation score U_f of an image f is given by:

$$U_f(\mathbf{x}, \theta) = \int_{\mathbb{R}^2} \overline{\psi\left(R_\theta^{-1}(\mathbf{y} - \mathbf{x})\right)} f(y)\, \mathrm{d}\mathbf{y}, \text{ for all } \mathbf{x} \in \mathbb{R}^2, \theta \in [0, 2\pi), \tag{1}$$

where ψ is the complex-valued wavelet aligned with an a priori axis (say the vertical axis $\theta = 0$), and the rotation matrix R_θ rotates this wavelet counterclockwise with the required angle θ and is defined by: $R_\theta = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$. A careful mathematical design of the cake wavelets [29, 30] allows to preserve all image information after "lifting" the image to the orientation score. With a proper choice of parameters that are used to construct the cake-wavelet, the approximate reconstruction of the image f from the orientation score can be achieved by a simple integration:

$$f(\mathbf{x}) = \int_0^{2\pi} U_f(\mathbf{x}, \theta)\mathrm{d}\theta.$$

Shortest Paths (geodesics) in the Orientation Score. After the input image is lifted to the orientation scores, a tracking algorithm is applied that finds the shortest path, or geodesic, between the endpoints of the crack in the orientation score, see Fig. 6. The geodesic can be represented by a parameterised curve $\gamma(t) = (\mathbf{x}(t), \mathbf{n}(t))$ in the orientation scores, the length of which is defined as the Riemannian distance between the chosen endpoints $\mathbf{p} = (\mathbf{x}_0, \mathbf{n}_0)$ and $\mathbf{q} = (\mathbf{x}_1, \mathbf{n}_1)$. Here, $\mathbf{p}$ and $\mathbf{q}$ are points in the lifted space of positions and orientations $\mathbb{M}_2 := \mathbb{R}^2 \times S^1$ and $\mathbf{n}_t := \begin{pmatrix} \cos\theta_t \\ \sin\theta_t \end{pmatrix}$. The asymmetric version of the Riemannian distance, that distance is single, so were should be was used in the experiments, is defined by:

Fig. 4 **a** Input image with chosen endpoints; **b** Real part of the cake wavelets with angle θ equal to 0 and $\frac{\pi}{2}$ respectively.

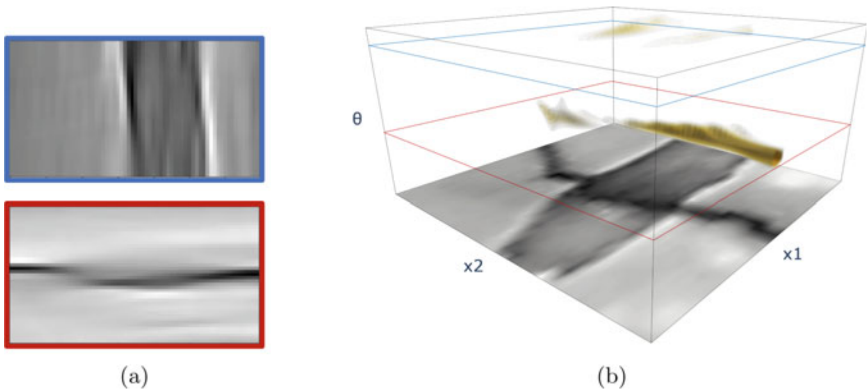

Fig. 5 **a** Results of applying filters from figure Fig. 4b to the image shown in Fig. 4a; **b** Orientation score of image shown in Fig. 4a. θ-levels represented by blue and red rectangles correspond to **a**.

$$d_G(\mathbf{p}, \mathbf{q}) = \inf_{\substack{\gamma(\cdot)=(\mathbf{x}(\cdot),\mathbf{n}(\cdot))\in\Gamma \\ \gamma(0)=\mathbf{p},\gamma(1)=\mathbf{q} \\ \dot{\mathbf{x}}(\cdot)\cdot\mathbf{n}(\cdot)\geq 0}} \int_0^1 \sqrt{G_{\gamma(t)}(\dot{\gamma}(t), \dot{\gamma}(t))}\mathrm{d}t \tag{2}$$

where the space of curves (are all piecewise continuously differentiable curves $\gamma : [0, 1] \to \mathbb{M}_2$), over which the optimization is done, is denoted by Γ, and with the Riemannian metric given by

$$G_{\mathbf{p}}(\dot{\mathbf{p}}, \dot{\mathbf{p}}) = C^2(\mathbf{p}) \left(\xi^2 |\dot{\mathbf{x}} \cdot \mathbf{n}|^2 + \frac{\xi^2}{\zeta^2} \left(\|\dot{\mathbf{x}}\|^2 - |\dot{\mathbf{x}} \cdot \mathbf{n}|^2 \right) + \|\dot{\mathbf{n}}\|^2 + \lambda \frac{\max\limits_{\|\dot{\mathbf{q}}\|=1} \left| HU|_{\mathbf{p}}(\dot{\mathbf{p}}, \dot{\mathbf{q}}) \right|^2}{\max\limits_{\substack{\|\dot{\mathbf{q}}\|=1, \\ \|\dot{\mathbf{p}}\|=1}} \left| HU|_{\mathbf{p}}(\dot{\mathbf{p}}, \dot{\mathbf{q}}) \right|^2} \right) \tag{3}$$

with $\mathbf{p} = (\mathbf{x}, \mathbf{n}) \in \mathbb{M}_2$ being a position and orientation, and $\dot{\mathbf{p}} = (\dot{\mathbf{x}}, \dot{\mathbf{n}})$ a velocity attached to the point $\mathbf{p}$, and where $C^2(\mathbf{p})$ is the output of the application of the multi-scale crossing/edge preserving line filter to the orientation score, for details see [32, App.D], [35], and acts as a cost function. The Hessian of the orientation score is denoted by HU. Parameter $\xi > 0$ influences the stiffness or curvature of the geodesics. Parameter $0 < \zeta \ll 1$ puts high cost on ξ^2/ζ^2 on sideward motion relative to the cost ξ^2 for forward motion. Parameter $\lambda > 0$ regulates the influence of the data-driven term relying on the Hessian of the orientation scores. In order to find the optimal curve that minimizes the distance, the anisotropic fast marching algorithm [33] is applied to solve the eikonal PDE [34]. The algorithm computes the distance map $d_G(\mathbf{p}, \cdot)$ given by Eq. (2) from one of the crack endpoints, $\mathbf{p}$, that serves as an initial condition (i.e. 'seed point') using an efficient propagating front approach. Afterwards, it finds the geodesics by backtracking using the steepest descent method [34] from the other endpoint $\mathbf{q}$, also called the 'tip point', using the computed distance map. The HFM library [36] was used to employ the described tracking algorithm efficiently.

Next, extra motivation for the curve optimization model given by Eq. (2) is provided. When considering crack propagation as a random Brownian process [37, 38] on $\mathbb{M}_2$ then Brownian bridges concentrate on geodesics [39]. Furthermore, the model given by Eq. (2) corresponds to a curvature-adaptive extension of the model in [34] whose optimal geodesics include 'in-place rotations' that the model automatically places at optimal locations during the geodesic distance front-propagation. Such 'in-place rotations' (due to the constraint $\dot{\mathbf{x}} \cdot \mathbf{n} \geq 0$ in Eq. (2)) are natural for 2D pictures of cracks in bridges, as there are often sudden changes in direction of a crack.

2.2 Crack Width Detection

Two distinct approaches are considered that allow to obtain a crack segmentation while having the crack path. The first approach is called'width expansion' (WE) and the second approach'edge tracking' (ET). The WE approach is expected to work better with cracks that have a conspicuous grain structure along their edges, e.g. cracks in pavement. In contrast, the ET approach gives better results for cracks that have relatively smooth edges such as cracks in steel.

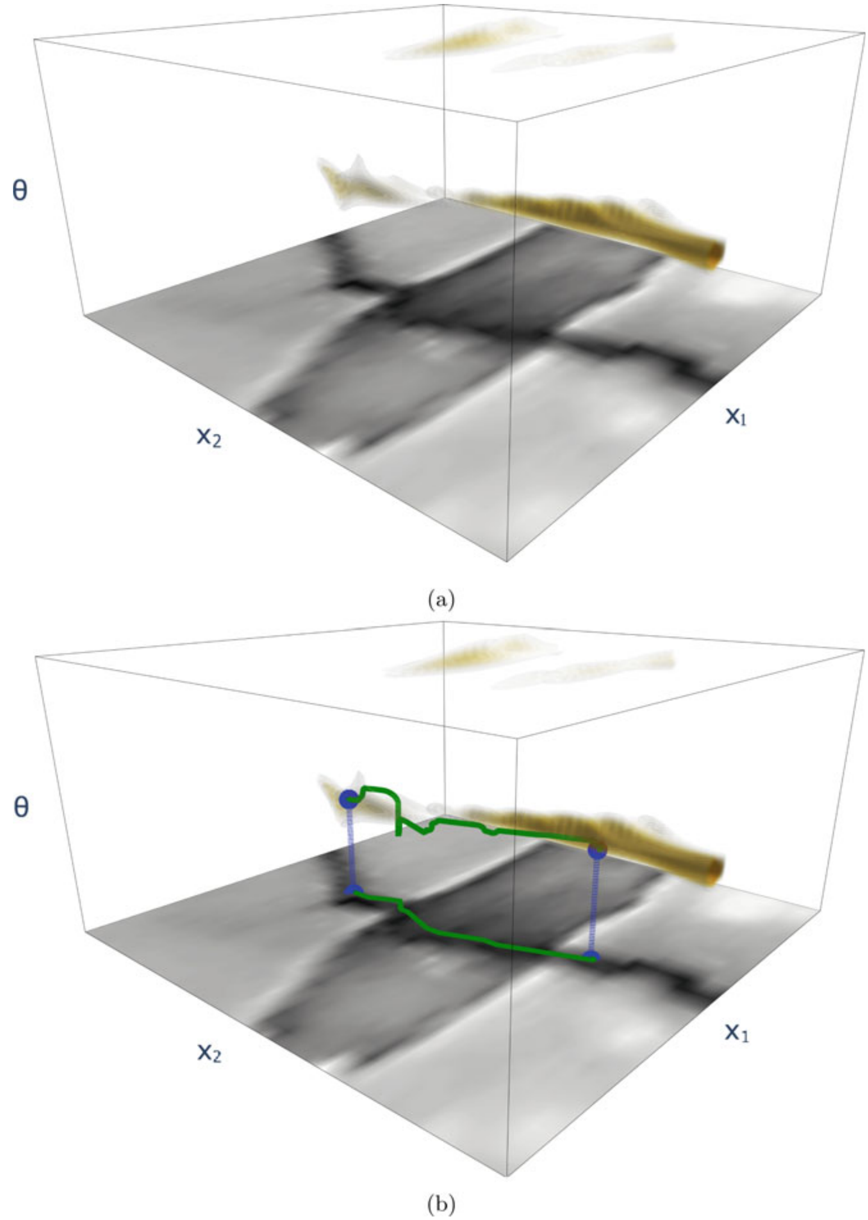

Fig. 6 **a** Orientation score; **b** An example of a geodesic (the shortest path γ from Eq. 2) in the orientation score and its projection onto $\mathbb{R}^2$.

Crack Width Expansion. This approach has been used in automatic crack segmentation algorithms [26, 27], and is applied to the image in the $\mathbb{R}^2$ domain without any preliminary transformations. In the first iteration of the WE algorithm, the pixels that lie exactly on the obtained crack path are assigned to a crack segment. In the subsequent iterations, pixels neighboring to the existing crack segment are assigned to a crack segment if their intensity value is below a threshold value $T_w = \mu_w - K_w \cdot \sigma_w$, where μ_w and σ_w are mean and standard deviation respectively of the existing crack segment pixels gray value distribution, and where K_w is a manually chosen parameter. The iterations continue until no new pixels are added to the crack segment. This approach is useful when the crack has an irregular shape as is the case for e.g. cracks in pavement, due to the noticeable grains of the material. However, the output of this approach depends significantly on the threshold value K_w. The necessity to accurately chose K_w restricts the autonomy of the method, since, its optimal value may vary significantly depending on the image.

Crack Edge Tracking. Similarly as for crack path tracking, for the ET a geometric tracking algorithm is applied to find an optimal path between crack endpoints, but with a few major differences.

First of all, a cost function $C(\mathbf{p})$ for the tracking algorithm is built that forces it to follow the crack edges instead of the crack centerline. To build this cost function, the crack path is divided into small segments for which crack path orientation is determined. Afterwards, around each path segment, a square part of image is chosen with a predetermined dimensions in parallel and perpendicular to the segment orientation. To these pieces of the image, an edge filter (Gaussian first order derivative) oriented in accordance with the crack path orientation is applied. Results of this operations are summed to construct a cost function for the whole image. In this way, the edge filter highlights mainly the edges of the crack and gives lower responses to edges not parallel to the crack. An example of a resulting image is presented in Fig. 7a.

Additionally, in the proposed ET method we use a version of the tracking algorithm described in Sect. 2.1 that in fact is the Dijkstra's algorithm in the image $\mathbb{R}^2$ domain. As a filter was applied that was specifically designed to highlight crack edges and ignore other edges on the image, it is expected to avoid the problems listed in Sect. 2.1 (namely crossing structures and poor visibility of the filtered crack edges). Hence, instead of doing tracking in the $\mathbb{M}_2$ domain as was done for crack path tracking, here the fast marching algorithm [33] for geodesic curve optimisation is directly applied in the image $\mathbb{R}^2$ domain that is computationally less expensive.

3 Results

3.1 Tracking Performance

First, the performance of the crack path tracking algorithm is evaluated against the steel structures dataset. The used dataset consists of images of actual steel bridge structures with fatigue cracks that was collected by Dutch infrastructure authorities. Ground truth crack tracks (actual track of a crack as it is visible on the image) were drawn manually for 19 randomly selected images from the dataset. In order to numerically estimate the performance of the tracking method, the metric $m = \frac{A}{L^2}$ is introduced, where A is the area between the ground truth track and retrieved track, measured in squared pixel, and L is the length of the ground truth track determined as the number of pixels it passes. The area A between to tracks represents a measure of how one track deviates from another. Division by L^2 makes the metric resolution-invariant. Lower values of the metric m mark lesser deviation of the retrieved crack from the ground truth track. Table 1 shows the mean value of the introduced metric.

Fig. 7 **a** Oriented edge filter applied to the image shown in the Fig. 4a; **b** Crack edges detected with the ET method.

The described tracking method was compared with the alternative methods. Table 1 shows the results of this comparison, where the considered algorithms are identified as:

– FF—the "FlyFisher" algorithm described in [24]. In this method a track propagates a track from the starting point and led by the local gray-scale pixel values patterns;
– DT—Tracking 2D paths using Dijkstra's algorithm in the $\mathbb{R}^2$ domain of the input image to minimize the cost function defined by the Frangi filter [40];
– TOS—Tracking in the Orientation Score: Tracking optimal paths defined by Eq. (2) in the orientation score via anisotropic fast marching algorithm (described in Subsect. 2.1).

Table 1 Average deviation of three different crack tracking algorithms from the ground truth crack on 19 images of cracks in steel structures

	FF	DT	TOS
$m \cdot 10^5$	4.46	0.980948	0.784308

Table 2 Crack segmentation results on the AigleRN dataset

	FFA	MPS	TOS+WE
Precision	0.61	0.82	0.91
Recall	0.32	0.6	0.75
F1	0.36	0.63	0.82

The results demonstrate that the proposed TOS method outperforms DT and FF algorithms. The path retrieved by the FF method follows a locally optimal direction (defined by a darker image region) but easily misses a globally optimal path. This problem results in the worst performance (see Table 1). In contrast, the TOS and the DT algorithm use a two step approach. First, they calculate the distance map on a Riemannian manifold (M, G) from the starting point and then perform a backtracking using the steepest descent algorithm. In case of TOS, the manifold $M = \mathbb{M}_2$ and metric tensor field G given by Eq. (3) while in the DT algorithm, the base manifold $M = \mathbb{R}^2$ and the metric tensor field $\mathcal{G}$ is now given by $\mathcal{G}_{\mathbf{x}}(\dot{\mathbf{x}}, \dot{\mathbf{x}}) = V(\mathbf{x})\|\dot{\mathbf{x}}\|^2$ with V the Frangi filter [40].

This two step approach allows us to find the optimal path resulting in significantly lower values of the metric m in Table 1. Here the DT algorithm follows the path with the lowest cumulative Frangi filter values V-intensity of pixels. The TOS algorithm improves upon this by using a crossing-preserving V- intensity [35], and moreover it includes alignment of locally oriented image features as explained in Sect. 2.1, resulting in better tracking performance (see Table 1).

3.2 *Segmentation on the AigleRN Dataset*

The AigleRN dataset contains images of cracks in pavement and provides ground truth crack segmentations [41]. In order to segment cracks on images from this dataset, the TOS method is used with the WE as described in Sect. 2.1. Seventeen images were randomly selected from the AigleRN dataset for the evaluation. To evaluate the performance of the tracking algorithm, criterions were used as in [28], namely precision, recall and F1-value. Recall shows what fraction of the crack pixels were retrieved by an algorithm. Recall equal to 1 means that all pixels that belong to a crack according to ground truth were identified by an algorithm as crack pixels. The precision value indicates what fraction of the pixels that were identified as crack by an algorithm, actually belong to a crack segment. Finally, the F1-value is the harmonic mean of precision and recall. Results are provided in Table 2.

In [41] crack segmentation results retrieved by minimal path selection (MPS) [27] and free-form anisotropy (FFA) [42] algorithms are also provided. Using these provided segmentation results, the performance parameters were determined for the MPS and the FFA methods for the same seventeen images. These performance parameters, are also shown in Table 2.

The FFA algorithm measures a local texture anisotropy for every pixel of the image. The pixels where an anisotropy is higher than a threshold value are assigned to a crack segment. This approach has the lowest performance.

The MPS algorithm finds potential crack pixels using a threshold of local minima in grayscale. Afterwards, the paths between these points are computed using Dijkstra's algorithm. These paths constitutes the so-called 'skeleton' of the crack. To find crack segments, this skeleton is used as a basis for the WE algorithm as explained in Sect. 2.2. The MPS algorithm does not allow to detect cracks with poor visibility, and this explains the low recall value. This can also be observed in Fig. 8, where the middle part of the crack with partial visibility was not detected by the MPS method. Also in Fig. 8, false detections by the MPS algorithm can be observed, whereas the TOS+WE algorithm avoids false detections and maintains the connectivity of the crack. Because of this effects the proposed TOS+WE algorithm outperforms its two counterparts by all three metrics as can be seen on Table 2.

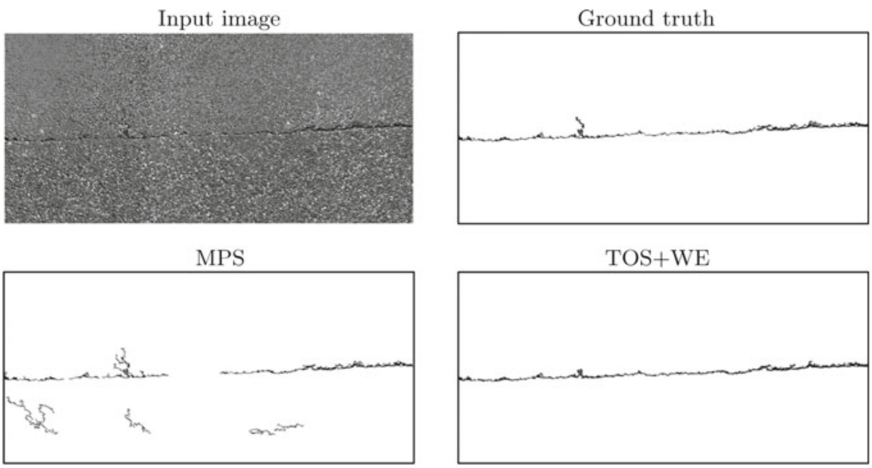

Fig. 8 Typical example in the AiglRN dataset with segmentations. The output of the TOS+WE algorithm is more connected and closer to ground truth than the MPS-output. This qualitatively supports the performance differences in Table 2.

3.3 Segmentation on Steel Structures Images

Finally, results are provided of the application of the segmentation algorithm to the images of steel bridge structures with cracks from the dataset introduces in Sect. 3.1. Ten images with visible crack edges from the dataset were used for the evaluation. Unlike in pavement, crack edges in steel structures have a smooth shape, and previously it was stated that the ET algorithm should work better than the WE algorithm in this case. Here this is shown by comparing the TOS+ET and TOS+WE algorithms in Table 3.

In Table 3, also the results for the reimplemented MPS algorithm are added for comparison. As was explained in the introduction of this paper, the fully automatic MPS method tends to have lots of false crack pixels identifications on images with non-crack dark elongated elements as can be seen on Fig. 9. This leads to only 49% precision for the MPS algorithm and low F1-value.

In contrast, with the proposed algorithms (TOS+WE and TOS+ET) the image structure of interest is identified at first using the crack path tracking. Thus, the precision of the proposed algorithms is higher than that of the MPS algorithm.

Furthermore, TOS+WE method has a slightly higher precision value than the TOS+ET method, but significantly lower recall value meaning that TOS+WE algorithm skips more crack pixel, marking them as background pixels. Thereby, by the F1-value the TOS+ET method shows the best performance on the images of steel structures.

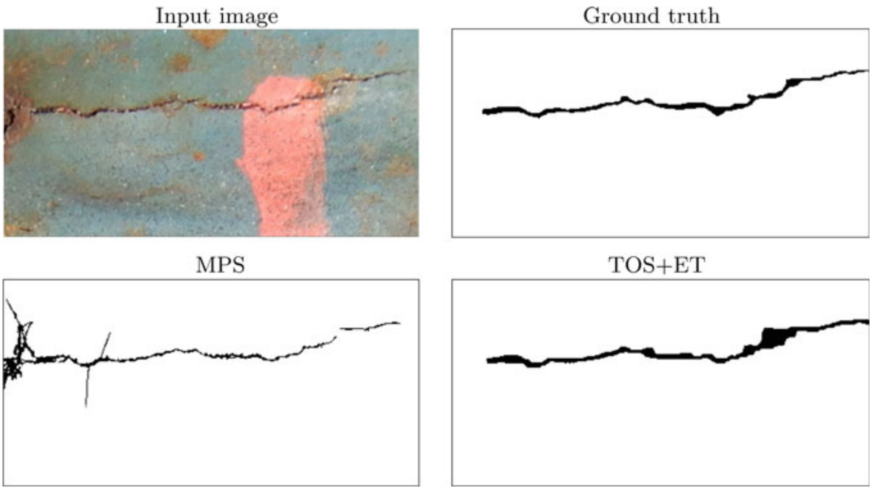

Fig. 9 Example of a steel bridge image and the corresponding results of its segmentation. The TOS+ET method suffers less from neighboring/crossing structures (paint, rust) because of the multi-orientation decomposition.

Table 3 Crack segmentation results on the dataset of images of steel structures

	MPS	TOS+WE	TOS+ET
Precision	0.49	0.9	0.86
Recall	0.66	0.69	0.85
F1	0.52	0.78	0.83

4 Conclusion

An algorithm for the crack segmentation was proposed, consisting of two major parts. The first part of the algorithm measures a crack track between manually selected crack endpoints. The second part of the algorithm performs the crack segmentation using a crack track obtained in the first part as a basis. The crack tracking part of the algorithm adapts the approach initially developed for the analysis of vascular systems on retinal images where an efficient fast marching algorithm performs line tracking on the image lifted into space of positions and orientations. For the width measurement part of the algorithm the novel approach was proposed for the crack edge tracking and it was compared with the width expansion approach that was used in earlier works.

The proposed semi-automatic algorithm allows for a crack segmentation of images with improved accuracy compared to the fully automatic algorithms, such as minimal path selection and free form anisotropy algorithms and resolves the problem of high false detections which is inherent to fully automatic crack detection image processing algorithms. While sacrificing autonomy of the segmentation algorithm, the accuracy significantly increases.

Potentially the developed algorithm may be used as a data labeling tool, to label images with cracks to train a machine learning algorithm. However, results show that the proposed algorithm does not fully reproduce the manual pixel-wise labeling. It should be studied how much this deviation affects the performance of the machine learning algorithm trained on the data labeled with the semi-automatic segmentation tool. Also, the algorithm can find its use in cases when it is necessary to measure a crack's geometry (length, width, curvature etc.) when the location of this crack is known, e.g. for research or for the purpose of more accurate inspection.

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Generating Pseudo Label of Object Detector for Construction Site Monitoring

Taegeon Kim, Giwon Shin, Seokhwan Kim, and Hongjo Kim

Abstract The performance of deep learning models can be significantly degraded on unseen data that has different visual characteristics compared to a domain where training data was collected. A simple and obvious way to maintain the performance of deep learning models is to prepare training data again in a new domain where target objects and backgrounds have different appearances compared to the original. However, it is not a trivial task considering time and efforts required in data preparation. To address this issue, this study proposes a pseudo label generation method from images that can automatically collect video clips for objects of interest and assign labels. The proposed method consists of a moving object detector to extract target objects in images and a classifier to assign labels on the extracted regions. The findings of this study provide important knowledge for construction site monitoring in securing the performance of computer vision models in various environments.

Keywords Automated Training Data Collection · Pseudo Label Generation · Construction Site Monitoring · Object Detection

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1 Introduction

Previous studies related to construction management utilized computer vision models based on deep learning technology for safety assessment, productive analysis, and progress monitoring [1–3]. It is essential for such applications to secure the performance of the computer vision models. Recent approaches actively investigated deep convolutional neural networks which can show state-of-the-art recognition performance. As they require a large amount of training data to be trained, a few studies have proposed large-scale image datasets for construction entities and used them as the performance benchmark [4, 5].

Although a deep learning model is trained with a large-scale dataset, it tends to show poor performance in the target domain where the data characteristics are different from the original source domain where the training data was collected. To address this problem, previous studies have investigated the effectiveness of data augmentation, domain adaptation, and synthetic image generation methods [6–9]. However, the performance of deep learning models in the target domain generally is not comparable to the original one in the source domain.

Obviously, an easiest way to secure the performance of a deep learning model is to collect training data again from the target domain to which the model is applied. However, it entails labor-intensive and time-consuming efforts of data collection and annotation. To address this issue, this study presents an automated pseudo label generation method in a new target domain based on image pre-processing, moving object detection, and image classification. The key idea is to detect moving objects from a new construction site scene as they are most likely the target foregrounds (objects of interest) such as workers, dump trucks, and excavators; the extracted moving objects are then classified into one of the original classes or irrelevant objects for automated labeling. The labeled moving object instances can be used as pseudo labels for training object detectors. To validate the capability of proposed method in extracting moving objects and labeling them, CCTV videos collected from two construction sites were used. The following chapters introduce the details of the proposed method.

2 Pseudo Label Generation with Moving Features

The proposed method is largely divided into two processes, as illustrated in Fig. 1. The first process detects moving objects based on moving features which represent the change of features' locations over time in consecutive video frames. This study employs Recurrent All-pairs Field Transforms for Optical Flow (RAFT) [10] to recognize moving features of foregrounds in construction site scenes. The second process assigns class labels to extracted moving object instances using EfficientNetV2 [11] which is an image classification model. Object instances with the target

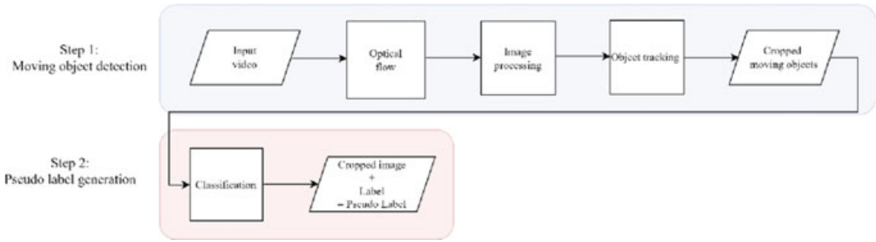

Fig. 1 An overview of the proposed method

class labels are used as pseudo labels that can be used to re-training a detection model.

2.1 Moving Object Detection

Optical Flow. Optical flow is a per-pixel motion estimation task between two consecutive video frames. The purpose of using optical flow is to automatically detect the location of moving construction objects of interest. The adopted optical flow model is RAFT, a supervised optical flow model that has reached high accuracy on KITTI dataset and showed a robust generalization capability [10]. RAFT outputs images displaying the moving objects in different colors according to the magnitude and direction of the movement, as shown in Fig. 2.

Image Processing. An output image generated by RAFT is converted into a binary image with bounding boxes, as shown in the left figure of Fig. 3. The boxes are created based on the coordinates of the contour of the detected moving objects. However, the binary images often contain numerous noises. Most of these noises are generated in the form of pixel-level noise, known as salt and pepper noise, by subtle movements of a camera and objects. To denoise the output binary images, this study applies three image processing methods including time-domain low pass filtering, morphological

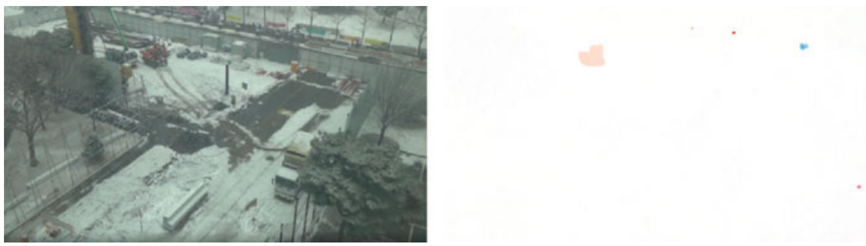

Fig. 2 An original construction site video frame (left) and the video frame processed by RAFT (right). Color blobs indicate moving objects

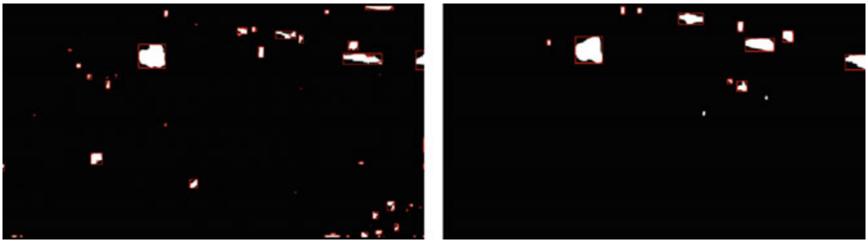

Fig. 3 Video frames before (left) and after (right) image processing

processing, and median blurring to get the accurate contour of moving objects, as shown in the right figure of Fig. 3.

Time-domain low pass filtering: The noise generated irregularly in consecutive video frames can be seen as a high frequency noise from the time-domain perspective. For example, if the movement of a feature is falsely detected in only two frames out of five consecutive video frames, this is a high frequency noise. This study applies a time-domain low pass filter to remove such noises from the batches of consecutive video frames.

Morphological processing: Morphological image processing such as opening and closing is applied to get the accurate contour of objects.

Median blurring: A median filter is used to remove outliers such as salt and pepper noise in the binary images.

Object Tracking. A lot of noise is removed by the previous image processing step, but some remains. To eliminate the remaining noise to obtain the consistent bounding boxes of the moving objects, Simple Online and Realtime Tracking (SORT), an object tracking algorithm, is used. SORT is an object tracking algorithm based on a Kalman filter and Hungarian algorithm which tracks the bounding boxes of the moving objects. SORT measures the Intersection over union (IoU) of the bounding boxes in consecutive frames and tracks them if the measured IoU is higher than a certain threshold [12]. Since most of bounding boxes falsely generated by some noises don't exist continuously, the measured IoU of them is either zero or small. Then, such bounding boxes are removed, and the moving objects of interest that are tracked by SORT are only cropped (Fig. 4).

2.2 Pseudo Label Generation

The classification model, EfficientNetV2, is employed to classify the bounding boxes into either one of the target classes or an irrelevant object category. EfficientNetV2 is known to have high accuracy with a training efficiency [11]. It is pre-trained by MOCS dataset [4] to leverage the benefit of transfer learning before used in the

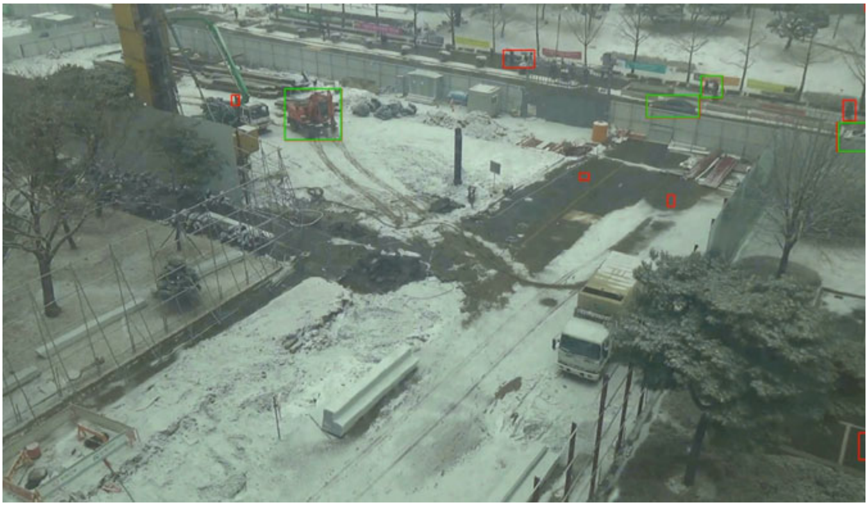

Fig. 4 Green boxes indicate the bounding boxes tracked by SORT

experiments. The classification model classifies the cropped images (the bounding boxes) as one of the target classes or a non-target class based on the class probability and the minimum threshold criterion. However, if the predicted probability is less than a certain threshold, it is labeled as a non-target class.

After the first cycle of pseudo label generation, the classification model is trained again with the generated pseudo labels. Then, the re-trained classification model is used to classify the cropped images labeled as a non-target class. With this, an image falsely classified as a non-target class can be correctly labeled as its true class. By iterating this process, more and accurate pseudo labels are obtained (Fig. 5).

3 Experiment and Result

3.1 Experimental Settings

To validate the proposed method, experiments were conducted to generate pseudo labels for moving objects of interest in two videos in different target domains. The length of videos was 70 s and 700 video frames were extracted. The target domain 1 had a single target class—excavators—and the target domain 2 had three target classes such as excavators, dump trucks, and workers, as shown in Fig. 6. As the same target classes are in MOCS dataset (the source domain), EfficientNetV2 was first trained by 800 training and 200 validation images for each class in MOCS datasets.

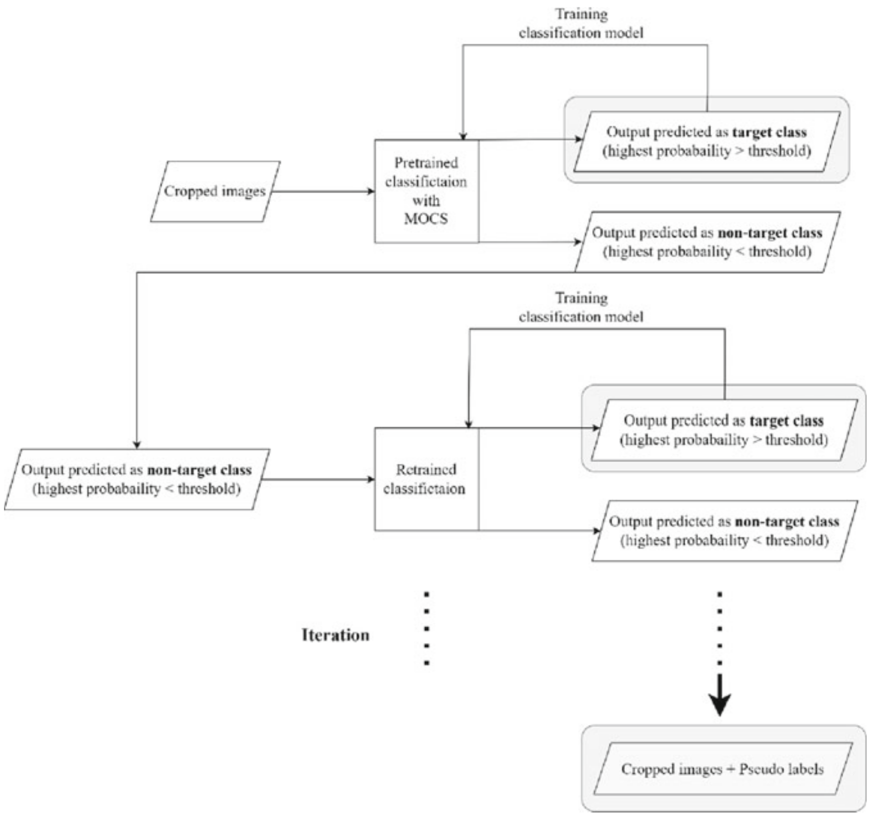

Fig. 5 Flowchart of generating pseudo label (Step 2)

Fig. 6 CCTV scenes of the target domain 1 (Left) and the target domain 2 (Right)

3.2 *Result and Discussion*

The moving objects were extracted by the first process, moving object detection, described in Sect. 2.1. Table 1 shows the results of detecting moving object instances.

Table 1 The number of the cropped images in the two target domains

	Total cropped images	Target class images	Non-target class images
Target domain 1	1136	314	822
Target domain 2	1147	863	284

For the cropped images, target and non-target class images were manually separated for the validation of the second process—pseudo label generation.

Since pseudo labels are used as training data, it is crucial to generate them with high precision. Therefore, the value of recall greater than 0.5 would be enough to obtain sufficient training images while achieving a high prevision value. The formula for recall and precision are shown as follows:

$$Recall = \frac{TP}{TP + FN} \tag{1}$$

$$Precision = \frac{TP}{TP + FP} \tag{2}$$

where TP represents true positives, FN represents false negatives, and FP represents false positives. To generate pseudo labels with high precision, the classification threshold of the classification model should be set to a high value such as 0.99. That is, EfficientNetV2 only assigned a target class label to a cropped image when the model has a confidence score greater than 0.99 in prediction.

Tables 2 and 3 show the results of pseudo label generation. It was found that the performance EfficientNetV2 to generate pseudo labels was improved when it was retrained with pseudo labels generated from the previous iteration. Recall was low when EfficientNetV2 was only trained in the source domain, but it was significantly improved from 0.012 to 0.824 when the model was re-trained with pseudo labels, as shown in Table 4. However, the precision value was decreased for dump trucks and workers as the iteration increased in the target domain 2, as shown in Table 5. The reason for the decrease in precision was conjectured that only the small number of pseudo labels were used to train EfficientNetV2, which caused the poor generalization of the model.

The precision of worker class in the target domain 2 is lower than other classes. A possible explanation for this result is that the worker instances in the target domain 2 are tiny and blurry. Since these images were used to train the classification model, resulting in producing more false positives.

Table 2 The result of the prosposed framework in video 1

		Predicted class			
	Iteration: 0	Dump truck	Excavator	Worker	Non-target class
Ground Truth	Dump truck	0	0	0	0
	Excavator	0	4	0	310
	Worker	0	0	0	0
	Non-target class	0	0	0	822
	Iteration: 2	Dump truck	Excavator	Worker	Non-target class
	Dump truck	0	0	0	0
	Excavator	0	259	28	27
	Worker	0	0	0	0
	Non-target class	0	0	0	822

Table 3 The result of the prosposed framework in video 2

		Predicted class			
	Iteration: 0	Dump truck	Excavator	Worker	Non-target class
Ground Truth	Dump truck	6	0	0	185
	Excavator	0	2	0	452
	Worker	0	0	10	208
	Non-target class	0	0	0	284
	Iteration: 2	Dump truck	Excavator	Worker	Non-target class
	Dump truck	173	0	0	18
	Excavator	21	421	0	12
	Worker	0	0	173	46
	Non-target class	1	0	91	192

Table 4 Performance of psuedo label in video 1

Number of iterations	Class	Precision	Recall
0	Excavator	1	0.012
2	Excavator	1	0.824

Table 5 Performance of psuedo label in video 2

Number of iterations	Class	Precision	Recall
0	Dump truck	1	0.031
	Excavator	1	0.004
	Worker	1	0.045
2	Dump truck	0.887	0.906
	Excavator	1	0.927
	Worker	0.654	0.788

4 Conclusion

This study presents the fully automated pseudo label generation method from construction site videos. The experimental results showed that the proposed method can extract target objects of interest successfully, and the annotation can be automated with high precision. The on-going research will further expand the investigation on the effectiveness of pseudo labels to train object detectors, thereby presenting the potential of automated domain adaptation of deep learning models for construction site monitoring.

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Instance Segmentation of Fire Safety Equipment Using Mask R-CNN

Angelina Aziz, Markus König, Sven Zengraf, and Jens-Uwe Schulz

Abstract In the construction field, Building Information Modeling (BIM) offers various application scenarios in the design, construction, and maintenance phases of a building's lifecycle. The utilization of BIM in the Operation and Maintenance (O&M) phase of existing buildings is a particular challenge, as suitable BIM models are usually not available as a basis. In this context, many researchers have investigated various methods to automatically create BIM models from existing information and data. Focusing on images, numerous methods have been investigated for detecting and classifying certain objects in buildings. However, despite the importance of fire protection in buildings, the research field has not focused on the benefits of the automatic recognition of fire safety equipment (FSE, e.g., fire blankets) in much detail. Particularly in existing buildings, the recurring inspection and maintenance of fire safety equipment is a responsible task and required by law. It is the responsibility of the owners and facility managers to ensure the availability and proper functioning of fire safety equipment in the building.

Consequently, this work aims to contribute to this research area by investigating the state-of-the-art Mask Region-Based Convolutional Neural Network (Mask R-CNN) for instance segmentation and object detection of FSE in RGB images. The results show that this approach automatically extracts valuable semantic information that provides the presence of fire safety equipment in images. In addition, this study investigates the influence of hyperparameter adjustment on the detection of FSE objects in indoor scenes. It is also examined how the additional use of augmented data improves the performance of the neural network.

Keywords Object Detection · Instance Segmentation · Mask R-CNN · Fire Safety Management

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1 Introduction

In the field of fire safety management, BIM can be utilized for several applications. For instance, in the early design process of a new building, a fire safety de-sign can be directly integrated into the BIM model. However, for many existing buildings, fire safety information is often missing or unclear due to a lack of doc-umentation. Typically, a well-prepared fire safety management plan outlines controlling, monitoring, and inspection of fire safety standards. Depending on the country-specific safety regulations for buildings, a minimum number of fire extin-guishers must be provided according to legal requirements. With the help of in-stance segmentation, for example, the number of fire extinguishers in an image can be determined. This information can be used to update the BIM model and check whether it is necessary to upgrade the building with additional fire extin-guishers (or other equipment) or not. In contrast to secondary components like FSE, previous studies mainly focused on detecting and segmenting large structural components such as walls, floors, ceilings, and columns [1]. Thus, this paper at-tempts to contribute to the automation of FSE inspection and maintenance by facilitating the manual work of a fire safety inspector. Consequently, the objec-tive of this study is to develop a neural network for the automatic detection of indoor fire safety equipment in RGB images. To achieve this goal, several steps are made:

- Construction of a customized Mask R-CNN framework.
- Deployment of transfer learning by utilizing pre-trained weights on the Microsoft Common Objects in Context (MS COCO) dataset [2].
- Performing the training and validation process with self-made images and additional image data from the FireSet dataset [3].
- Performance analysis and further improvements of the network's hyperparameters.
- Use of data augmentation to increase the number of training images.

2 Related Work

Several pieces of literature point to making fire maintenance and prevention more sensing, data-driven, and BIM-related [4–6]. In [4], a system for semantically linking video object recognition results with building information models for fire safety and incident management was proposed. It gives feedback about the loca-tion estimation, fire location, evacuation guiding, and fire forecasting. For thermal image analysis on fireground understanding, the authors implemented a Faster R-CNN network which was trained and evaluated on the Microsoft COCO visual object detection dataset. The COCO dataset consists of 200.000 labeled images for 80 object categories and supports object segmentation.

Also, several researchers [7, 8] addressed the recognition and pose estimation of selected FSE in their experimental studies. However, their work is limited to 3D point clouds. Moreover, [7] highlighted the poor quality and resolution of or-thoimages generated from point clouds for the detection of components and em-phasizes the need for new strategies. In [9], researchers trained a You only look once (YOLO) neural network for the detection of fire emergency assets like fire extinguishers and exit signs. They took use of the COCO dataset weights for transfer learning. However, their study is limited to obtaining bounding boxes rather than object instance masks.

It is noticeable that instance segmentation is often used as a method for vision-based robotic grasping through object tracking and localization [10–12]. But re-cent advances in computer vision and pattern recognition have also stimulated the investigation of instance segmentation in the construction and operation field. In [1] the authors presented a fully automatic approach to recognize and segment as-is BIM objects with arbitrary shapes (wall, door, lift, ruler) from images by adapting Mask R-CNN. Besides studies investigating the detection of simple vehi-cles and pedestrians [13], researchers utilized Mask R-CNN to detect and segment two types of construction machinery using RGB data [14].

Nevertheless, there has been no detailed investigation of the utilization of Mask R-CNN [15] for the detection of FSE. To address the aforementioned limitations, this study investigates the detection of FSE in RGB images at instance level. First-ly, this paper gives an overview of the specific architecture and functionality of Mask R-CNN. Subsequently, the setup of the training system and implementation details for instance segmentation of FSE are specified. After training, the influ-ence of hyperparameter adjustments is evaluated using test image data. Finally, the discussion and conclusion part deals with the juxtaposition of the results and limitations of the case study.

3 Methodology

3.1 Technical Background

The recent evolution of machine and deep learning methods in the computer vision field shows promising results for object detection, especially in images. Currently, the Mask R-CNN [15] outperforms previous object detection methods like Fast R-CNN [16] and Faster R-CNN [17]. It combines object detection, where the goal is to classify objects of interest and localize each using a bounding box, with semantic segmentation, where each pixel is classified into a fixed set of clas-ses without differentiating object instances [15]. Thereby, instance segmentation can be carried out on images, which means identifying object outlines at the pixel level. Mask R-CNN [15] adopts the two-stage system of Faster R-CNN [17]. The first stage scans the image and generates proposals on whether the area contains an object or not. In the second stage, in parallel to predicting the class and box offset, Mask R-CNN also outputs a binary mask for each Region of Interest (RoI). Thus, Mask R-CNN extends Faster R-CNN with a branch for predicting an object mask in parallel to the existing branch

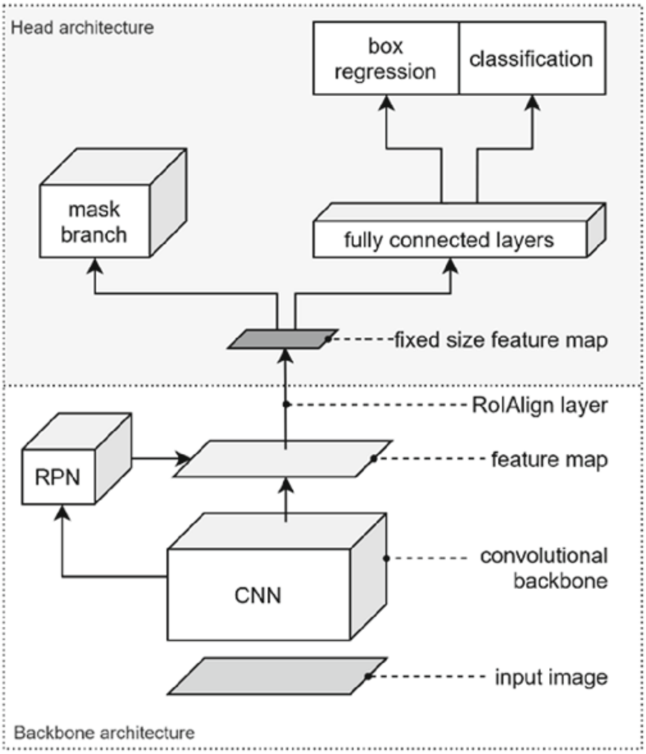


Fig. 1 The network architecture of Mask R-CNN

for bounding box recognition [15] (see Fig. 1). The motivation behind this study is to get closer to the human way of object perception. Rather than Faster R-CNN, recent YOLO networks or other algorithms only output a bounding box and a class probability label associated with that box. The way humans locate objects in real life is not by drawing a box around them, rather we examine the outline and pose of the object.

Therefore, this study aims to detect fire protective blankets, portable fire extinguishers, manual call points and smoke detectors at an instance segmentation level in RGB images. The specific network's architecture and its use for transfer learning in this study are explored in the next subsections.

3.2 Network Architecture

The backbone architecture of Mask R-CNN starts with a Deep Convolutional Neural Network (DCNN) which is applied to the input images (Fig. 1). While Fast R-CNN [16] still used a not trainable selective search algorithm to generate RoIs, it was found to be feasible that selective search could be replaced by a region proposal network (RPN). The feature maps from the CNN are used for the RPN to generate region proposals and for the RoIAlign layer in the following part.

The RPN itself has a classifier and a regressor. The classifier determines the probability of a sliding window having the target object by computing the Intersection-over-Union (IoU) with the Ground Truth (GT) boxes. Box regression corrects the coordinates of the proposals. The RPN algorithm is a robust and transla-tion invariant method for obtaining object proposals. Next, the feature maps including the RoIs are processed through the RoIAlign layer which extracts a fixed-size window from the feature map. RoIAlign uses bilinear interpolation to compute the exact values of the input features at four regularly sampled loca-tions in each RoI bin, and the result is then aggregated by using max or average pooling. Because pixel-level segmentation requires much more precise alignment than bounding boxes, Mask R-CNN improves the RoIPool layer from Faster R-CNN by the RoIAlign layer, which solves the problem of harsh quantization by representing fractions of a pixel. In the head architecture, the fixed-size feature maps are processed forward into three outputs. In parallel to predicting the class and box offset, Mask R-CNN additionally outputs a binary mask for each RoI [15]. For a more detailed explanation of RPN and other network components, the reader is referred to [15] and [17].

3.3 FSE Datasets

To train the network, labeled input data is necessary. Since this study makes use of transfer learning, pre-trained weights on the COCO dataset [2] are used. The pretrained COCO weights are used to boost the performance of the network and improve the recognition in real scenarios by the presence of multiple objects. However, large-scale datasets like COCO or ImageNet [18] do not contain specific FSE. It is also a common practice to pre-train neural networks on large datasets before fine-tuning them on smaller domain-specific datasets. To refine the pre-trained network, a domain-specific dataset is considered.

Data Acquisition. For additional input images, FireNet [3] is used which is an open machine learning training dataset for visual recognition of fire safety equipment. This dataset is well structured and links the objects directly to their respective Uniclass, a classifica-tion management system for object naming convention. It enables several ma-chine learning scenarios like classification, object detection, and semantic segmentation. Since the data is recorded in England, additional self-made images from different countries were considered for this study to balance and increase the data for the four FSE objects (Table 1). The goal was to let the images vary due to different environmental conditions, such as different lighting conditions (e.g., daylight, artificial light) or backgrounds. Likewise, the FSE objects contain different designations due to different languages. Nevertheless, the object masks of the individual FSE classes are almost the same regardless of which country the image originates from. The composition of training and validation datasets is presented in Table 2.

Data Preparation. Besides data acquisition, the neat annotation of the images was an important part of this work. For this purpose, the VGG Image Annotator Tool (VIA) [19] was used to manually define and describe FSE regions in an image.

In total 760 images were labeled by annotating 1046 FSE objects. More precisely, 215 blankets, 299 fire extinguishers, 338 manual call points, and 194 smoke detectors were annotated. There is no consensus in the literature on whether a certain minimum number of images in a dataset is necessary to improve network recognition of the object at first sight and with a high level of confidence. In projects similar to this one, a training set of 50 to 500 images is usually compiled for transfer learning with Mask R-CNN. Depending on the use case scenario, it is also typical for the dataset to be

Table 1 Extract of self-made FSE Dataset

Fire blanket	Fire extinguisher
	
Manual call point	Smoke detector
	

Table 2 Number of images in the training and validation dataset

Dataset	Training dataset	Validation dataset
D01	100	25
D02	200	50
D03	300	80
D04	400	100
D05	500	130
D06	600	160
D07	538	59

slightly imbalanced, as there are several annotated objects in each image belonging to different object classes.

Still, it is of interest how many images are required for the neural model to provide sufficient results. Therefore, different compilations of the datasets are created, which are shown in Table 2. The dataset D01 consists of the maximum number of annotated images in this study. From D01 to D06, we allocated 75% of the images to training, and 25% to validation. However, after the evaluation of the first training sessions and a quality check, a modified dataset was prepared which was cleaned up by disregarding different versions of FSE objects. For example, a fire blanket can be stored in a PVC box (hard case) or a PVC bag. Since there are predominantly images showing fire blankets in PVC bags, the images with PVC boxes were excluded because they could lead to confusion of the neural model and are also not sufficient to form an additional class. In addition, D07 focuses on a different distribution of the datasets. 90% of the images belong to the training dataset and 10% to the validation dataset.

All networks were tested with the same test dataset to make the tests comparable. This test dataset consists of 26 test images.

3.4 *Training Setting*

In the presented study, Python 3.8.8, CUDA v.11, and CUDNN 8.0 were utilized. The study uses the latest GitHub repository release of Mask R-CNN 2.1 from Waleedka [20] which is compatible with a Tensorflow version higher than 1. Therefore, Tensorflow 2.4.1 and Keras 2.4.3 were utilized. The repository provides the source code of Mask R-CNN built on Feature Pyramid Network (FPN) and a ResNet101 backbone. However, the pre-trained COCO weights are not updated in this release. Thus, the weights as a.h5 file are used from release 2.0. As mentioned earlier, these weights are obtained from a Mask R-CNN model which was trained on the COCO dataset.

Next, the model configuration parameters are specified. These parameters control the number of classes including background (= 5), image size, number of GPUs (= 1), number of images to train with on each GPU (= 1), and more. Follow-ing the Eq. (1), we set the batch size to 1 since inference should only run on one image at a time:

$$BATCH\_SIZE = IMAGES\_PER\_GPU * GPU\_COUNT \tag{1}$$

Also, the mode of the Mask R-CNN model is set to “training” instead of “inference”. The inference mode is selected at a later stage which refers to the process of using the trained algorithm to predict new data.

Detection Metrics. To rate the network’s performance after the training, several important object detection metrics must be clear. Many object detection challenges like PASCAL VOC or the COCO challenge are using the same evaluation metrics intending to compare the models. For more information on the metrics explained below, the reader is referred to [21].

One popular evaluation metric for object detection is the mean Average Precision (mAP) which is used for evaluating the neural model. Before understanding mAP, the terms precision and recall should be clarified. Precision is a metric value that is defined as the number of True Positives (TP) divided by the sum of True Positives (TP) and False Positives (FP):

$$precision = \frac{TP}{TP + FP} \tag{2}$$

For object detection, precision is not enough since it is only concentrating on how accurate the predictions are. For this purpose, recall is defined as the number of True Positives (TP) divided by the sum of True Positives and False Negatives (FN). The sum of TP and FN represents the number of ground truths:

$$recall = \frac{TP}{TP + FN} \tag{3}$$

To calculate precision and recall, one must decide whether a prediction for an object is correct or not. This is defined by the Intersection over Union (IoU). It is the area of the intersection divided by the area of the union of a predicted bounding box

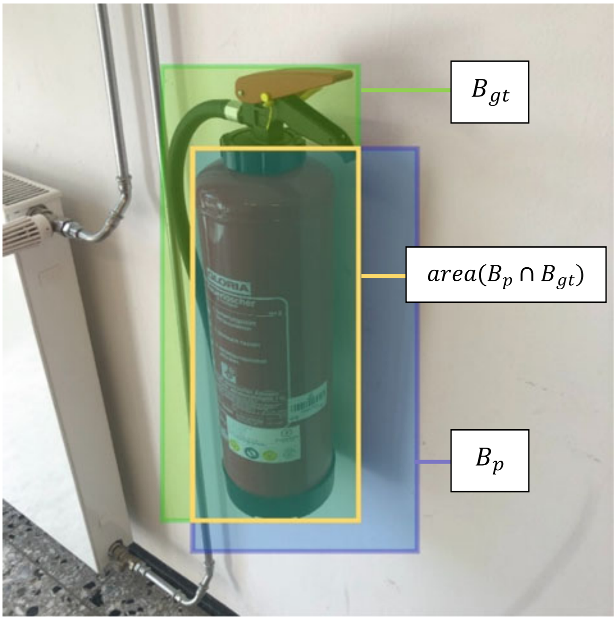


Fig. 2 Calculation of Intersection over Union (IoU)

and ground truth object (see Fig. 2). The formula for calculating the IoU is:

$$IoU = \frac{area(B_p \cap B_{gt})}{area(B_p \cup B_{gt})} = \frac{Areaofoverlap}{Areaofunion} \tag{4}$$

Also, this IoU value needs to be specified as a threshold in advance before calculating precision and recall. Consequently, a detection is considered TP when the predicted bounding box has an IoU greater than a threshold (e.g., > 0.5) with the ground truth.

The precision-recall (PR) curve indicates the association between precision and recall. Average precision (AP) which is based on the precision-recall curve, represents the area under the PR. In essence, AP is the precision averaged across all unique recall levels. The precision at multiple recall levels is interpolated before calculating AP. The interpolated precision p_{interp} at a certain recall level r is defined as the highest precision found for any recall level $r' \geq r$:

$$p_{\text{interp}}(r) = \max_{r' \geq r} p\left(r'\right) \tag{5}$$

The definition of interpolation methods varies from competition to competition. It has a minimal but still significant impact on the resulting outcome. However, the calculation of AP only involves one class. In object detection, there are usually K > 1 classes like in this study. Thus, mean average precision (mAP) is defined as the mean of AP across all K classes:

$$mAP = \frac{\sum_{i=1}^{K} AP_i}{K} \text{ for K classes} \tag{6}$$

Like AP, Average Recall (AR) is also a numerical metric that can be used to compare detector performance. In essence, the calculation of the mAR is similar to the mAP, except that the recall behavior is analyzed using different IoU thresholds. AR is the recall averaged over all IoU ∈ [0.5,1.0] and can be computed as two times the area under the recall-IoU curve, where o is IoU and recall(o) is the corresponding recall.:

$$AR = 2\int_{0.5}^{1} \text{recall}(o)do \tag{7}$$

Mean average recall (AR) is defined as the mean of AR across all K classes:

$$mAR = \frac{\sum_{i=1}^{K} AR_i}{K} \tag{8}$$

Also, the F1 score can be interpreted as a harmonic mean of the precision and recall, where an F1 score reaches its best value at 1 and worst score at 0. The relative contribution of precision and recall to the F1 score are equal. The formula for the F1 score is:

$$F1 = 2\frac{(precision * recall)}{(precision + recall)} \tag{9}$$

In the multi-class and multi-label case, this is the average of the F1 score of each class with weighting depending on the average parameter. In the following chapter, the evaluation metrics mAP, mAR and F1-score are used to compare the performance of different training sessions.

The next chapter summarizes and compares the results of the different training sessions and their hyperparameter modifications.

3.5 Training Modifications

To contrast the performance of different training sessions and the effect of hyperparameter adjustment, Table 3 serves as a technical overview.

In the first training sessions T01 - T06 in Table 3, the model is trained on different datasets which are presented in Table 2. The goal was to test the effects of the different numbers of images in the datasets provided to the algorithm for training. This was done to eliminate data that resulted in poor performance due to incorrect annotations or extremely imbalanced object classes. It was also of interest, how much data is necessary to achieve a robust detection of the respective object classes. Hyperparameters such as the number of epochs, learning rate, IoU, and network components such as backbone were adjusted to observe their relevance for training the algorithm. Previous training sessions were made which are not shown in the table.

Table 3 Overview of different training sessions and their hyperparameter adjustments

No	Dataset	Description	mAP	mAR	F1
T01	D01	30 epochs, ResNet101	3.21%	82.05%	6.17%
T02	D02	30 epochs, ResNet101	9.62%	76.92%	17.09%
T03	D03	30 epochs, ResNet101	19.23%	57.69%	28.85%
T04	D04	30 epochs, ResNet101	35.26%	41.67%	38.20%
T05	D05	30 epochs, ResNet101	31.09%	59.62%	40.87%
T06	D06	30 epochs, ResNet101	65.93%	84.62%	74.12%
T07	D06	60 epochs, ResNet101	46.15%	65.38%	54.11%
T08	D07	30 epochs, ResNet101	70.19%	83.97%	76.47%
T09	D07	30 epochs, ResNet101*	**79.17%**	**91.67%**	**84.96%**
T10	D07	30 epochs, ResNet50*	51.28%	55.13%	53.14%

* Applying the data augmentation to the training dataset

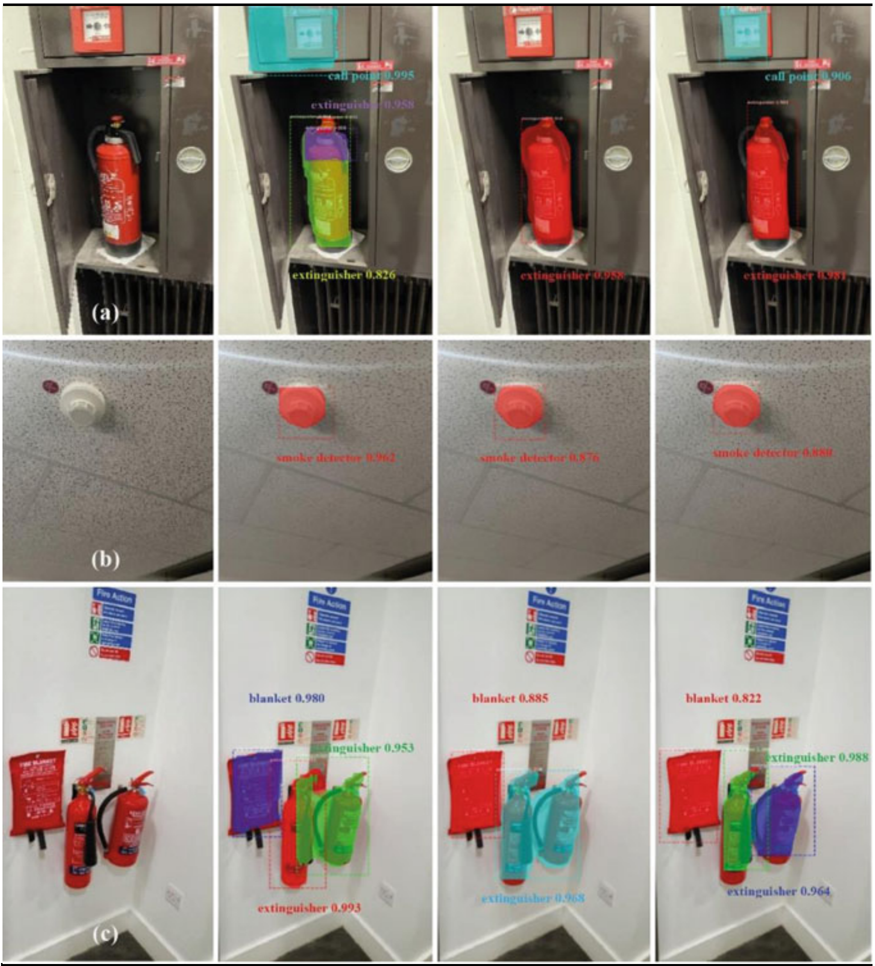
The purpose was to vary the image size for training. The best results were always made with an image size of 1024 × 1024 pixels. The validation graphs of training sessions using image sizes like 128 × 128 pixels, 512 × 512 pixels, and 1600 × 1600 pixels were extremely noisy. Thus, the training sessions stick to an image size of 1024 × 1024 pixels. The training session T07 comprises 60 epochs which is the only difference from T06. The sessions T08 to T10 utilize the D07 dataset. In T09 and T10 augmentation techniques were set up. In addition, T10 uses ResNet50 as a backbone instead of ResNet101. T09 model performs best by correctly detecting two fire extinguishers and one fire safety blanket. T06 also correctly detects the objects of interest. However, the output masks and the bounding boxes are not as refined as in the T09 output. T08 performs not badly as well, but it summarizes the two extinguishers as one extinguisher object which is not correct. The fire blanket is detected correctly.

3.6 Evaluation

Considering sessions T01 to T06, it is noted that the number of images in the dataset plays an important role in the accuracy of the model. From T01 to T06 the mAP, mAR, and F1-score increase drastically (small fluctuation at T05). This confirms the fact that machine learning models are only as powerful as the data provided for training. Since T06 performed best, the next training session (T07) stuck to dataset D06 but has an increased number of epochs for training. The results indicate that the performance of the model got worse over the training. The model has started to memorize the training set, especially object classes that occur more frequently in the data set than others. Thus, T08 focuses on 30 epochs and utilizes D07, a quality-assured dataset. This dataset eliminated some difficult images that could confuse the model during training. This led to better results for the model than in T06. For further improvements, augmented images are generated in T09. This training session produced the best results in this study. The mAP is 79.17%, mAR 91.67% and the F1-score 84.96%. In the T10 model, a ResNet50 backbone is considered instead of ResNet101. However, the results show that it leads to poorer results. Table 3 illustrates the different results of the tested weights of sessions T06, T08, and T09 since these received acceptable results. Three different testing images (a-c) were chosen for a comparison of the trained models. The respective Mask R-CNN models return predicted class IDs, confidence scores, bounding box coordinates, and segmentation masks. The IoU threshold is set to 0.8 which is often used as a default threshold. The ground truth image (a) in Table 4 shows a fire extinguisher and a manual call point. The prediction of the T06 model shows bulky masks and a wrong detection of the number of objects. In total two fire extinguishers and one manual call point were detected. The T08 model performs better by detecting the fire extinguisher. However, the manual call point is not detected. The optimized model trained on augmented images performs best. It recognizes one manual call point and one fire extinguisher in the test image (a). Also, the output masks are adequate. In test image (b), all models

Table 4 Overview of inference results

Ground Truth	T06 - Inference	T08 - Inference	T09 - Inference



perform well. The smoke detector is detected by all models with high confidence (> 88%). For test image (c), different results are noticeable.

4 Discussion

After evaluating the performance of different trained models, several assumptions can be made. Several factors exist and influence the performance of a neural model. The most important factor for training a robust neural model will always be the amount

Table 5 Training Data Distribution of Dataset D07

Dataset	Blanket	Call point	Extinguisher	Detector
D07	117	253	222	153
Total	16%	34%	30%	20%

of data and its quality. In this study, experiments were conducted by training models on different datasets. It was found that the more images available, the better the accuracy of the models. However, after a quality check of the annotated images, some minor mistakes were found and eliminated for the next training sessions. Quality assurance is an essential step before training the algorithm, especially when multiple people annotate the dataset. An incorrectly labeled object can lead to incorrect feature extractions. Also, in images, some objects can be overrepresented, whereas others can be underrepresented. However, most of the machine learning algorithms start to bias toward one class if it is more present in the training data than other classes. A query about the number of objects in dataset D07 gives the distribution shown in Table 5. It is significant, that the object class call point is most prominent and probably contributes more to the loss function. Also in [21], it is discussed thoroughly how sample size per object class affects a deep learning model performance metrics.

The distribution of the test data was also checked, and it is much more balanced than the training data. If there was no difference in distribution between the training and testing dataset, the results would be better. In addition, the presence of redness and the boxed shape of similar FSE assets (e.g., call point and blanket) can lead to confusion between classes and no clear separation. In most cases, this leads to overfitting of the neural model.

Nevertheless, the presented results show a trained model which can detect FSE objects in images. The architecture of Mask R-CNN enabled an efficient training of the FSE classification task. The output masks of the detected FSE objects are most of the time precise. However, the pixel accuracy and the precision of the output masks can be fine-tuned by increasing the amount of data.

5 Conclusion

The segmentation of instances in image data has become an increasingly important, complex, and challenging area of research within machine learning. It localizes different classes of object instances in an image by predicting the class label and the pixel-specific instance mask. This paper contributes to the use of instance segmentation in the field of the facility management of a building. More specifically, this study is intended to serve as a foundation for future studies on automating fire safety inspections. In this paper, an approach for detecting four classes of objects (fire blanket, fire extinguisher, manual call point and smoke detector) in RGB images is presented. It included image data acquisition and labeling for the instance segmentation task. The use of the neural network Mask R-CNN, transfer learning, and augmented images enabled a well-performing FSE detection in unknown images. Future work will concentrate on localizing the detected objects and transferring them to an existing BIM model.

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Blockchain Technology as a Monitoring Tool for Sensor Data

Jascha Brötzmann, Jyotiraditya Panda, and Uwe Rüppel

Abstract In the scope of this paper the profitable use of blockchain technology or so-called distributed ledger technologies in the context of Structural Health Monitoring (SHM) will be examined.

SHM is the continuous or periodic and automated method for determining and monitoring the condition of an object. This is done by measurements with permanently installed or integrated sensors and by analyzing the hereby generated data. During those monitoring periods it often happens that some of the installed sensors are not working correctly. This may be caused by interference, by a corruption or even a manipulation. Therefore, the sensors can deliver abnormal data. Consequently, the delivered data is the starting point to overwatch the function of the sensors. Since on the monitored object multiple sensors are in use the measured data of those different sensors can be compared. If one sensor delivers deviating data it is likely that the sensor is not working the way it should. This verification process is being automated with blockchain technology. The correctness of the sensor data is then stored with the measured data itself on the chain. Thus, the entire generated information is securely and reliably tracked within the blockchain. Another advantage is the high scalability and decentralization of the blockchain. This is especially important when dealing with monitoring systems that can also have the need for scaling. For this described use case the implementation and application of the blockchain *Hyperleder Fabric* will be shown in the scope of this work.

Keywords Blockchain · Data security · SHM

1 Introduction

In the area of blockchain respectively distributed ledger technologies a lot has changed since the publication of the white paper about *Bitcoin* from Satoshi Nakamoto [1] almost fifteen years ago. Many different types of blockchains emerged with a wide range of possible applications. The reason for that is the transferability

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of the original thought of a peer-to-peer electronic cash system onto other sectors. For example, these areas are healthcare, logistics, media or, like discussed and implemented in the scope of this paper, the AEC industry (Architecture, Engineering and Construction). The AEC sector itself is characterized by a high collaborative process because of the involvement of a lot of different participants like architects, engineers, technicians, planers or managers. These participants are well known and trusted but are not always involved with the same interests. As well, a lack of collaboration can make it more difficult to archive the set goals. In today's known working environment exist different ways to ensure control functionalities and trustworthiness to tackle those problems. Also, it is possible to grant different access options to ensure privacy of data. The most used software solution for that is the common data environment [2]. It centralizes data storage of the project and allows further and different functionalities. However, here lies one of the first weaknesses of this system. With the centralization the scalability of the software is limited. Furthermore, the external clients have to trust the third party, which is offering the software, that everything works correctly, e.g. data verification and analysis. Blockchain or so-called distributed ledger technologies offer a solution for these described problems [3].

Another increasingly important topic in the AEC industry is the monitoring of already existing structures, often referred to as Structural Health Monitoring (SHM). Shortly, the aim is to have an intelligent infrastructure that can monitor itself. Thus, it needs to be equipped with sensors and IoT (Internet of Things) devices to monitor the structure [4]. Those installed sensors generate a lot of data. During the monitoring periods these devices can have malfunctions or even manipulations. But if the incoming data is monitored the devices are as well monitored so that unusual deviations in the measurements of the different devices are detectable. The mentioned blockchain technology can be used to automate this verification process of the sensors. Furthermore, with its high scalability and decentralization the blockchain is a perfect solution for this use case. The verified data is then securely, reliably and tamper-resistant stored within the blockchain. In addition, blockchains deliver the possibility to encrypt the transferred data which may be useful when dealing with sensitive monitoring data.

2 Conceptual Overview

Like briefly described, most structural health monitoring and data storing systems in civil engineering use centralized systems. E.g., a centralized so-called common data environment [2] is used for storing project specific information like documents, three-dimensional models and other data. This as well is mainly the case for cloud-centric IoT architectures [5]. In a centralized framework, data collected by sensors are pushed to one centralized server and analyzed locally on that server. There are many points of failure in a system like this. Any failure of the centralized server would lead to a complete failure of the monitoring framework. A centralized framework has limited scalability since a single server has limited storage and can only handle

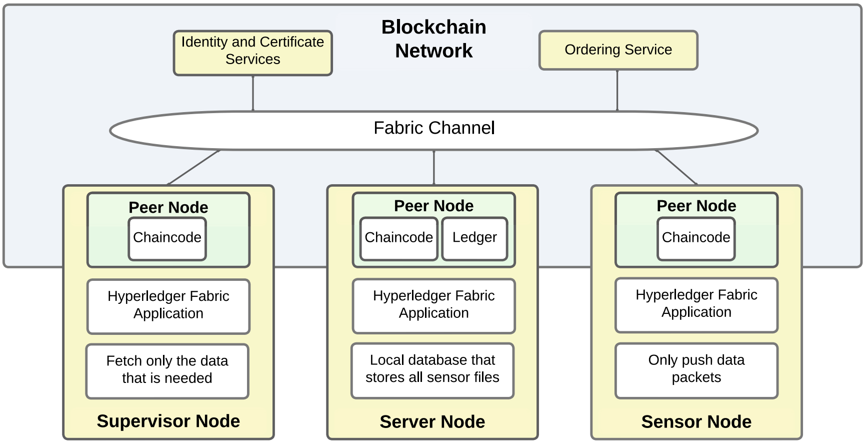


Fig. 1 High level schematic of the blockchain framework

a limited number of network requests. Lastly, any external client has to trust that the data verification and analysis carried out on the server is correct since processes in a centralized server can't be audited without introducing data security risks.

To tackle the aforementioned problems, we propose a distributed structural monitoring framework based on blockchain in which data from individual sensors from every structure in the monitoring network gets verified and added to a distributed network of servers. A high level schematic of the framework is shown in Fig. 1. Data pushed by each sensor first gets verified by the blockchain network to ensure the coherence and validity of the data. Then, the sensor data gets stored in a local server and a backup copy in a remote server. Lastly, the distributed ledger of the blockchain records the data verification results and the main and backup storage locations of the data. Any authorized client can interact with the network by pulling the sensor data based on the records stored in the blockchain and add comments and scores about the stability of the structures in the network.

Unlike a centralized framework, a distributed framework similar to the description above gives significant advantages of trustworthiness, robustness and scalability. Multiple server nodes in the network will carry out the verification of each sensor data packet pushed to the network. So, a client does not have to blindly trust one centralized agent. Furthermore, this framework has no single point of failure like a centralized server and it scales proportionally to the size of the network in terms of storage capacity and computational power.

3 Research Background

3.1 Blockchain Respectively Distributed Ledger Technology

The terminologies blockchain (or block chain) and distributed ledger technology are being used interchangeably since the meanings of the terms are similar. There are small differences but in general one of the main goals of this still further evolving technology is the immutable storing of data. Nevertheless, this technology is not just meant as a different database. With the so called consensus protocol and smart contracts (or chaincode) it is as well possible to set rules how data is stored in the chain [6]. That is why there are many possible areas of application in different fields of the economy.

Well known blockchains are *Bitcoin* and *Etherum* which among other things are used as a peer-to-peer electronic cash system and thus mainly in the finance sector (keyword: *definance*). These are originally un-permissioned ledgers. This means that the technology is open to any person who wants to use it and in consequence anyone can push data to the blockchain. The opposite to un-permissioned ledgers are permissioned systems [6]. In the AEC domain, like already described, mostly known members are contributing to the shared project. That is why a permissioned ledger makes more sense because then, for example, a proof-of-work protocol like Bitcoin is using [1] is not necessary.

Since there are different permissioned ledgers available it is necessary to analyze for what it will be used. There are already papers looking into those different ledgers and comparing them [7]. For the here planned monitoring tool of sensor data the ledger *Hyperledeger Fabric* is chosen. *Hyperledeger Fabric* is an extensible open-source and modular architecture developed in an umbrella organization [8]. Written in general-purpose programming languages and with the help of container technology, e.g. Docker, it is a highly flexible and quickly implemented software. Since it is Linux based it can be run completely open source. It is widely applicable through its modularity. The network is formed through a set of nodes [9]. Because of all of these properties, *Hyperledeger Fabric* is best suited for the use-case presented in this paper.

3.2 Blockchain Technology in the AEC Sector

In the AEC sector most ongoing research is looking into the profitable combination of blockchain and Building Information Modeling (BIM). The main reason for that is the decentralization and tracking of the data. There are already papers summarizing the progress like *Kuperberg and Geipel* [10]. Therefore, this will not be further discussed in this paper since the focus lies on the tracking and verifying of sensor or as well IoT data. Generally, the tendency is that the blockchain technology will run in the background of the existing and well known BIM-software. No one will use it actively or implement a separated tool as this is too time consuming [3]. In the area of using blockchain for sensor or IoT devices the situation is a bit different. There are also proprietary systems from different providers available that offer specific solutions for their own monitoring systems like the company *HBM* [11]. However, these systems could be replaced with blockchain based new applications that offer an open source solution. A look at the Technology Readiness Level [12] confirms this. It shows that most concept phases ended in 2020 and that now the demonstration phase started [13]. This as well is visible in the research field where more and more specific applications of blockchain technologies are described and implemented. An overview gives, for instance, the paper from *Uddin et al.* [14]. Also firms are using the now applicable blockchain technology. For example, Nokia offers a *Blockchain-Powered IoT Sensing as a Service for Smart Cities* [15]. Even so, here the question arises how this is implemented and how much this solution costs. This paper is showing an application and therefore a demonstration of a possible use case of the here chosen ledger. Like described, it is based on the open source architecture *Hyperledger Fabric* and can thus be used anywhere.

4 Data Verification and Consensus

Since the distributed system framework proposed in this paper is for a very wide-scale implementation, it is important to ensure that data packets being recorded by the network are valid and un-corrupted. Sensors that monitor structures such as acceleration and strain sensors are extremely sensitive. Minor changes in installation conditions could yield wildly different results. Hence, in a large scale implementation it is possible that a significant number of sensors might provide corrupted results. If data packets from corrupted sensors get added without proper data management, it would become very difficult to separate *good* data from *bad* data. This would cause a lot of problems when the data stored in the blockchain network is used for structural or other further analysis.

With a blockchain-based automated data verification protocol, the correctness of all data packets being pushed to the network can be analyzed and recorded with the data packets when they are being stored. As a result, engineers and data analysts can easily find and analyze the inconsistent data to investigate whether there are defects or other irregularities with the structures in the network. Additionally, having a measure for correctness for sensor data packets would help to keep track of sensors that regularly send inconsistent data. Since constructions and infrastructures, like bridges, don't normally change significantly over time, sensors should report quite consistent results. Hence, a sensor trust score can be created to keep track of how inconsistent sensor data packets are. This will help to keep track of sensors that are performing somewhat *badly*.

4.1 Verification Process

In most structural monitoring frameworks, structures are equipped with multiple sensors. Many sensors are also installed very close together and, as a result, they produce very similar data packets. Making this assumption and taking this as a requirement for the network, a sensor verification process can be implemented. In this process the correctness of a data packet is analyzed by comparing the data packet to data packets from neighboring sensors and analyzing if the differences between those data packets are consistent over time. During a new data report we classify the data packet from the sensor as being faulty if there are significant differences between a data packet from a sensor and data packets from its neighboring sensors. Figure 2 shows a detailed schematic workflow of this verification process that will be explained in more detail in the following part.

In the context of this paper, only data from acceleration sensors is considered. Nevertheless, the process is valid for any type of sensor. An acceleration sensor gets activated and generates a data packet when the structure it is installed on experiences some change in load or another trigger event. Data packets provided by the sensor encode the vibration the structure experiences as a result of the change in load. By analyzing the vibration response in frequency domain, we can obtain frequency peaks of the vibration experienced by the structure. As described in [16] and [17], most significant components of these vibrations correspond to the natural frequencies of the bridge. Due to the non-linear nature of most structures, sensors might report slightly different frequency peaks depending on the location where they are installed [16]. However, if they are reporting different set of peaks, the difference should stay roughly the same. If a singular sensor reports wildly different peaks than neighboring sensors, it is most probably due to faults in that sensor itself. Hence, it is a good indication that a sensor is faulty if the sensor's frequency peaks suddenly change and become significantly different while the peaks of other sensors continue maintaining the same difference with each other. If the differences in the set of peaks reported between neighboring sensors start varying significantly, a change in the structure is possible.

Numerous approaches can be implemented to analyze the frequency response of acceleration sensors. Analyzing arithmetic means of raw acceleration curves, comparing PSD responses of acceleration curves and evaluating the arithmetic means of PSD responses themselves are some common ways to analyze the frequency responses generated by acceleration sensors.

Various algorithms can be used to convert a vibration response in time domain into a response in frequency domain. Two common algorithms include Fast Fourier Transform (FFT) and Power Spectral Density (PSD) [18]. Unlike FFTs, PSDs are normalized to the frequency bin width preventing the duration of the data set (and corresponding frequency step) from changing the amplitude of the result [18]. Since data packets received by sensors are of variable lengths, PSD is the superior algorithm for dealing with data packets from acceleration sensors.

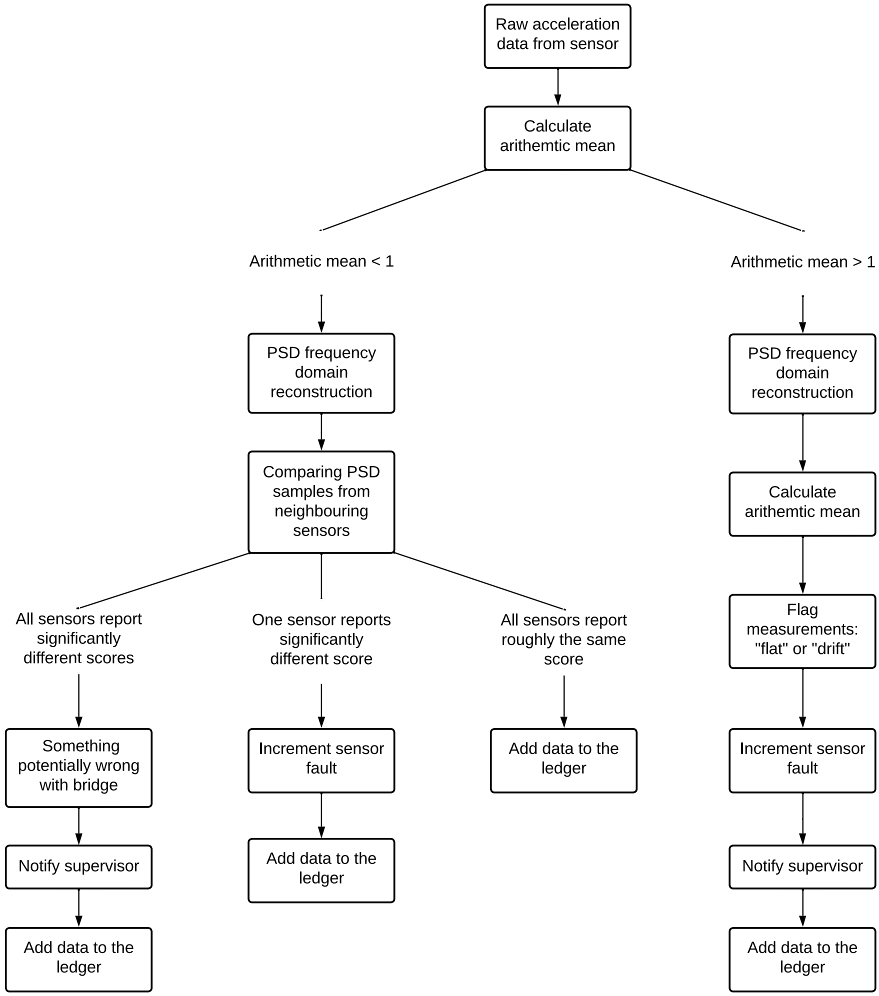


Fig. 2 Detailed schematic workflow of the verification process

A common occurrence when acceleration sensors are improperly installed is that they either generate acceleration curves that are flat (with or without a constant offset) or have a linear drift. For example, see Fig. 4. Because of the linear drift or the flat curve with an offset, the means of these faulty acceleration curves have a large offset. On the other hand, normal acceleration curves are centered around zero and have means with magnitude significantly lower than one. Hence, we can distinguish faulty or inconsistent acceleration data samples from normal acceleration data samples by analyzing the arithmetic means of raw acceleration data.

Once we have identified acceleration curves that are flat or have a linear drift by finding the arithmetic mean of raw data, means of PSD of faulty acceleration curves can be used to differentiate between acceleration curves that are flat and those with linear drift. PSDs of acceleration curves that are flat show no frequency response and have a mean very close to zero. PSDs of acceleration curves with linear drift have full frequency response like a normal acceleration curve, and hence, have a large mean. Therefore, it is straightforward to differentiate between flat acceleration curves and acceleration curves with linear drift using the means of PSDs. Those measurements than can be flagged as “flat” or “drift” in order to differentiate them afterwards.

For normal acceleration curves, the verification analysis can involve PSD peak comparisons. As described in [19, 20] and [21], the first major peak in a un-corrupted and well-functioning sensor’s PSD representation corresponds to the first fundamental frequency of the bridge. If all sensors installed on a bridge are operating normally, we should expect neighboring sensors on the bridge to have the first major peak at roughly the frequency. This is because the first fundamental frequency of the bridge would change marginally throughout the span of the bridge. To verify whether a sensor is functioning correctly, its first major peak from its PSD can be isolated and compared to the first major peaks of the PSDs of neighboring sensors.

The faultiness of a sensor can be defined based on whether the first major peak in its PSD is close to the first major peaks of other neighboring sensors. We can compare the first major peak from the latest unverified data sample of a sensor with first major peaks from verified data samples of neighboring sensors from the previous time step. If the peak difference is larger than a threshold value, we can label the latest data sample collected by the sensor as being faulty. The threshold value should be designed by taking into account the noise trend of the bridge and the sensors installed on the bridge. One way to do this is by collecting peak difference values of correctly operating neighboring sensors over a period of time, creating a distribution and assigning twice the standard deviation of that distribution as the peak difference threshold value. This is a good threshold value because it would capture most of the peak difference values for correctly operating sensors as being valid.

Once the verification of individual data samples from different sensors has been implemented, trends in overall faultiness of sensors can also be evaluated. A sensor trust score can be maintained for every sensor for every time step. The current trust score for a sensor can be generated by subtracting the added data sample fault scores for the previous few hundred data samples from the total number of data samples. This number then gets divided by the total number of data samples. The higher the trust score for a sensor, the more trustworthy the sensor is. With an implementation like this, we can measure how faulty a sensor is over time while also forgiving the sensor for very old faults.

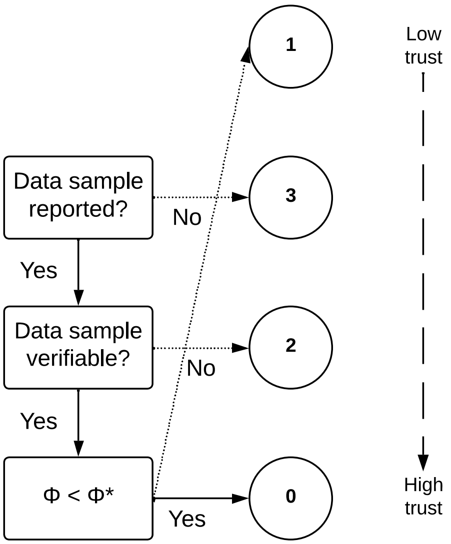
4.2 Consensus of the Verification Process

There are four possibilities for each sensor that is in use. A data sample from a sensor was either uploaded or it has not been uploaded (yet). If it has been uploaded, the data sample is either verifiable or not verifiable. In the case that it is verifiable, the result of the comparison is either under the set threshold or it exceeds it. The four options are shown in Fig. 3 and are sorted in increasing order of trust. The highest trust case is when a sensor data sample has been verified because the data sample is within the peak difference threshold. The lowest trust case is when the peak difference for a data sample has been exceeding the threshold. This means that the verification process is the main arbiter of trust in the blockchain network.

To recapture and summarize, each data sample reported to the network can be in either of the following three states.

- Data sample uploaded and verifiable.
  In this case, the data sample reported by a sensor has been verified against data samples from neighboring sensors from the previous time step. If the data sample passes verification, it reaches the highest trust case. If the data sample fails the verification, it reaches the lowest trust case as shown in Fig. 3.
- Data sample uploaded but unverifiable.
  In this case, the network has not yet been able to verify the uploaded data sample.
- Data sample not uploaded.
  In this cases, the network did not receive any recent data samples from a sensor.

Fig. 3 Order of trust in the verification of the sensors



To ensure user trust in the network during the entire data upload and verification process, each sensor is labeled with one of the aforementioned tags depending on the state of the latest data sample uploaded to the network by the sensor.

5 Implementation and Simulation

5.1 *The Verification Process*

For the implementation and simulation of the verification process in the blockchain network the data of the Z24 benchmark bridge is used. There are enough publications about the bridge, the monitoring system itself, its generated data and its meaning. For example, see [21] and [22]. Therefore its description is kept short here. The bridge got monitored for nearly a year. Measurements were collected every hour for a period of almost eleven minutes from eight different acceleration sensors. With this system in place a lot of data has been generated. Thus, it is perfect to extensively test the verification process, the consensus of the trust score and the blockchain itself. The implemented blockchain would work the same way with a live monitoring system. The data generated from the sensors would be collected on an edge device, the sensor node, sent to the network and verified like described in this paper. The simulation has shown, that the blockchain based monitoring system of sensors is working.

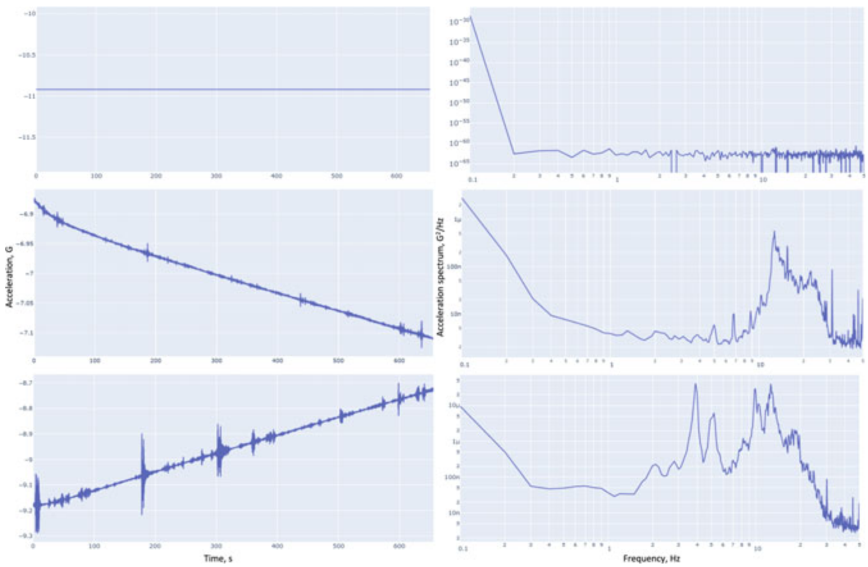


Fig. 4 Vibration response in time domain and corresponding PSD in frequency domain of three measurements of not correctly functioning sensor number ten.

With the implemented verification process faulty sensors can be detected. For example, in the used data set sensor number ten is not working like the other sensors. Three exemplary measurements and its corresponding PSDs are shown in Fig. 4. Those kinds of measurements can be found in the whole data set of sensor ten. The left diagrams are the vibration responses. Here its already visible that the sensor has deviations. In the data set are a lot of measurements that have not picked up any signals. So the response is flat. Those look like the first vibration response in Fig. 4. The arithmetic mean is, caused by the offset, greater than one. Furthermore, for those measurements it is not possible to calculate a PSD respectively the PSD shows no frequency response and has a mean very close to zero. Therefore, these measurements get flagged as “flat”, the sensor fault score gets incremented and, finally, the data added to the ledger. Additionally, the supervisor of the monitoring system will get a warning so that the sensor gets checked. Otherwise it could happen that the sensor is not measuring anything during its implemented time period.

Furthermore, sensor ten as well has measurements with a linear drift. Those are the vibration responses number two and three shown in Fig. 4. Here a PSD can be calculated and the difference between the peaks does not necessarily exceed the threshold. That is why in this case the peaks are not being compared. (See the right side of the workflow in Fig. 2.) Nevertheless, the sensor is still not working correctly. The linear drift can be found with the arithmetic mean of the vibration response. If this value is greater than one, the sensors fault score as well gets incremented. The measurements get flagged as “drift” and then added to the ledger. Moreover, the supervisor will be notified to check the sensor. E.g. a cable could be loose or there is an interference caused by a crossing cable that can be easily fixed. This is an simple adjustment to get better results of the monitoring system.

Like already described, the data set of sensor ten has a lot of deviations. Figure 5 shows the distribution of the flagged measurements. As visible, the sensor only

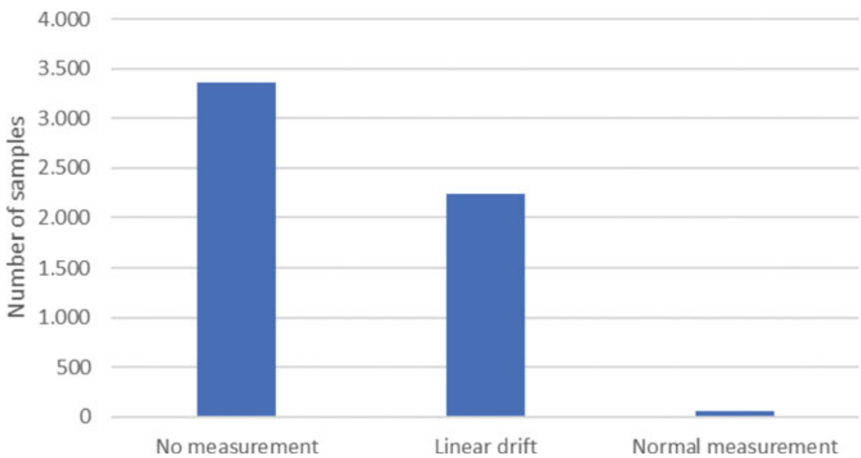


Fig. 5 Distribution of the vibration responses of sensor ten

captured a few "normal" measurements (one percent of 5.652 samples). That is why the sensor gets an overall low trust score. The overall trust score could exemplary be calculated as follows: $(5.652 - (55 \cdot 0 + 5.597 \cdot 1))/5.652 = 0,01$. Nevertheless, measurements with a drift can still be used since there are functions to get rid of the drift. But this means an adjustment and additional calculations. If the data set is big enough and the analyst or engineer is not dependent on all of the data, those flagged measurements could be initially not used.

Another example for a detected malfunction is sensor number three. This sensor shows an arising impairment in its function at the end of the monitoring period (week fortyone). Here the arithmetic mean of the vibration response is zero (so not greater than one) since the measurement does not have an offset. So it doesn't fall directly into the right side of the workflow. But since the arithmetic mean of the PSD always gets calculated, those failures as well get detected and the measurements get flagged as "flat".

An example of normal working sensors is shown in Fig. 6. The arithmetic mean of the vibration responses is smaller than one. Therefore, the PSD can be calculated and show a frequency response. That is why the peaks, respectively the first peak that is corresponding to the first natural frequency of the bridge, can be compared with its neighboring sensors. If the difference is smaller than the set threshold, there are no major deviations in the captured structural response caused by the change of load. So, the sensor fault score does not get incremented and the data can be added to the ledger. Those sensors get an overall high trust score and are therefore

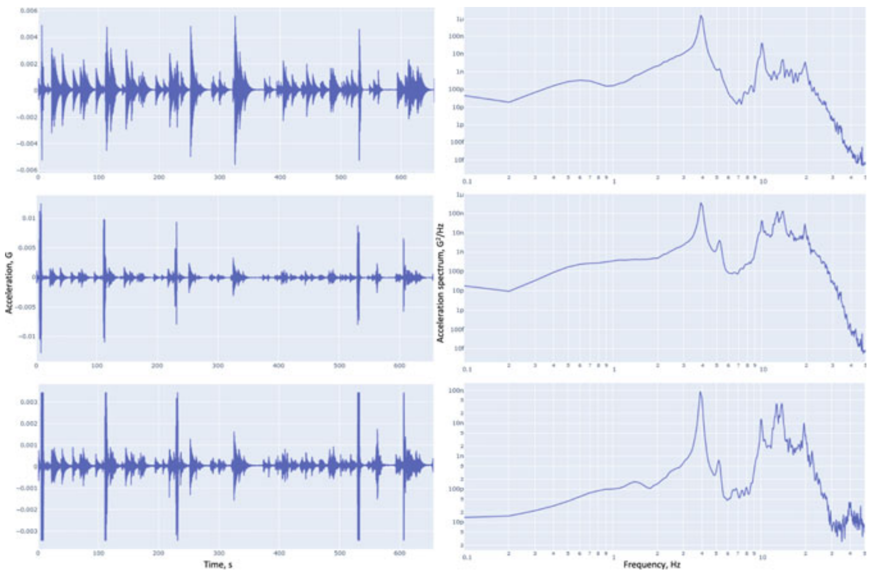


Fig. 6 Vibration response in time domain and corresponding PSD in frequency domain of normal functioning sensors five, six and twelve.

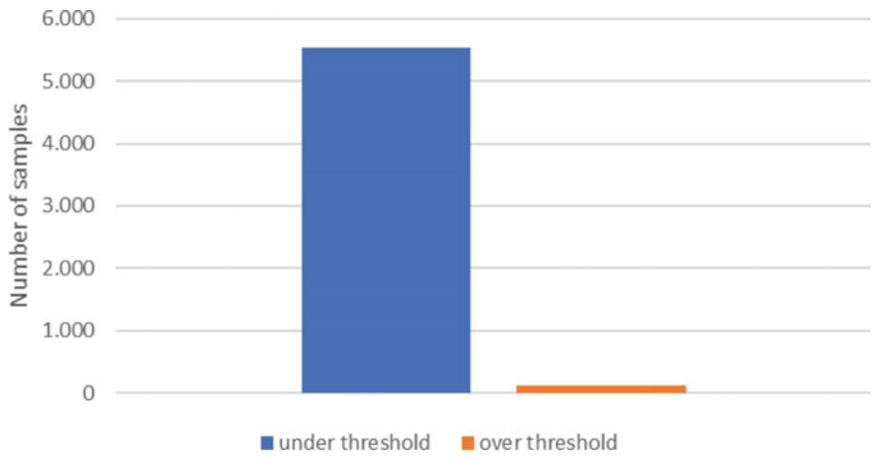


Fig. 7 Distribution of the peak comparison between sensors fourteen and sixteen

completely trustworthy. The overall trust score could exemplary be calculated as follows: $(5.652 - (5.532 \cdot 0 + 120 \cdot 1))/5.652 = 0{,}98$.

In addition, as already described in chapter four, Fig. 6 and the data in general show that the natural frequencies can change marginally throughout the span of the bridge. This is due to the non-linear nature of most structures. Since the set threshold is two times the standard deviation, most of the comparisons are under the threshold. Nevertheless, there are also measurements marked as a deviation since the difference of the compared peaks exceeds the threshold. This can have different reasons and doesn't necessarily mean that the sensor has malfunctions. Figure 7 shows an exemplary distribution of the peak comparison between sensor fourteen and sixteen. Here it is visible that normally those marked deviations are just a small part of the data set (in this case around two percent of 5.652 samples).

The main reason for the deviations can be a missing clear peak in the PSD. Figure 8 shows an example for that. On the left side a clear peak is visible around the first natural frequency of the bridge at approximately four Hertz. (For the natural frequencies see e.g. [21].) The PSD on the right side does not show a peak there. Since there should be a peak, the marked deviation is correct.

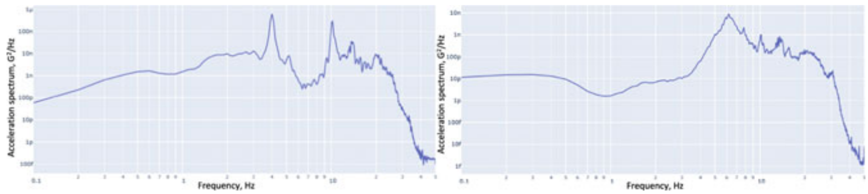


Fig. 8 Peak comparison between two sensors that result in exceeding the threshold

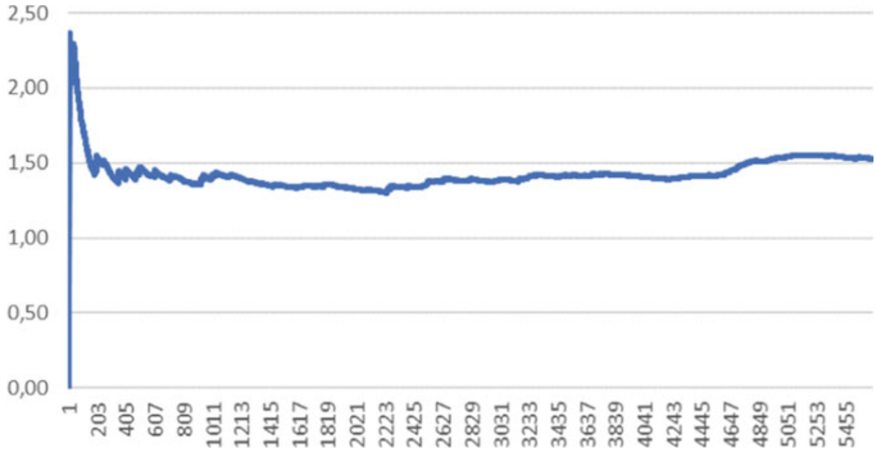


Fig. 9 Threshold of the comparison of sensor fourteen and sixteen

Another point to keep in mind regarding the threshold is that in the beginning of the verification process the population of the samples is pretty small. Therefore, the threshold is varying a lot in the beginning, shown in Fig. 9. Hence, sufficient data must first be collected. Then, retrospectively, the threshold can be applied and used.

As visible in the shown PSDs, no filter (e.g. Butterworth) was applied. Since the verification process is based on a comparison a filter is not that relevant since the same noise is present in both PSDs. Furthermore, the method is searching for peaks and therefore high but flat areas in the part of low frequencies (smaller than one Hertz) don't matter. Another point to keep in mind when using a filter is that a few but important decisions have to be made. For example what order is applied or what the critical frequency or the type of the filter should be. This has to be done individually with every new data set.

5.2 The Blockchain Network

The blockchain network for this project is implemented using *Hyperledger Fabric* based on the architecture already shown in Fig. 1. The network consists of three types of nodes: Sensor Node, Server Node and Supervisor Node. Each individual sensor communicates with an edge device that is collecting all the data. This edge device communicates with the network as a sensor node. Server nodes are data storage servers present in different geographical locations that capture and save a copy of the data being sent by the sensor nodes. Supervisor nodes refer to supervising engineers who pull sensor data from the network to analyze them. *Fabric Channel* is the communication framework implemented by *Hyperledger Fabric* to facilitate communication and data transmission between different nodes. There are different types of channels, like global or private channels, possible. The identity and certificate service assigns, manages and validates the identity, credentials and access control for all nodes. Ordering service manages the order in which different data blocks are added to the network.

The network manages and keeps track of two different types of assets: Bridge ID Asset and Sensor Data Asset. Sensor Data Asset consists of the following information: sensor ID, timestamp, sensor type (e.g. acceleration, strain, temperature), installation type (bridge or train), bridge ID, sensor location, data packet, sensor fault score and sensor trust score. Bridge ID Asset consists of the following information: bridge ID, bridge geometry. Sensor Data Asset packets are created by sensor nodes and pushed to the network for distributed verification. Once the data packet is verified and the fault and trust scores have been added to the Sensor Data Asset, the data packet is added as a new block to the blockchain. Once a sensor data packet is added to the network, server nodes update the geometry of the corresponding bridge and create a new Bridge ID Asset packet. This packet is added to the blockchain as a new block.

To handle verification of sensor data samples, *Hyperledger Fabric* uses a package called chaincode. A chaincode is just like a smart contract in the sense that it handles and verifies every transaction or input to the blockchain in a distributed manner to ensure trust in the verification process throughout the network. Multiple nodes, which have been selected randomly, run a copy of a chaincode transaction to ensure that the majority of the nodes get the same result. The workflow for that is already described and shown in Fig. 2. If a majority of the nodes get the same result from the chaincode, the transaction or input is added to the blockchain.

6 Conclusion

As shown in the scope of this paper, the application of blockchain technology in the AEC sector is proving to be very promising. Here it is implemented as an exemplary tool for monitoring sensor data. With this technology it is not only possible to track and store the generated data but also to verify it to generate trust in the data. With the implemented blockchain this is usefully automated and the participants can easily access the data. Additionally, since the AEC sector itself with its projects and constructions is a very distributed sector, the blockchain itself offers a perfect solution as a distributed technology. The sensors installed on bridges or other constructions are distributed all over a country. Therefore, the Server Nodes can and will be distributed as well. The blockchain technology handles that perfectly and is easily scaled to the needed dimensions. Another advantage is that the technology is open source and can thus be used without any costs.

In future work, more data sets should be applied to test the proposed workflow. Furthermore, it could also be integrated in other projects that deal with SHM. For example, digital twins get more and more common as a tool to digitize and automate the monitoring of infrastructures and constructions. Here, sensors get used as well and generate a lot of data. To appropriately verify, order and store the data, the blockchain technology respectively the here shown use case is predestined. This tool could not only be used for that but as well for all the data used in a digital twin like the digital models of the bridges or documents. The blockchain technology would therefore run as a backend and handle all the data transactions. As a result, all the data inside the SHM project is verified and trusted.

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Worker Activity Classification Using Multimodal Data Fusion from Wearable Sensors

Chi Tian, Yunfeng Chen, Yiheng Feng, and Jiansong Zhang

Abstract Accurate and automated classification of workers' activities is critical for safety and performance monitoring of workers, especially in highly hazardous working conditions. Previous studies have explored automated worker activity classification using wearable sensors with a sole type of data (e.g., acceleration) in controlled lab environments. To further improve the accuracy of worker activity classification with wearable sensors, we collected multimodal data from workers that conduct highway maintenance activities such as crack sealing, and pothole patching, in an Indiana Department of Transportation (INDOT) facility. Several activities were identified through field videos, including crack sealing, transferring material and walking. Two datasets were developed based on the collected data with one containing acceleration data only and the other one fusing acceleration data with multimodal data including heart rate, electrodermal activity (EDA), and skin temperature. The K-nearest neighbors (KNN) models were built to classify workers' activities for the two datasets respectively. Results showed that the accuracies for detecting crack sealing, transferring material, and walking without the data fusion were 1.0, 1.0 and 0.71. With the data fusion, the accuracies for detecting crack sealing, transferring material, and walking became 1.0, 0.93, and 0.93. The overall accuracy for classifying the three activities increased from 0.9069 to 0.9535 with the data fusion.

Keywords KNN · Worker activity classification · Data fusion · Highway maintenance

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1 Introduction

The construction industry is facing two major challenges, which are a high probability of fatal safety accidents and decreasing productivity. For the safety challenges, the construction industry had 1,102 fatal injuries in 2019, which was recognized as one of the most dangerous industries in the U.S. [1]. The number of fatal injuries in the construction industry accounted for 22.4% of the whole occupational fatalities in 2019 [2]. Meanwhile, the productivity of the construction industry is at a low level and the improvement is lagging behind comparing with other industries [3]. In addition, some studies even found a continuous productivity decrease in the construction industry for the past 40 years [4].

To tackle the safety concerns and productivity decrease issues in the construction industry, monitoring construction workers' activities is critical. For example, monitoring and detecting hazards around workers can reduce the probability of safety accidents [5]. Also, the monitoring and classifying of workers' activities can be used to measure construction workers' productivity [6]. With the development of wearable sensors, it is possible to classify workers' activities based on the collected data such as accelerations [7]. Machine learning methods, such as decision trees, K-nearest neighbors KNN, and neural networks can classify workers' activities based on the acceleration data collected from the wearable sensors [8, 9]. Furthermore, the findings of the recent studies showed that the data fusion of multimodal data can improve the accuracy of the workers' activities classification. For example, the data fusion of acceleration data and electromyography improved the classification of scaffolding activities [9]. The workers' physiological data such as heart rate, EDA and skin temperature change [10], however, were not considered for workers' activities classification in existing studies.

Therefore, the objective of this study is to investigate if the data fusion between workers' acceleration data and physiological data can improve workers' activity classification. To achieve the objective, onsite data was collected at an Indiana Department of Transportation (INDOT) facility. Then, multiple classification models were trained for the two datasets (1) with acceleration data only and (2) with the fusion of physiological data. Then, the classification results on the two datasets were compared and discussed.

2 Literature Review

Classification of workers' activities using wearable sensors has attracted much research attention in the past years. The benefits of applying wearable sensors include relatively low cost and no occlusion issues by the complex objects in construction sites compared with computer vision methods [11]. Previous studies showed the acceleration data collected by the wearable sensors can classify various construction workers' activities with high accuracy. For example, acceleration data collected by the wearable sensors was used for masonry workers' activity classification and the accuracy was 88.1% [12]. Also, acceleration, angular velocity and magnetic field were used for highway workers' activities classification and the results showed a higher than 95% accuracy on three different datasets [13]. The acceleration data was used to classify construction workers' ten activities and the results showed 93.69% accuracy [14].

However, two major limitations exist in previous studies about the workers' activities classification. First, previous studies collected workers' activity data in a controlled environment [14, 15]. The evidence of the classification performance of workers' onsite data should be provided to further push this technique to field application. Second, previous studies mainly used the sole type of data for workers' activity classification. For example, the kinematic data (i.e., acceleration, angular velocity, etc.) was mainly used [8, 12, 16]. Another study showed data fusion between workers' electromyography (EMG) data, which was one type of workers' physiological data, and acceleration data improved the classification results [9]. Other types of physiological data such as heart rate, EDA and skin temperature also could change with different activities [10]; however, the data fusion with these additional physiological data were not considered before. Therefore, more types of physiological data should be fused with kinematic data to investigate if the classification accuracy can be improved.

To fill the gaps mentioned above, this study collected workers' acceleration, heart rate, EDA, and skin temperature data in a fieldwork. Two classifiers were trained on the dataset, including the one with acceleration data only and the one fusing all types of collected data. The classification results on two datasets were also compared and discussed below.

3 Methodology

3.1 Data Collection

The data collection was performed in an INDOT facility in June 2022. The workers were asked to perform crack sealing and pothole patching activities. The E4 wristband included several sensors, such as 3-axis accelerometer, photoplethysmography (PPG) sensor, EDA sensors and infrared thermopile, which were used to collect workers' 3-axis accelerations, EDA, skin temperature and heart rate, respectively [10]. The 3-axis accelerations data was recorded in 32 Hz, the heart rate data was calculated based on the photoplethysmography(PPG) signal and stored in 1 Hz, and the EDA signal and the skin temperature were both recorded in 4 Hz.

Workers were required to wear the E4 wristband on their dominant hand during the data collection as shown in Fig. 1, which was the commonly used method in previous study [10]. Figure 2 shows the three activities used for classification, including crack sealing, transferring materials, and walking.

Fig. 1 The worker wearing E4 wristband for the data collection

Fig. 2 Three activity classes identified for this study, crack sealing (left), transferring materials (middle), and walking (right)

3.2 Data Analysis

The data analysis consisted of data labeling, data preprocessing, model training and testing for activity classification. The data collected by the E4 wristband was labeled manually by comparing the timestamps of the recorded videos, including 5,792 data points for crack sealing, 2,304 data points for transferring materials, and 3,008 data points for walking.

The data preprocessing included data resampling, data balancing, data standardization, and dataset development for training. First, linear interpolation was used to resample the heart rate, EDA, and skin temperature data into 32 Hz. Linear interpolation was commonly used to resample the data for machine learning [17, 18]. Second, 2,304 data points of each activity were extracted to form a balanced dataset with 6,912 data points in total. Each data point has six features (3-axis accelerations, heart rate, EDA, and skin temperature) and one label. The balanced dataset prevents the classification results from being biased toward the majority class and increases the classification accuracy for minority classes [19]. Third, six features were standardized to keep the impacts of each feature to be consistent [20] and improve the accuracy of classification [21]. Each feature was standardized by subtracting the mean of the feature and divided by the standard deviation of the feature [22]. Fourth, two datasets were developed with a window size of 2 s and a 1 s sliding window from the labeled data. The first dataset only had three features, which were the three-axis accelerations. The second dataset included six features, which were the three axis accelerations, heart rate, EDA, and skin temperature. Also, both datasets were split into training and testing datasets by the ratio of 80% and 20%. The both training datasets had 171 data points and both test datasets had 43 data points.

The KNN models were trained for the two datasets in this study, which were also applied in previous studies and showed high accuracy in classifying workers' activities [8, 23]. A new instance was labeled by the most common class of the K nearest instances in the feature space. Euclidean distance was used in this study as shown in Eq. (1). In addition, the number of neighbors to determine the class of a new instance was tuned in the range of 1 to 20 for the two datasets. The best number of neighbors for both datasets is one based on the tuning results. Therefore, the K = 1 was selected and the performance of the models on two test datasets will be discussed in the next section.

$$Distance(X_i, X_{new}) = \sqrt[2]{\sum_{r=1}^{d} (X_i - X_{new})^2} \tag{1}$$

where d represents the number of features.

4 Results and Discussion

The performance of the KNN models on the testing dataset were shown in Fig. 3 and Fig. 4 respectively. Figure 3 shows the confusion matrix of the KNN model on the dataset without data fusion (i.e., with the 3-axis accelerations data only). The accuracies for classifications of crack sealing, transferring materials and walking were 1.00, 1.00 and 0.71, with the acceleration data only. Figure 4 shows the confusion matrix of the KNN model on the dataset with the data fusion of workers' heart rate, EDA, and skin temperature data. The results showed the classification accuracy for crack sealing was still 1.00 and the classification accuracy for transferring material decreased from 1.00 to 0.93 and the classification accuracy for walking increased from 0.71 to 0.93. The overall classification accuracies for all three activities increased from 0.9069 to 0.9535 with the data fusion. Previous studies showed that different activities had different impacted on workers' heart rate, EDA and skin temperature data [10].

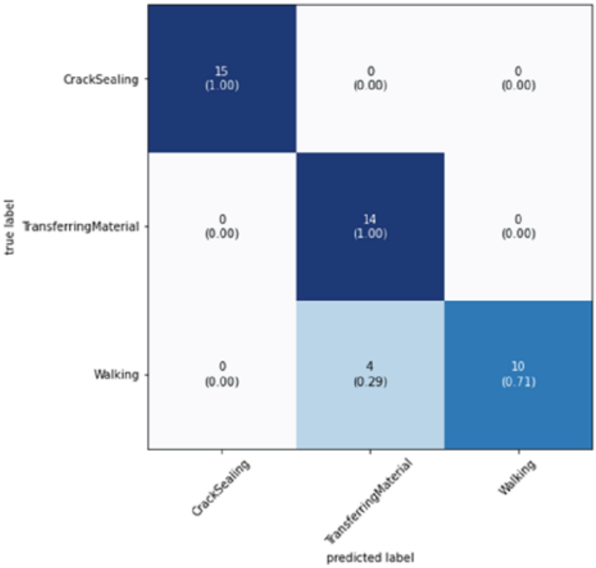

Fig. 3 Confusion matrix of the KNN model on the dataset without data fusion

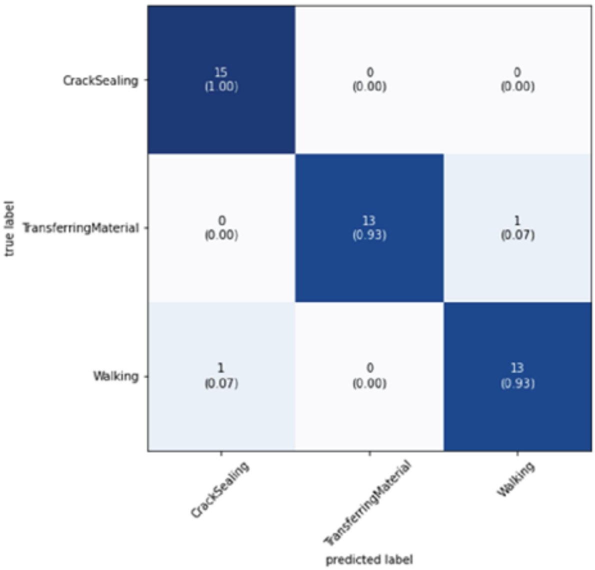

Fig. 4 Confusion matrix of the KNN model on the dataset with data fusion

Therefore, adding these data can improve the accuracy for workers' activity classification. The conclusion is consistent with previous studies that data fusion between acceleration and physiological data can improve the classification accuracy [9].

5 Conclusions

This study compared the performance of a machine learning method (i.e., KNN) on the classification of workers' activities with acceleration data only and data fusion between acceleration and physiological data. Onsite data was collected at an INDOT facility, and three activities were identified for the classification. The results showed that with the data fusion, the overall classification performance increased. However, the case varied for different classes of activity. For example, the accuracy for classifying material transfer decreased with the data fusion whereas the classification accuracy for walking increased.

The authors acknowledge the following limitations of the study. First, the size of the dataset was small. More data should be collected in the future to train more complex classification models, such as deep learning models. Second, the study only considers three activities. More types of activities should be considered in the future.

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Comparing Object Detection Models for Water Trash Monitoring

Seokhwan Kim, Taegeon Kim, Jeongho Hyeon, Jonghwa Won, and Hongjo Kim

Abstract If water trash exceeds the allowable load of a trash barrier, water trash barriers could be destroyed and the spilled waste negatively impacts the environment. Therefore, it is essential to measure the trash load in the water infrastructure to process collected water trash in a timely manner. However, there has been little investigation about how to monitor water trash in an automated way. To fill the knowledge gap, this study presents detailed investigation of water trash monitoring methods based on object detection models. To verify effective detection models and their performances, a new dataset is established, called the Foresys marine debris dataset. The dataset consists of a total of 6 water trash categories (Plastic, Vinyl, Styrofoam, Paper, Bottle, and Wood). State-of-the-art detection models were employed to test their performance, such as YOLOv3, YOLOv5, and YOLOv7 pretrained on the COCO dataset. The experiments showed that the detection models could achieve decent performance with proper amount of training image data; a number of training data required to secure decent performance varies by target class. The findings of this study will give a fresh insight for developing an automated water trash management system.

Keywords Water Trash Detection · Object Detection

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1 Introduction

Recent years, increasing water trash and its detrimental impact on water environments has attracted attention. To investigate the environmental impact of water trash and devise a proper water trash disposal method, monitoring methods are required to record the amount and types of water trash. However, there has been little discussion about automated monitoring methods for water trashes in the literature. The Ministry of Oceans and Fisheries of South Korea has been reporting national coastal waste statistics twice a month since 2008, but, the waste monitoring method relies on human observation which is labor-intensive and costly [1].

To protect the function of dams and water ecosystems, it is essential to remove water trash such as vegetation debris or residential wastes produced by nature or human activities. A trash barrier is a critical water infrastructure which blocks floating water trash in river or ocean. The blocked water trash is collected later for recycling or trash disposal. It is important to estimate the load of water trash because the trash barrier could be destroyed by the excess load of the accumulated debris [2], resulting in dissemination of collected trash and recovery costs. However, weighing the collected water trash is not trivial as the monitoring area is generally large and the weight of each trash can vary by its materials.

To address the inefficiency of manual water trash monitoring, this study investigates the potential of using deep convolutional neural networks (DCNNs) to detect water trash in images. DCNNs-based object detection models—the YOLO series (YOLOv3, YOLOv5, and YOLOv7)—are tested to evaluate their detection performance with respect to water trash image data named as Foresys marine debris dataset.

2 Related Work

2.1 Water Trash Monitoring

Various approaches have been proposed to address water trash issues. A previous study classified major water trash types as 6 categories such as rubber, plastic, metal, glass, other trash, and no trash for submarine debris in the Adriatic Sea [3], while Wolf et al. [4] suggested 6 categories such as water, vegetation, sand, litter-high, litter-low, and others for floating water debris in Cambodia. Jang et al. [5] offered 6 categories such as hard plastic, film, fiber (fabric), styrofoam, other foamed, and other polymer for water debris on beaches of Korea. The previous studies presented their own taxonomy of water trash to monitor the subject area. Likewise, this study defines six water trash categories as Plastic, Vinyl, Styrofoam, Paper, Bottle, and Wood that are usually seen in the target monitoring area with the trash barrier facility.

2.2 Object Detection

Object detection algorithms have been widely used to localize and classify objects of interest. The YOLO series is one of the most popular and effective object detection models [6]. To name a few examples, Son and Kim [7] used the YOLOv4 to detect workers in construction sites. Park et al. [8] used YOLO and YOLOv3 with sonar and laser sensors to detect crack in infrastructure. Cui et al. [9] used YOLOv3 to identify concrete surface erosion. The literature demonstrated the potential of the YOLO series in recognizing various types of objects. Therefore, this study investigates the applicability of the YOLO series to detect floating water trash.

3 Methodology

3.1 Object Detection Model

To localize and classify the water debris, YOLOv3 [10], YOLOv5 [11], and YOLOv7 [12] were employed. Since there are different types of hyperparameters and modules that can be replaced by one another, many variants of a certain YOLO model exist. There are two versions of YOLOv3: the original version [13] and the Pytorch-based version [14]. This study used the Pytorch-based version of YOLOv3 in consideration of the code compatibility with the YOLOv5 and YOLOv7 which are based on the Pytorch framework. YOLOv5 has variations, for example, YOLOv5n and YOLOv5 $\times$ 6, depending on a feature extractor type. This study used YOLOv5l6 and YOLOv7-X models which show a good performance among other variants.

3.2 The Foresys Marine Debris Dataset

The Foresys marine debris dataset was collected by the Foresys in 2021. It is one of the unique datasets that has images with floating water trash densely clustered. The dataset has 7,960 images with bounding box annotation and 5,000 images with polygon annotation. The image resolution is 3,024 by 3,024. This study only used images with bounding box annotation. The image data were collected in an indoor water pool due to the difficulty of data collection in river. There were five main factors to create the image data simulating the outdoor environment: a shape of the barrier, a filming time, water color, a shooting angle, and a density of trash. Table 1 details the main factors and Fig. 1 shows samples of the images.

There were totally 120 scenes, derived from all possible combinations of the factors: 2 conditions for the shape of the barrier, 3 conditions for the filming time, 2 conditions for the water color, 5 conditions for the shooting angle, and 2 conditions for the trash density. Dozens to hundreds of images were collected for each scene.

Table 1 Factors considered to create image data

Factor	Applied condition	Consideration
Shape of the barrier	U-type, J-type	Shape of the clustered trash
Filming time	10AM, 13AM,15AM	Illumination changes over time
Color of the water	Brown, Green	Watercolor changes by mud and algal
Shooting angle	30º, 45º, 60º, 75º, 90º	Installation changes of a camera
Density of trash	50%, 100%	Changes in amount of water trash

A training dataset was prepared with six trash classes—plastic, vinyl, styrofoam, paper, bottle, and wood. Table 2 shows the details of water trash.

Data Labelling. To prepare bounding box annotations, 'LabelMe' [15] was used, which is a freeware program. Figure 2 shows the labelled results. The total number of labelled bounding boxes is 499,629. There are 162,552 instances of bottles, 124,186 instances of styrofoam, 74,542 instances of plastic, 60,034 instances of wood, 44,144 instances of vinyl, and 34,171 instances of papers.

3.3 Transfer Learning

Transfer learning generally improves the performance of the deep learning models in the target domain with insufficient amount of training data [16]. Because the size of the dataset would be insufficient to train the models from randomized parameters, transfer learning is adopted to ensure the detection performance. As shown in Fig. 3, the experiments start from data augmentation. The following step is to train YOLO models, pretrained on the MS COCO dataset [17], with the Foresys dataset. The last step is the performance evaluation of the models to verify their effectiveness to detect water trash.

Table 2 Description with exam

Class	Description	Example
Plastic	Stiff object. This class does not include plastic bottles.	
Vinyl	Disposable bag	
Styrofoam	Styrofoam box, Styrofoam bowl	
Paper	Paper pack, Box	
Bottle	Plastic bottle, Glass bottle	
Wood	Vegetation	

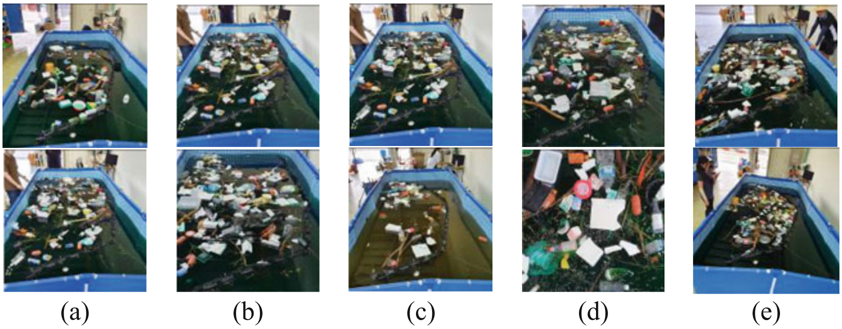

Fig. 1 **(a, upper)** U-type barrier, **(a, below)** J-type barrier, **(b, upper)** filming at 10AM, **(b, below)** filming at 15 PM, **(c, upper)** Green colored water, **(c, below)** Brown colored water, **(d, upper)** filming at 30º, **(d, lower)** filming at 90º, (**e, upper)** High density trash cluster, **(e, below)** Low density trash cluster.

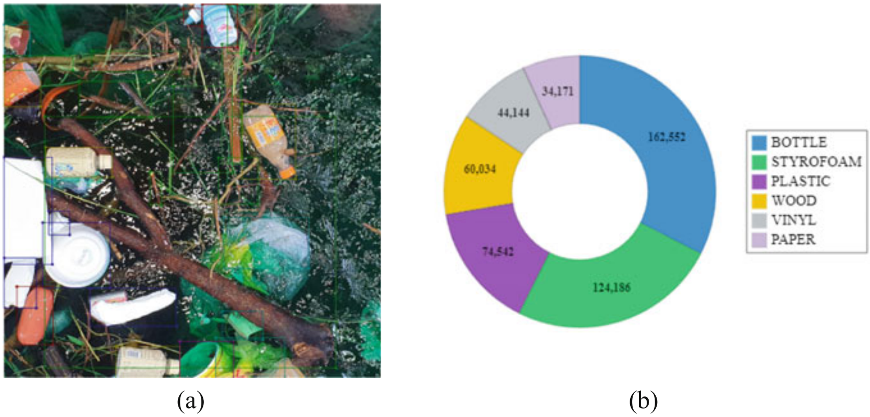

Fig. 2 **a** An example of labelled water trash. **b** A chart about the number of bounding boxes per category flowchart of experiments

4 Experiments and Results

4.1 Experimental Settings

The specification of a computer used in this study was: AMD Ryzen 7 5800X 8-Core CPU, 64 GB DDR4 DRAM, a Nvidia RTX 3090 GPU, and Ubuntu 20.04 LTS OS. The 7,920 data were divided into training, validation, and test sets: 6,835 for training images, 723 for validating images, and 402 for testing images. The training images were augmented int the training step. The augmentation techniques

Table 3 Important hyperparameters and augmentation setting

	YOLOv3	YOLOv5	YOLOv7
Batch size	20	20	20
Epochs	100	100	100
Input resized image size	640 × 640	640 × 640	640 × 640
Learning rate scheduler	Linear Decay		
Initial learning rate	0.01		
Final learning rate	0.0001		
Optimizer	SGD		
Warm up epochs	3		
Warm up bias learning rate	0.1		

were composed of flip left–right, flip up-down, HSV-Hue, HSV-Saturation, HSV-Value, rotation, translate, mosaic, and resize. Table 3 details the hyperparameters of YOLOv3, YOLOv5, and YOLOv7.

4.2 Evaluation Metrics

Average Precision is widely used as an evaluation metric for object detection tasks. An Intersection over Union (IoU) threshold is also an important indicator to calculate precision and recall. The IoU threshold of 50% was used in experiments.

4.3 Experimental Results

YOLOv7 achieved the best mAP of 96.8%; YOLOv5 recorded mAP of 95.8%; YOLOv3 recorded mAP of 94.4%. The category 'Wood' showed the lowest score, and the category 'Bottle' showed the best score among the models. Table 4 shows the detection performance of each class and Fig. 4 presents samples of the detection results.

5 Discussion

The experiment result showed that the highest performance model was achieved by YOLOv7, while YOLOv3 recorded the lowest performance. The YOLOv7 also achieved best score for each category. A possible explanation is that the improved

Table 4 Performance table with respect to the test dataset (%)

	mAP@0.5	AP@0.5 per a category						Recall	Precision	F1-score
		Wood	Styrofoam	Plastic	Vinyl	Bottle	Paper			
YOLOv3	94.4	91.0	96.4	93.7	92.8	96.6	95.7	96	100	94
YOLOv5	95.8	91.8	97.0	95.0	94.9	98.1	97.9	97	100	93
YOLOv7	**96.8**	**92.6**	**97.9**	**97.2**	**95.3**	**98.9**	**98.2**	**98**	100	**95**

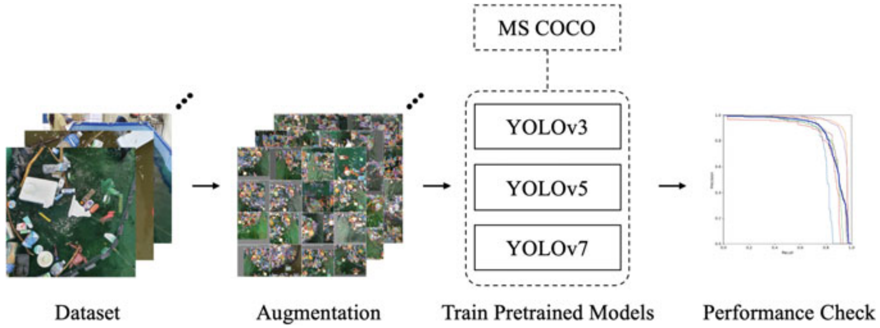

Fig. 3 A flowchart of experiments

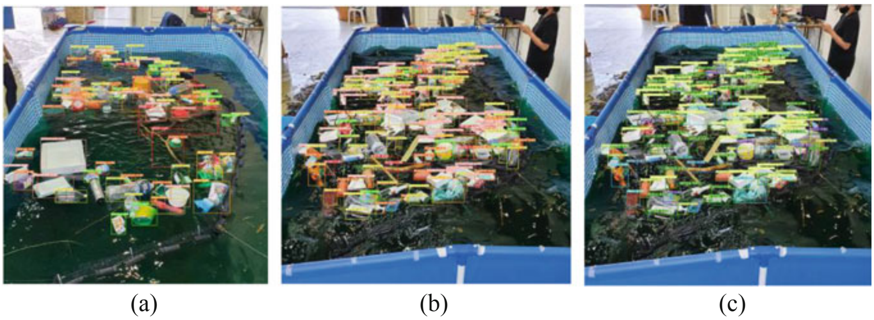

Fig. 4 Examples of detection results on the test dataset by (a) YOLOv3, (b) YOLOv5, and (c) YOLOv7

architecture of YOLOv7 contributed to the better performance. The class 'Wood' was found to be most difficult to detect as all the models scored the lowest mAP for the class. On the other hand, all models recorded the highest mAP on the class 'Bottle'. It is conjectured that objects having a common shape such as bottles are relatively easy to detect, while objects having many deformable shapes such as woods are hard to detect. The number of training images.

6 Conclusion

This study investigates a way to detect different types of water trash using object detections models. Three object detection models such as YOLOv3, YOLOv5, and YOLOv7 pretrained on MS COCO achieved the high performance, mAP of 94.4%, 95.8%, and 96.8%, respectively. The dataset was collected from the indoor environment to simulate the presence of water trash in river with a barrier facility. Future study should further investigate the applicability of deep learning models to recognize types of water trash in river or ocean.

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Extracting Information from Old and Scanned Engineering Drawings of Existing Buildings for the Creation of Digital Building Models

Tariq Al-Wesabi, Andreas Bach, Phillip Schönfelder, Inri Staka, and Markus König

Abstract As a 3D model is considered the core element of building information modeling (BIM) applications, current research focuses on optimizing and automating the creation of BIM models, especially for existing buildings. In this regard, engineering drawings are the most common data source for extracting geometrical information. With the recent emersion of artificial intelligence (AI) applications and the availability of advanced algorithms, researchers have utilized computer vision approaches to process engineering drawings. However, the data used in previous studies is rarely derived from actual projects and is, in many cases, noise-free. Such datasets overlook the need to create BIM models for existing structures, which account for most buildings. To address this issue, the current paper describes an approach for extracting information from engineering drawings that originate from an existing infrastructure project in Germany. More precisely, the drawings depict the buildings located on both sides of a subway line. The scanned drawings are old and, in some cases, damaged. Moreover, such data collections are usually submitted or archived without a clear structure or logical naming convention, making data organization time-consuming and labor-intensive. The presented approach divides the extraction of information into two levels. The first level classifies the drawings according to the main content, such as different views of the building. The second level collects information from the first level's identified views concerning structural and architectural aspects such as staircases, rooms, and openings. As the approach follows the idea of a data-centric AI, the pipeline includes an intensive exploration of the data, as well as its preprocessing, augmentation, and handling of damages in the drawings. The described approach is tested across multiple datasets and shows

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promising results. This study may represent an important step toward the automatic creation of digital twins for existing buildings.

Keywords Building information modeling · Information extraction · Engineering drawings · Computer vision · Deep learning · Data-centric AI

1 Introduction

With the wide expansion of building information modeling (BIM) across various disciplines in the field of civil engineering, large amounts of data need to be collected and analyzed to build and enrich the BIM models. Engineering drawings are one of the most important sources of building data, and as a result, engineers spend a lot of time parsing the drawings to obtain the information needed for creating the BIM models of structures. The need to perform this time-consuming task can be mitigated using computer technology to retrieve the information in a manner which does not require constant human input.

Initial studies focused on extracting information using image processing techniques such as the Hough transform [2] or a bag-of-words model [13]. Ghorbel et al. [4] proposed a method to automatically retrieve information from drawn documents by using an interpretation method called IMISketch, which incorporates the user during the process. With the recent rise of artificial intelligence (AI) applications and the availability of advanced machine learning algorithms, computer vision (CV) has been used to extract information from 2D drawings in an automated manner. The use of a deep learning-based framework for on-the-fly spotting of symbols in floor plans was investigated by Rezvanifar et al. [28]. Mishra et al. [23] studied the use of Cascaded Mask R-CNN [3] for object detection in floor plans. Cho et al. [5] proposed a method of recognizing more complex floor plans using deep learning-based style transfer algorithms. Zhao et al. [29] used the neural network You Only Look Once (YOLO) for the purpose of detecting building components in scanned 2D drawings. The studies mainly focused on using the publicly available datasets in order to train and validate their models and solutions. For instance, Kalervo et al. [15] have proposed the CubiCasa5K dataset comprised of 5,000 annotated sample images with over 80 floorplan object categories. Delalandre et al. [6] introduced an approach based on the definition of a set of constraints that permits the placement of symbols on a pre-defined background according to the properties of a particular demand. Goyal et al. [10] created the BRIDGE dataset consisting of 13,000 annotated images, originating from architecture offices and the internet.

This paper tackles the problem of analyzing 2D drawings of mainly old buildings. Since most of the drawings used in this study were created more than 40 years ago, it is a challenging task to create a robust method to retrieve information from these drawings in a fast and automated process, lowering human input considerably. Contrary to the datasets mentioned above, the drawings in the created datasets often suffer from damages due to aging and archiving. The scanned drawings are usually provided without any storage structure or naming convention, making working with them a cumbersome task. This study proposes a multi-level approach which divides the information extraction into two levels. The first level extracts top-level information such as the types of views illustrated in the plan. For this task, a convolutional neural network (CNN) is trained and used. The network outputs coordinates of the detections, which are later on analyzed by the second level of the approach. The second level provides more detailed information about architectural and structural elements in the identified views by using another CNN in order to obtain the information.

The paper is organized as follows: Sect. 2 reviews some of the latest publications about 2D drawing processing. Section 3 introduces the multi-level information extraction approach as the main methodology developed during this study. The results of its application are presented and discussed in Sect. 4, and an outlook is given in Sect. 5.

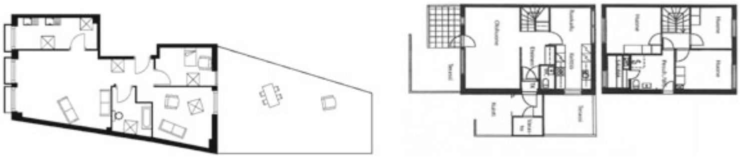
2 Related Works

Object detection has been an active area of research for decades [22], and has gained particular interest in developing high-performance CNNs. As a result, the application of object detection for the purpose of automating information extraction from legacy 2D drawings has also gained particular attention. Lewis et al. [17], contributed to the creation of a program called Building Model Generator (BMG), which was prompted by a desire to have 3D computer models of present and future buildings. The procedure of cleaning up the 2D plans comprises a significant part of the system. After plans have been cleaned up, a polyhedral model of the building can be created, which should serve as a satisfactory model for applications such as heat-, fire analyses, or sound simulations. Nichols et al. [24] developed a similar system, but they added an extra process to automatically place and align building models using a map for guidance. Their aim was to automate the modeling of the Massachusetts Institute of Technology (MIT) campus.

Since CAD tools are a relatively recent development, with the first ones being developed during the 1960s, many drawings exist only on paper or as scanned images. Dosch et al. [8] proposed a complete solution for analyzing raster images of drawings and re-constructing the corresponding 3D models. The system vectorizes the input images as sets of polylines and arcs during the processing and feature extraction phase. Large images are supported because of the utilized tiling strategy. During the 3D modeling, the system extrudes individual 3D models for each floor and then assembles them to form the whole building. Among the 2D modeling methods, the authors considered the extraction of dashed lines and stairs mature and stable, in the case of stairs coupled with the user interface for user input. The 3D reconstruction was considered to work well with the drawings considered by the authors, but its validity for more complex buildings remains to be proven. With the emergence of neural networks and deep learning, Dodge et al. [7] proposed a CNN-based method for parsing and analyzing floor plan images using wall segmentation, object detection, and optical character recognition. They introduced a new dataset called R-FP, and after evaluating different wall segmentation methods, they propose a fully convolutional network for the task. Ziran et al. [30] worked with a dataset which was generated using images of floor plans they found on the web. It consists of 135 images of variable sizes containing 4,973 objects of 15 different classes. The objects were divided into 2,697 objects for training, 1,165 objects for validation and 1,111 objects for testing. Another dataset was provided by an architectural firm. They trained an object detection model based on the Faster-RCNN architecture to identify the listed object types in the drawings. With the trained model, they achieved a mean average precision (mAP) score of 0.32 for the dataset which was collected using the search engine, and 0.83 for the dataset which was provided by the architectural firm. They explain the discrepancy between the results with the higher homogeneity of the second dataset. Further research was conducted by Goyal et al. [10] who have constructed the BRIDGE dataset which consists of 13,000 images of floor plans including annotations. The images were collected from existing available datasets and various websites. The retrieved web images contained no annotation data and therefore had to be annotated manually. Two different model architectures were used for the detection, YOLO and Faster-RCNN. For the selected object types, an mAP of 0.77 was achieved with YOLO while 0.75 was achieved with Faster-RCNN. Kalervo et al. [15] developed the CubiCasa5K dataset containing 5,000 floorplans with man-made annotations. They used a network structure similar to the one used in [21], which is based on ResNet-152 pre-trained with ImageNet [16]. Related research was conducted by Mishra et al. [23], but in this case the Cascade Mask R-CNN [11] network was employed. The floor plans which are used as the base of the Synthetic Floor Plan Images (SFPI) dataset come from the Systems Evaluation Synthetic Data (SESYD) dataset, in other words, the layout of the walls is similar between the two datasets, and the difference comes as a result of the augmentation of furniture objects. The images were augmented with random rotation angles, leading to an mAP of 0.981 for the SFPI validation dataset. The authors also validated the model trained on the SPFI dataset using the SESYD dataset and the resulting mAP was 0.763. It is worth mentioning that the referenced studies mostly apply and optimize single-step object detection algorithms for the information extraction. In doing so, the proposed methods deal with image-level information, and while they offer valuable solutions for the automation of tedious tasks, they are incapable of processing entire drawing collections. This paper stands out in the way that it proposes a pipeline which can deal with a whole set of drawings originating from a real construction project.

3 Methodology

To improve the efficiency of searching for information in the dataset and the look-up of specific 2D plans, a thorough insight into the dataset should be generated and documented. However, with a dataset as described in Sect. 3, such insights and documentation are still created manually. To resolve this issue, multiple machine learning algorithms are applied to extract information from the 2D plans. Based on the research done on the topic of processing and analyzing image data using machine



(a) A sample drawing from the SESYD dataset [6].

(b) A sample drawing from the CubiCasa5k dataset [15].

Fig. 1 Drawings of datasets used to train and validate neural networks

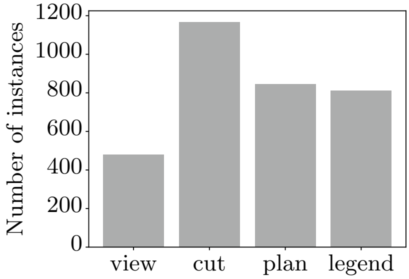
learning algorithms, CNNs are suitable to handle the data at hand. CNNs are a special type of neural networks known for their ability to extract and recognize features in images. Multiple architectures based on CNNs are used to evaluate the proposed approach, namely Faster R-CNN, RetinaNet and YOLO. Details about the mentioned architectures are discussed in Sect. 3. The content in 2D drawings is depicted in a nested fashion: lower level content such as architectural and structural elements as well as project information are part of higher level content such as different views and the legend of the drawing. Therefore, a multi-level information extraction approach is found to be advantageous. Moreover, multiple datasets are created to train the adopted machine learning algorithms at both levels of the extraction. The adopted machine learning algorithms are trained with all different versions of the datasets and the results are recorded and discussed in Sect. 4.

Datasets Description

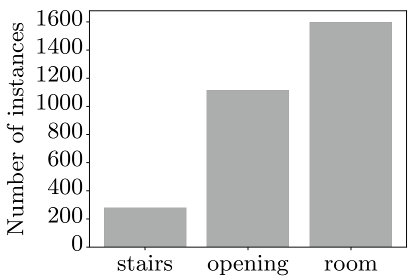
In order to evaluate the approach described in this study, multiple labeled datasets are needed. In previous years, various datasets for the analysis of 2D plans have been proposed, however, these datasets mostly contain floor plans only, are rarely derived from an actual project and are, in many cases, noise-free. Two examples are depicted in Fig. 1.

In addition, such datasets overlook the need to create BIM models for old existing structures, which account for the vast majority of structures [1]. The lack of datasets with the mentioned characteristics poses a research gap in automatic analysis of 2D plans. To close this gap, three different datasets are assembled from old 2D plans, each containing several unique element classes. The 2D plans in the datasets originate from an infrastructure project in Germany. More specifically, the drawings cpntain not only floor plans, but also cut views and elevation drawings, as well as the legends to the drawings. As explained in Sect. 3, this raises the need for a two-level information extraction approach, which requires multiple training datasets.

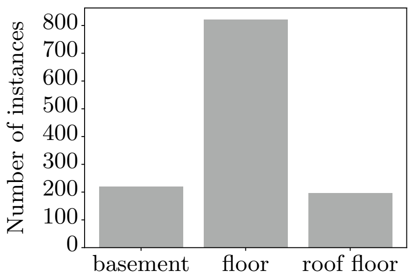
The first level is concerned with classifying drawings according to the main contents of the drawing and for that a dataset of full-sized engineering drawings is created. This dataset consists of 1,500 labeled engineering drawings containing objects



(a) The distribution of the labels across classes for the first dataset



(b) The distribution of the labels across classes for the floorplan dataset



(c) The distribution of the labels across classes for the cut-views dataset

Fig. 2 Instance distribution of all the classes in the three datasets

in four classes namely *Cut*, *View*, *Plan*, *Legend* with a total number of 3,303 objects, and their distribution as illustrated in Fig. 2(a). The second level collects information from the previous level's identified views concerning structural and architectural aspects.

It is noted that the set of classes to be detected in the second level depends on the view type detected in the first level. For instance, *Rooms* and *Openings* can only be found in Plans, and only Cuts represent the classes of the different floor types, namely *Basement*, *Middle floor*, and *Roof floor*, which are unique to this view. Therefore, from the output of the first level, two different datasets are created to be fed into the second level information extraction process. One of the datasets consists of 200 images of floor plans and contains a total of 3,012 objects distributed across the three objects classes Room, *Stairs* and Openings, as illustrated in Fig. 2(b), while the other consists of 200 images of Cut views containing 1,238 objects in the three classes Middle floor, Basement and Roof floor, as illustrated in Fig. 2(c).

Datasets Preparation

The raw data collection amounts to 2,000 PDF files containing scanned engineering drawings of the buildings. They are over 40 years old, and most of them exhibit damages of varying extent. Therefore, extensive exploration is needed, and several steps are taken to prepare the datasets. In addition, inspired by the Data-Centric AI (DC AI) mindset, different versions of the three datasets are prepared to track the effect of dataset optimization on the results rather than only the effect of different architectures of neural networks. On a related note, DC AI is an emerging field that encourages the focus on quality data rather than super high performing algorithms, big data and powerful infrastructure [9].

Prior to the following manual data preparation steps, the collected data is converted from PDF format to JPEG format to be processed by the machine learning algorithms.

Step 1: Elimination of duplicates and irrelevant datapoints. This step is to investigate the dataset to discover identical samples that may or may not have the same name as well as to eliminate drawings that do not contain objects of interest such as foundations drawings or detailing drawings of structural elements.

Step 2: Classifying and handling damages. In this step, the drawings are investigated thoroughly to classify the types of damages, their severity and curation methods. The most common types of damages are yellowing and folding lines due to physical archiving. Further types of damages are stains and paper tearings which appear less frequently. To handle the damages, image processing techniques such as median blur and image normalization are applied as illustrated in Fig. 3.

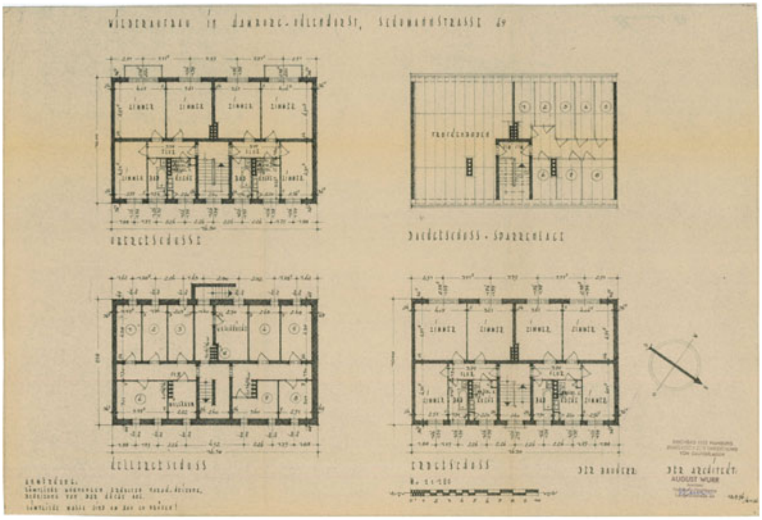
Step 3: Data Labeling. A labeling team is assembled from volunteering engineers and students. The volunteers are briefed about the protocol to be followed during the labeling process to avoid ambiguity and contradiction in labels. The datasets created by the labeling team are investigated and optimized by ensuring the quality and consistency of the labeling, providing the second version of the datasets. Both versions of the datasets, called *Labeled* and *Labels-optimized*, respectively, are used to train the machine learning algorithms to investigate the effect of dataset optimization on the results in addition to the effect of different algorithms.

Step 4: Data augmentation and splitting. Multiple data augmentation techniques are applied to improve the performance of the deep learning models namely scaling and rotation. The data is then split into three parts of 80%, 10%, and 10%, to be used for training, validation, and testing, respectively.

Framework and Extraction Algorithms

The overall framework of the proposed approach is divided into three phases:

1. Classifying and annotating the full size 2D plans according to their main content, which is the different views of the building illustrated on the drawing and a legend if existing.



(a) Original drawing without pre-processing.

(b) Drawing after processing.

Fig. 3 Images of the drawings go through preprocessing steps such as median blur and image normalization

2. Retrieving detailed information, about the elements in the floor plan views detected in the first phase and floor information from the respective cut views.
3. Harmonizing the outputs of the previous two phases into a general output. Figure 4 illustrates the phases of the framework as well as both levels of information extraction.

Extraction Algorithms. Both one-stage and two-stage detection algorithms are used and compared in this study. The size of the input images is 640×640 pixels and the initial weights are taken from models pre-trained on the MS-COCO [20] dataset. Faster R-CNN [27] is a prominent two-stage object detection network which makes region proposals using a deep convolutional neural network. As a backbone for the architecture, ResNet-101 [12] is used, combined with a Feature Pyramid Network (FPN) [18]. The other algorithm used is YOLO, which has the main purpose to achieve accurate results while maintaining a reasonable speed while processing inputs. The architecture conducts bounding-box regression and object classification without pre-calculating region proposals. The utilized YOLO version in this study is the YOLOv5 [14]. It uses the CSPDarknet53 as a backbone and PANet is added on top of it. The YOLOv5 is implemented using the PyTorch [26] framework. RetinaNet [19] is a popular one-stage object detector which addresses the problem of class imbalance by using a focal loss. The authors identified class imbalance as the main obstacle to achieving state-of-the-art accuracy so to tackle this they incorporated a focal loss as a solution. The loss function is a cross entropy loss which scales dynamically to zero as confidence in the correct predicted class gets higher.

4 Results

To evaluate the performance of the different algorithms applied in this study, unified evaluation metrics are selected. Object detectors attempt to determine the positions of particular objects in an input image. Typically, the result is presented by giving the coordinates of the bounding boxes that encapsulate the detected objects, their predicted classes, and the confidence scores which is usually a value between zero and one.

Precision and Recall. Precision is the ability of a model to identify only relevant objects. It is the percentage of correct positive predictions, or the ratio between true positives (TPs) and all detections. Recall is the ability of the model to find all relevant cases. It is the ratio between the TPs and all ground truths [25].

Mean Average Precision. Average precision (AP) is the weighted mean of precision values for each intersection over union (IOU) threshold where the increase in recall constitutes the weight [25]. The mean average precision (mAP) is calculated by averaging the average precision across all the classes of the dataset. Mathematically that is

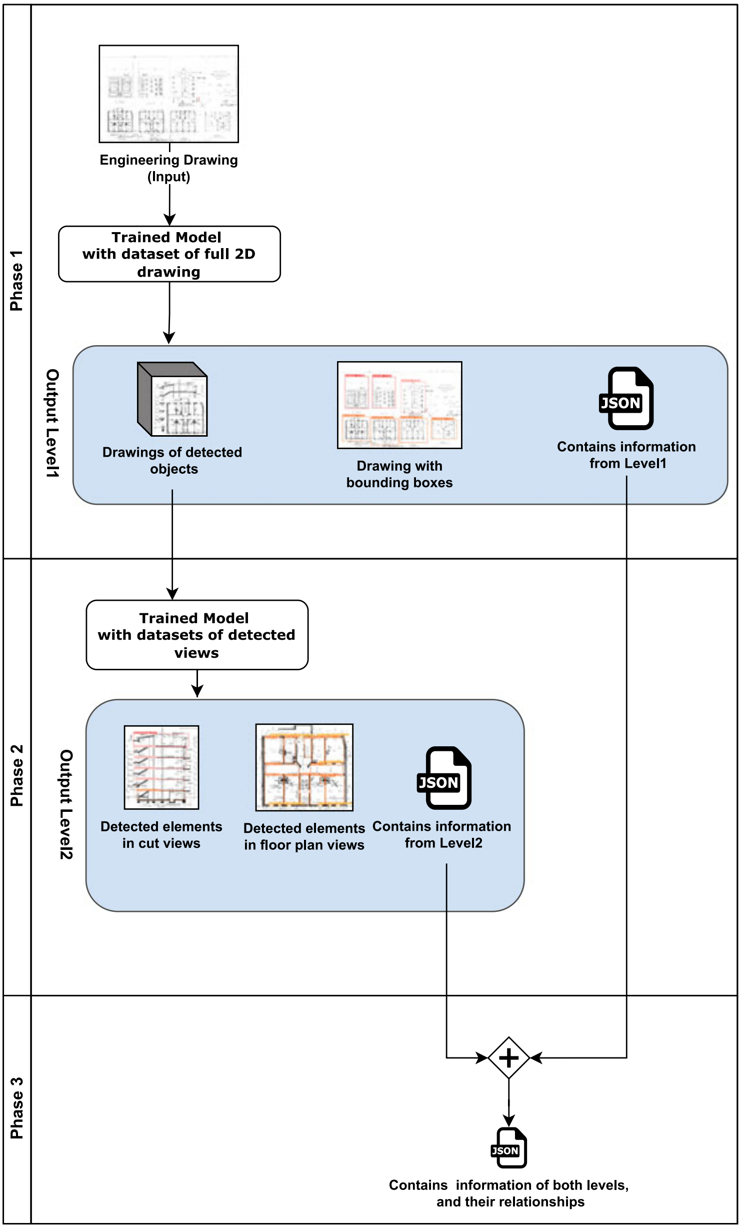


Fig. 4 Illustration of the framework of the approach

$$mAP = \frac{1}{C}\sum_{i=1}^{C} AP_i, \tag{1}$$

where AP_i is the average precision of the i-th class and C is the number of classes contained in the dataset [25].

The proposed multi-level framework is assessed on authentic datasets comprised of scanned engineering drawings belonging to old buildings. To compare the performance of the different models as well as measure the impact of the quality of the annotation and optimization process, the models are trained and evaluated on different versions of the datasets. The performance of models across classes is also analyzed, however, only for the label-optimized versions of the datasets.

First Level. Table 1 summarizes the performance of all different architectures on both versions of the dataset. Looking at the results for the Labeled dataset, the best performing architecture is YOLOv5 having the highest mAP with 0.86. At this point, the review and investigation process are undertaken where each annotation is double-checked and corrected if necessary. A review report is created for the labeling team to take notice of where the corrections have taken place. During the review it is noticed that the most common problems are consistency and semantics. The AP across classes is summarized in Table 2. In many drawings, as is to be seen in Fig. 5, the section cuts are merged with facade views in the same drawing making the process of drawing the bounding boxes more complex. Additionally, the legend class introduced the highest inaccuracies in labeling since their appearance differs between drawings. The reason for this difference is the absence of a unified structure for drawings. The labeling team could not clearly identify the legend from among the different tables and structured text blocks that might be present on the drawing. For the Labels-optimized dataset the mAP improved for all architectures. However, YOLOv5 is still leading the list with a difference of 0.03 compared to the second ranked architecture.

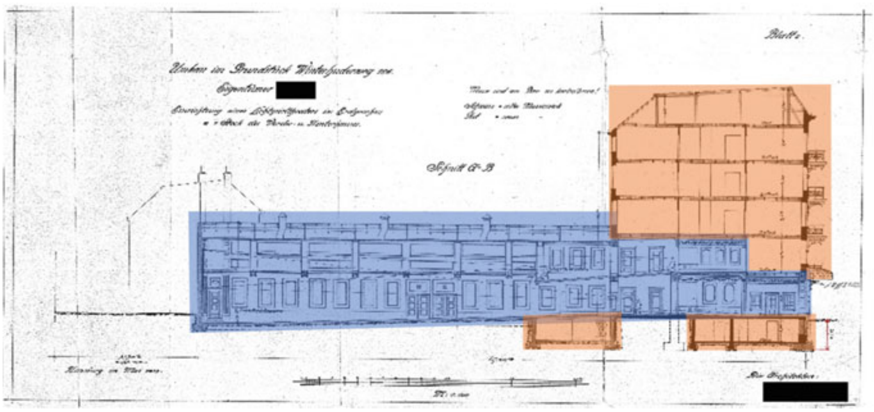


Fig. 5 Example drawing from the first dataset, showcasing the complexity of the bounding boxes. Facade-views are shown in blue while cut-views are shown in orange

Table 1 Mean average precision of each architecture for the two versions of the dataset

Architecture	Labeled	Labels-optimized
YOLOv5	0.86	0.91
RetinaNet	0.77	0.88
Faster R-CNN	0.77	0.82

Table 2 Class-wise AP for each architecture for the Labels-optimized version of the dataset

	YOLOv5	RetinaNet	Faster RCNN
View	0.87	0.81	0.78
Cut	0.92	0.87	0.85
Plan	0.88	0.89	0.76
Legend	0.97	0.93	0.89

Second Level. The two datasets, namely floor-plans dataset and cut-views dataset, are derived from the output of the first level. Analogously, both datasets are labeled by the volunteering labeling team and are used to train all models. The next step was to review and optimize the Labeled dataset, thus creating the dataset called Label-optimized. Afterwards, all models are trained again with the Label-optimized version. In the floor-plans dataset, the main inconsistencies are related to the Room class and how it should be labeled. As can be seen in Table 3, the performances of all architectures improved substantially with the Labels-optimized dataset, with YOLOv5 reaching the highest mAP at 0.94. From Table 4 it is noticed that the Stairs class scores the lowest in all corresponding architectures, however, YOLOv5 generalizes better in this particular case while other architectures confuse the stairwell with Rooms.

Table 3 Mean average precision of each architecture for the two versions of the floorplan dataset

Architecture	Labeled	Labels-optimized
YOLOv5	0.78	0.94
RetinaNet	0.30	0.75
Faster R-CNN	0.42	0.83

Table 4 Class-wise AP for each architecture for the Labels-optimized version of the floorplan dataset

	YOLOv5	RetinaNet	Faster RCNN
stairs	0.93	0.59	0.75
rooms	0.95	0.89	0.90
openings	0.95	0.77	0.85

Table 5 Mean average precision of each architecture for the cut-views dataset

Architecture	Labeled
YOLOv5	0.98
RetinaNet	0.87
Faster R-CNN	0.87

Table 6 Class-wise AP for each architecture for the Labels-optimized version of the cut-views dataset

	YOLOv5	RetinaNet	Faster RCNN
basement	0.98	0.93	0.84
floor	0.98	0.89	0.87
roof floor	0.98	0.78	0.89

As Table 5 shows, the highest scores of mAP achieved by all architectures across all datasets is with the cut-views dataset. Moreover, the dataset has a high-quality labeling and there were no editing carried out during the review. The clarity of the classes, in addition to the experience that the labeling team has gained, eliminated the need of Label-optimized dataset. Moreover, the results across classes in Table 6, gives a closed look how each model performed across classes.

On a general note, the results shows that the model YOLOv5 generalizes better in all experiments while the other models' performance scores drops with decreasing object size and increasing complexity of the local surroundings.

5 Conclusions

The application of deep learning models in extracting information from 2D engineering drawings gained a lot of attention from the research community. However, the developed methods use data that rarely originates from real projects and in is many cases free of noise. Therefore, in this paper, a multi-level approach is presented to analyze and extract information from legacy 2D engineering drawings to facilitate the creation of BIM models for old existing buildings. Multiple datasets are created from data that originates from a real project in Germany. Inspired by the concept of DC AI, multiple algorithms are trained with different versions of the developed datasets to track the effectiveness of the quality of the datasets on the results and not only the effect of different deep learning models. The experimental results show that the YOLO architecture is surpassing other models in both levels of information extraction. Moreover, the improvement in performance across all models through the optimization of the datasets is noticeable.

The main contribution of this study is to extract information automatically and systematically from old and scanned 2D engineering drawings through deep learning models, which are trained with real data. The second contribution is putting the different existing deep learning architectures into the test against data which is complex, nested, and contains some noise. Moreover, the improvement of results through the optimization of datasets as well as the improvement of the labelers and the labeling process were critically investigated. With these contributions, the gap in research caused by the lack of original datasets has been addressed.

Additionally, this study has several paths for further improvement. First, an even wider range of architectural and structural components should be considered for the detection, such as columns, beams, and furniture. Second, the semantic factor through the recognition and transcription of text on the 2D drawings is going to be addressed in future works. Finally, the output of the presented approach should be used in the automatic creation of the BIM models.

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Context-Aware PPE Compliance Check in Far-Field Monitoring

Wei-Chih Chern, Jeongho Hyeon, Tam V. Nguyen, Vijayan K. Asari, and Hongjo Kim

Abstract Context-aware safety monitoring based on computer vision has received relatively little attention, although it is critical for recognizing the working context of workers and performing precise safety assessment with respect to Personal Protective Equipment (PPE) compliance checks. To address this knowledge gap, this study proposes vision-based monitoring approaches for context-aware PPE compliance checks using a modularized analysis pipeline composed of object detection, semantic segmentation, and depth estimation. The efficacy of two different approaches under this methodology was examined using YUD-COSAv2 data collected from actual construction sites. In experiments, the proposed method was able to distinguish between workers at heights and on the ground, applying different PPE compliance rules for evaluating workers' safety. The depth estimation model achieved an Average Precision of 78.50%, while the segmentation model achieved an Average Precision of 86.22%.

Keywords Context-Aware Safety Monitoring · Object Detection · Semantic Segmentation · Depth Estimation · Personal Protective Equipment

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1 Introduction

Fall accidents accounted to 33.5% of all construction-related fatalities in the United States in 2018 [1]. To prevent such accidents, it is important for workers to use fall protective equipment when working at heights. However, this safety guideline is frequently ignored. Computer vision-based monitoring technology, such as CCTV (closed circuit television) installed at an elevated position, can record workers at heights and on the ground and alert the absence or inappropriate use of fall protection equipment. However, such systems may trigger false alarms for workers on the ground due to the absence of fall protection equipment [2]. Raw images cannot provide depth information, as a video is a 2D projection of 3D reality. Previous studies have suggested techniques for evaluating worker safety, but there has been no detailed investigation in far-field monitoring settings to differentiate the working contexts of workers at heights or on the ground.

To address this knowledge gap, this paper presents a context-aware safety assessment method to detect the absence of required PPE such as a hardhat, safety harness, safety strap, and safety hook. Two different approaches are presented and compared for context-aware safety monitoring. *The first approach* consists of three Convolutional Neural Networks (CNNs) for object detection, semantic segmentation, and depth estimation. The object detection and semantic segmentation models are mainly used to identify workers and their PPE. The depth estimation model estimates the distance between a camera and a worker to identify the working context. PPE assignment and connectivity analysis are used to build a relation vector to analyze the working context and safety status. Based on the working context and instance segmentation findings, the safety of the worker is evaluated. *The other approach* has the same architecture as the first approach, except for the depth estimation module. In this approach, the working context was directly inferred by height labels in the segmentation model. The main contributions of this study were: (1) proposing a modular system for context-aware worker safety monitoring, (2) demonstrating the efficacy of explicit labels of the working context in semantic segmentation, and (3) examining the capability of a depth estimation model to analyze the working context. The findings had a significant impact on the field of construction safety monitoring.

2 Methodology

The proposed methods assessed the safety status of workers based on their working context (at height or on the ground) using object detection, semantic segmentation, and depth estimation, as shown in Fig. 1. This paper investigated the effectiveness of two approaches: one with a depth estimation model and the other with a segmentation model with explicit height labels. In the first approach, a depth estimation model directly measured a worker's working height to determine whether they were at height or on the ground. In the second approach, it did not directly estimate the

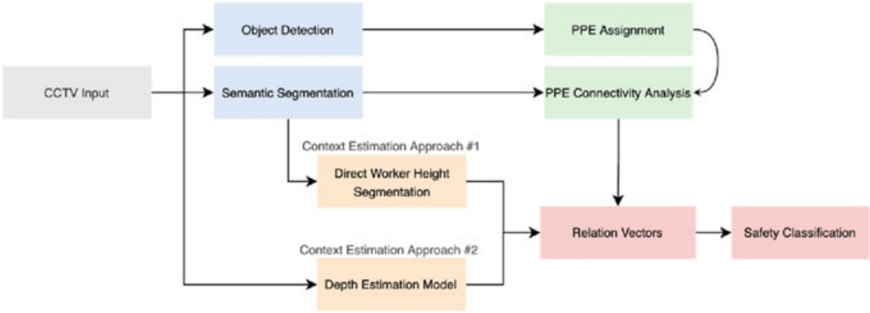

Fig. 1 The overview of the proposed safety monitoring system

working height, but instead predicted the working context using a semantic segmentation model with explicit working context labels such as "working at height" or "working on ground." This design was inspired by the previous work [3] which used a detection model to detect workers as safe or unsafe, teaching it to recognize relevant information within bounding boxes, such as PPE, with safe and unsafe bounding box labels. Similarly, this study hypothesized that working context labels such as "Height" (working at height) or "Ground" (working on ground) could be predicted from the segmentation masks of workers. In other words, the second approach considered working context analysis as a subset of a segmentation task.

2.1 Recognition Models

This work employed a modified instance segmentation technique with a different mechanism than the conventional instance segmentation method, which segments pixels solely in bounding boxes. The updated approach for instance segmentation began by detecting target objects. Then, semantic segmentation was performed on each pixel in the whole image. This design was introduced because some small objects, such as safety straps and hooks, may not be detected by a detection model, but they could be recognized by a segmentation model due to the models' distinct processing mechanisms. The separate use of detection and segmentation might detect more difficult target objects, even if the object detector was unable to recognize them.

A YOLOv5 (You Only Look Once Version 5) [4] model was used for object detection. A FPN (Feature Pyramid Network) segmentation model was employed for semantic segmentation. To train the FPN model, compound loss functions comprising of Jaccard and focal losses were utilized to boost the performance of more demanding objects [2]. Target labels for FPN varied based on the two different approaches for safety assessment. The first approach used five target labels, including 'worker,' 'hardhat,' 'harness,' 'strap', and 'hook'. The second approach included two extra labels on top of this, such as 'working at height' and 'working on ground'.

2.2 PPE Assignment

To verify a worker's PPE based on the working context, detected PPE must be assigned to individual workers. This process is named as "PPE Assignment." YOLOv5 was used to identify instances of each class because semantic segmentation cannot differentiate each instance of the same target class. After object detection, bounding box coordinates were used to assign PPE by calculating an intersection over PPE area between detected workers and PPE. Each PPE was used to calculate overlap scores between all workers and was assigned to the worker with the most overlap and a score larger than 0.1. The equation to calculate the overlap is:

$$Overlap\left(p_i, w_j\right) = \frac{I(p_i, w_j)}{A(p_i)}, \tag{1}$$

where I calculates the intersection, A calculates the total area given top-left and bottom-right coordinates, p_i represents detected PPE, w_j represents detected workers, and p_i and w_j contain top-left and bottom-right 2D coordinates, respectively. Definitions of I and A are formulated as:

$$I\left(p_i, w_j\right) = max\left(0, A\left(min\left(p_{i_{br}}, w_{j_{br}}\right) - max\left(p_{i_{tl}}\right)\right)\right), \tag{2}$$

$$A(p_i) = \langle p_{i_{br}} - p_{i_{tl}} \rangle. \tag{3}$$

This study assigned a safety hook to an individual worker in two steps. PPE connectivity analysis checked whether segmentation masks were connected between pixel regions of a worker and PPE. A new bounding box that included a worker and PPE was used for PPE connectivity analysis. In this analysis, a sub-region segmentation mask of the bounding box was generated to ensure workers wore PPE based on the target class connectivity. A depth estimation model or an extended semantic segmentation model estimated the worker's working context to determine if they were on scaffolds or the ground. Based on the context information, a relation vector was created for each worker's safety assessment.

2.3 Connectivity Analysis

A semantic segmentation model was used to collect pixel-level localization results of workers and PPE for connectivity analysis, which confirmed if the assigned PPE from object detection (PPE assignment) were actually connected to the worker. In this study, an FPN model was used to obtain worker and PPE segmentation masks. The Flood Fill algorithm was used to analyze worker connectivity with PPE. It recursively looked for neighbor pixels within a threshold to verify the connectivity.

2.4 Working Context Estimation

This paper presented two approaches for the working context analysis. An encoder-decoder depth estimation model [5] was used in the first approach. The depth estimation model estimated camera-to-pixel distances using a semantic segmentation-like architecture. This study employed the NYU Depth V2 dataset [6] to train the depth estimation model. Since the depth model was not trained for construction scenes, the predicted depth map has errors, as shown in Fig. 2. However, for the safety monitoring application, the error was tolerable if the working context of workers could be appropriately determined based on the predicted depth map. This study binarized the predicted depth map by the mean pixel distance. Then, the working context—working at height or on the ground—could be decided, as shown in the right column of Fig. 2. In the third column of Fig. 2, white pixels represent at height, and dark pixels represent on the ground.

In the second approach, the target class labels of the segmentation models were expanded to directly estimate the working context of workers based on extended labels—working at height or on the ground. The inference results of the extended segmentation model were shown in Fig. 3. Gray pixels represented workers at height, and white pixels represented workers on the ground.

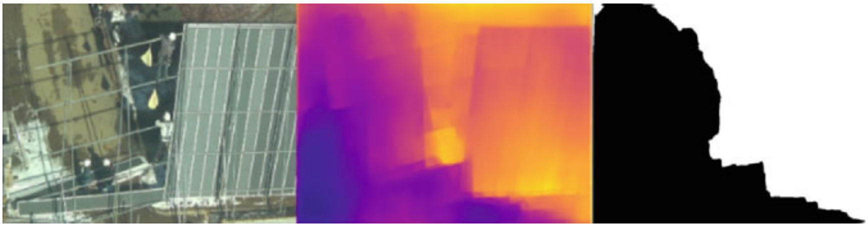

Fig. 2 Original RGB image (Left). An 8-Bit depth estimation result (Middle). The thresholding result using the mean value of the entire depth map (Right)

Fig. 3 Segmentation results for PPE (Left). Height estimation results on workers. (Right)

2.5 Safety Analysis

To determine the safety status of a worker, a relation vector was created for each worker based on the context information from object detection, semantic segmentation, the PPE assignment, and the connectivity analysis. The relation vector indicated whether a worker was with PPE and properly using it. It contained 5 elements, representing the working context and the presence of a safety strap, a hardhat, a harness, and a safety hook from left to right. For instance, a relation vector, such as [0 0 1 0 0], suggested that a worker on the ground was wearing a hardhat, therefore, the safety status was assessed to be safe. Similarly, if a relation vector indicated a worker at height was wearing a hardhat, harness, safety strap, and safety hook, the status would be safe.

3 Experiments

Experiments were conducted on images from the YUD-COSAv2 dataset, which was first introduced in [2], as shown in Fig. 4. In YUD-COSAv2, two construction scenes were added: one for a training set and the other for a testing set.

The image resolution used for YoloV5 and FPN models was 960 × 544. The data augmentation techniques used for YoloV5 included Mosaic [4], vertical and horizontal flips, HSV color jittering, random perspective transform, and mixup [7]. On the other hand, the data augmentation techniques used for FPN included horizontal flip,

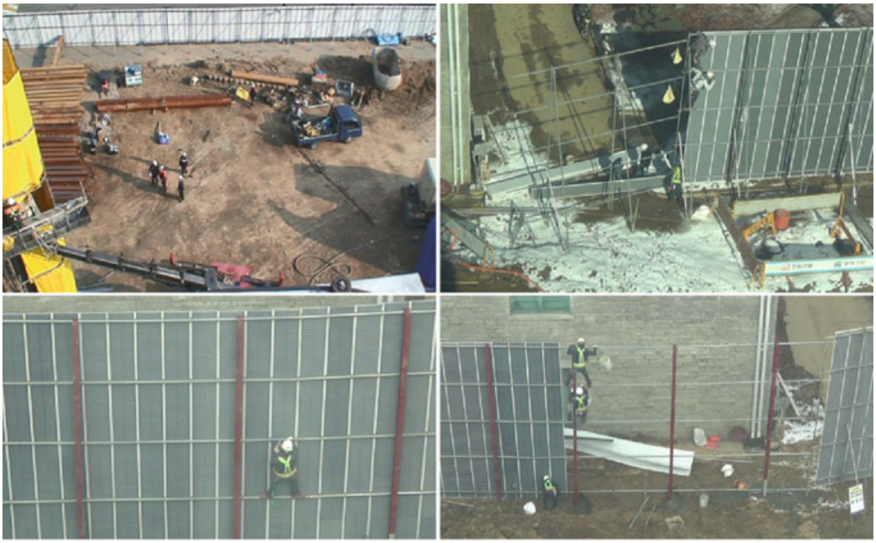

Fig. 4 Construction site scenes of the YUD-COSAv2

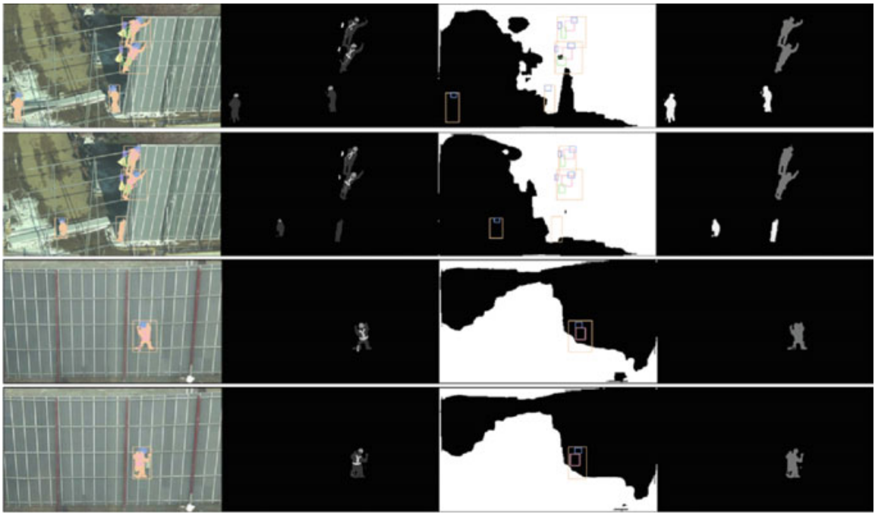

Fig. 5 Visualization results of the proposed method. 1st Column: RGB images overlaps with detection and segmentation masks. 2nd Column: Segmentation results of five target classes such as worker, hardhat, strap, harness, and hook. 3rd Column: Binarized depth estimation results overlapped with detected bounding boxes of target objects. 4th Column: Height estimation results from extended segmentation labels

shifting, scaling, rotating, HSV color jittering, and Copy-Paste [8]. To evaluate object detection and semantic segmentation, mean average precision (mAP) and mean intersection over union (mIoU) were used as they are representative performance indicators in object detection and semantic segmentation, respectively. A confusion matrix, F1 scores, and average precision were used to evaluate the performance of worker safety assessment. The recognition results of object detection, semantic segmentation, depth estimation, and height estimation from semantic segmentation were shown in Fig. 5.

Table 1 showed mAP, mIoU, precision, and recall of the two methods. As shown in Table 1, YOLOv5m and FPN showed reasonable recognition performance on large object classes such as worker and hardhat, while recorded lower performance on small object classes such as harness, strap, and hook. This phenomenon was expected before the experiments, as previous studies, identified the challenges of recognizing small objects in far-field monitoring settings. The challenges include a lack of visual features due to a small number of pixels, the color similarity between foreground and background, and irregular shapes of target objects. It was observed that safety harnesses suffer from color similarity more than other classes, resulting in poor recognition performance in both detection and segmentation.

Table 1 Performance of YOLOv5m and FPN with the resolution of 960 × 544

Network	mAP/mIoU	Worker	Strap	Hardhat	Harness	Hook	Height	Ground
Yolov5m	85.3%	99.4%	58.8%	99.4%	91.9%	77.0%	-	-
FPN	75.74%	82.98%	50.45%	89.51%	71.48%	59.79%	89.03%	86.94%

4 Conclusion

This study presented the context-aware safety assessment system to determine the safety status of workers considering their working contexts. To identify a worker's working context, two different methods were designed: one with depth estimation and the other one with semantic segmentation-based context prediction. The experiments showed that both methods were able to analyze the working context to determine the safety status. The second method using extended segmentation labels was slightly better than depth estimation in determining the working context. The proposed method had several limitations, including poor performance of the depth estimation model on construction datasets, a separation of detection and segmentation processes that increased computational burden, and lower recognition performance for small object classes compared to large object classes. These limitations could potentially be addressed in future work through training and optimizing a depth estimation model on construction site-specific data, enhancing detection and segmentation recognition performance with advanced techniques such as self-supervised learning, and combining the detection and segmentation pipelines into a single pipeline with multiple prediction heads.

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Challenges in Road Crack Segmentation Due to Coarse Annotation

Jeongho Hyeon, Giwon Shin, Taegeon Kim, Byungil Kim, and Hongjo Kim

Abstract To facilitate road image data collection, participatory sensing has been proposed in the literature utilizing a dashboard camera of a normal vehicle. It is not trivial to identify road cracks in such crowdsourced images due to the dynamic natures of photographing conditions which results in inconsistent the image quality. Although previous studies presented promising ways to identify road damages using deep convolutional neural networks (CNN), the performance is insufficient to be implemented in practical monitoring purposes. This study investigates core problems in improving the road crack segmentation performance by applying state-of-the-art segmentation models based on CNN and transformer architectures. Using a benchmark dataset, it was found that coarse annotation on crowdsourced images is detrimental to the performance evaluation and further development of participatory sensing-based monitoring technology. Interestingly, segmentation models could be trained by training data with coarse annotation. This study will give a fresh insight of advancing the knowledge in participatory sensing-based infrastructure monitoring.

Keywords Road Crack Segmentation · Participatory Sensing · Coase Annotation · Semantic Segmentation

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1 Introduction

Road maintenance and repair costs of South Korea amounted to $2.9 billion in 2021, which was increased from the previous budget of $2 billion in 2015 [1]. The increasing costs are problematic for municipal agencies to maintain the serviceability and safety of road assets while initiating new infrastructure construction projects. A previous study reported that the maintenance and repair costs can be significantly reduced when the road damages are timely repaired with proper methods [2]. For that, road damages should be monitored in a timely manner. However, it is not trivial to identify existing damages on road surfaces due to insufficient numbers of monitoring resources in responsible governmental agencies.

Previous study proposed an alternative monitoring method for road surface based on participatory sensing, which utilizes citizen's data collection capability [3]. It investigated the applicability of deep CNN to segment road cracks and proposed a benchmark dataset called the AIM crack dataset collected from multiple dashboard cameras of normal cars. However, the road crack segmentation performance was insufficient for practical monitoring applications. Since then, there has been little investigation how to improve the segmentation performance. To bridge the knowledge gap, this study investigates the issues in road crack segmentation on crowdsourced data by comparing the segmentation performance of state-of-the-art segmentation models. Two architectures—DeepLabv3+ [4], SegFormer [5]—are employed and compared their segmentation performance in the AIM crack dataset. In experiments, a coarse annotation problem was found in the dataset and its detrimental effects in the performance evaluation is discussed in Section Experiments and Discussion. The findings of this study will advance the knowledge in road crack segmentation based on crowdsourced data.

2 Method

To identify road cracks at a pixel level, semantic segmentation models are used to classify each pixel. FCN [6] is one of the first successful segmentation models which proposed an encoder and decoder architecture to efficiently process image data. The FCN architecture was also adopted in the road crack segmentation task for images collected by dashboard cameras [3]. However, the crack segmentation performance was not high due to harsh monitoring conditions such as irregular noise by different speeds of cars, vibrations, weather conditions, and illumination changes. The best performance recorded in the previous study on the AIM crack dataset was Intersection over Union (IoU) of 59.65% for road cracks when ResNet-152 for the encoder and the modified version of FCN for the decoder was used [3].

This study hypothesizes that the crack segmentation performance on dashboard camera images can be further improved with advanced segmentation models such as DeepLabv3+ [4] and SegFormer [5] compared to FCN. Because the two models showed decent segmentation performances in a road crack dataset [7]. However, as the photographing conditions of the AIM crack dataset is different from the one used in the previous study [7], it is worth investigating the effectiveness of such segmentation models.

DeepLabv3+ has the advantages in segmenting target objects which are sharp and multi-scale, building upon Xception adapted for segmentation and depthwise separable convolution operations, recording state-of-the-art performance on PASCAL VOC 2012 and Cityscapes in 2018. SegFormer is a recent segmentation model based on Transformer architectures and lightweight multilayer perceptron decoders, which outperformed the FCN and DeepLabv3+ on the ADE20K dataset.

3 Experiment

3.1 *Experimental Settings*

Experiments were conducted by using a desktop equipped with AMD Ryzen 7 5800X 8-Core Processor (CPU) and a NVIDIA GeForce RTX 3090 (GPU) with VRAM of 24 GB operated on Ubuntu 20.04. The AIM crack dataset has images of dashboard cameras and they were collected in Seoul, Korea. The original image resolution is 2,560 × 1,440. The total number of images is 527, and the number of images used in training, validation, and testing was 316, 105, and 106, respectively. The image resolution was adjusted to 1,920 × 1,024, to facilitate the training process.

Among variants of SegFormer, SegFormer_b1 pre-trained on ImageNet was used. The learning rate of 0.0006, two images per mini-batch, the cross-entropy loss, and the optimizer of AdamW were set as the training setup. In implementation of DeepLabv3+ , the encoder part was mit_b5, which is SegFormer pre-trained on ImageNet. The mini-batch had 6 images, the learning rate of 0.0001 before 25 epochs and 0.00001 after, and the optimizer of Adam were set to train the model. IoU for road cracks was used to evaluate the segmentation performance of each model.

3.2 *Experimental Results*

The experimental results showed that both SegFormer and DeepLabv3+ did not achieve high IoU scores, as shown in Fig. 1. The best IoU scores were 25.0% and 19.8% by SegFormer and DeepLabv3+ , respectively. Tables 1 and 2 show the examples of segmentation results by each model.

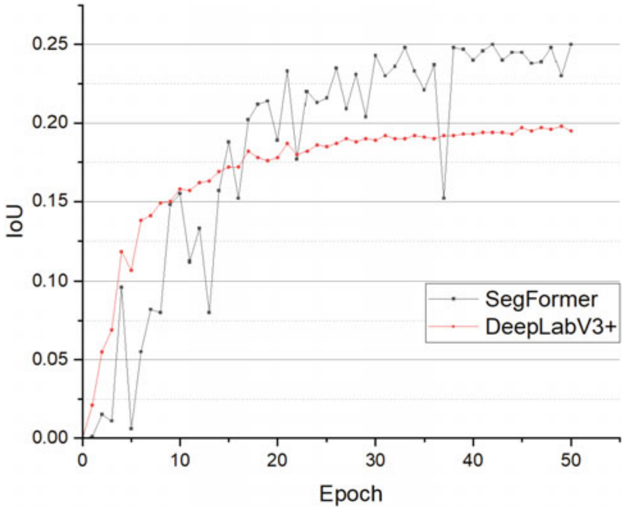


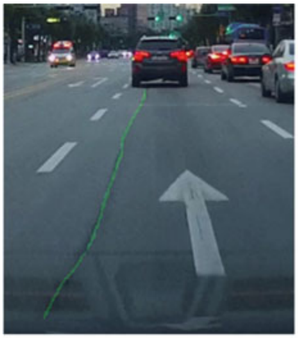
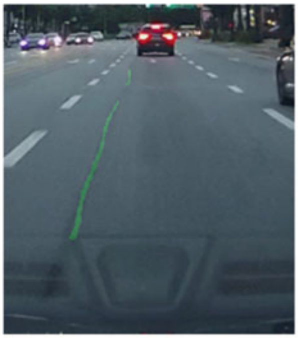
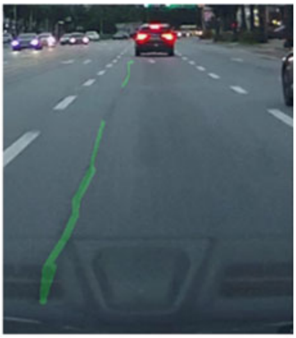
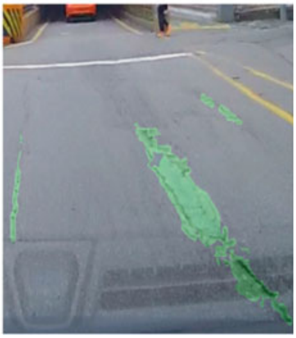
Fig. 1 IoU for road cracks using SegFormer and DeepLabV3

4 Discussion

Surprisingly, the IoU scores for road cracks indicate the poor segmentation performance of the advanced segmentation models, SegFormer and DeepLabv3+. It is possible that a simple model design such as FCN variants could be more suitable to segment road cracks on dashboard camera images. However, the interpretation on the segmentation results should be carefully made, as IoU scores would not represent the true performance of state-of-the-art segmentation models. Since SegFormer outperformed FCN and DeepLabv3+ on the ADE20K dataset [5], the results seem implausible.

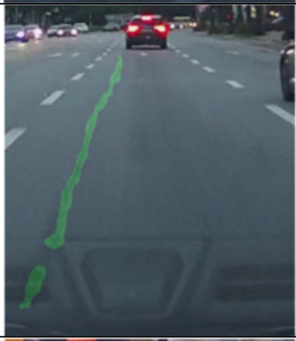
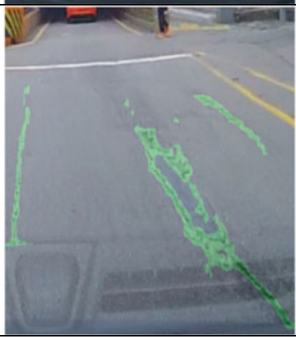
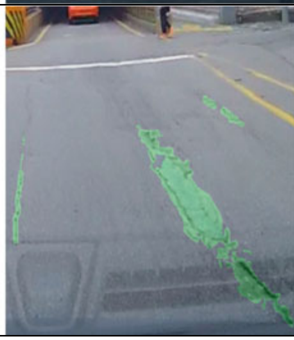
To further investigate the performance issue, the prediction results were visualized as shown in Tables 1 and 2, and a problem in annotation was found. The AIM crack dataset has coarse annotations for road cracks. That is, the boundary of road cracks is not accurately drawn. The image samples in Tables 1 and 2 present the ground truth and predicted results. As the IoU scores were 25.0% for SegFormer and 19.8% for DeepLabv3+ , it was expected that the predicted crack masks did not capture the existing cracks on the images. However, in the sample images, road cracks were accurately segmented and the segmentation quality is even better than the ground truth. The visualization results suggest two implications: (1) state-of-the-art segmentation models can be trained with coarse annotations of road cracks, and (2) the performance evaluation of segmentation models based on coarse annotations should be cautiously conducted.

Table 1 Crack segmentation results of SegFormer

IoU	Prediction	Ground Truth
0.616		
0.326		
0.237		

This study examined each image and its annotation, and found that it is challenging to draw accurate contours of road cracks in images of dashboard cameras due to noise and their thin shape. This is a unique challenge of dashboard camera images when preparing annotations. Most of other crack datasets collected images from the orthogonal view on the structural surface, it is relatively easier to make accurate annotations. However, this is not the case for images collected from harsh photographing conditions such as moving cars. It would be extremely difficult to

Table 2 Crack segmentation results of DeepLabV3+

IoU	Prediction	Ground Truth
0.281		
0.485		
0.409		

draw accurate boundaries of road cracks on images with noise that blurs the appearance of cracks. In such case, it would be beneficial to devise a new evaluation metric that can check whether a crack segmentation model identifies existing cracks without much sensitivity to the accurate matching between predicted and ground truth crack boundaries.

5 Conclusion

This study investigates the effectiveness of state-of-the-art segmentation models to segment road cracks in dashboard camera images. The experimental results showed that the two models were successfully trained even with coarse annotations, but it was difficult to evaluate the true segmentation performance. It would be an interesting research topic for future study to devise a new evaluation metric for road damage classes in participatory sensing contexts. As raw images in participatory sensing do not have high quality, the reliability of data should be carefully considered to design machine learning-based algorithms in performance evaluation.

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Comparison of Various Methodologies to Detect Anomalies in a Time Series Data Taken from a Tunnelling Project

Keyur Joshi and Elham Mahmoudi

Abstract A major concern in urban mechanised tunnelling projects is avoiding damage to the existing buildings and the tunnel boring machine (TBM), which may be adjusted by an advanced precise excavation simulation. Because a realistic simulation must account for multiple interactions between the boring machine and the subsurface, an exact representation of the ground's geological profile must be created beforehand. Due to the limited monitoring and sampling, several geologic anomalies may have been overlooked when sketching the geologic profile. As a result, the geological profile should be updated alongside the construction phases when new information becomes available. To accomplish this, one can use the boring machine's recorded data to detect any irregularities in the drilling process caused by changes in geological conditions. This research compares various cutting-edge anomaly detection approaches on time series. Due to a large amount of sensor data, the visualization of multiple sensors/features over time was first performed, and the critical features with the highest impact on the detection process for identifying anomalies were selected. Anomaly detection techniques include isolation forest, k-Means, k-Means Sequential Time Series Cluster, Auto-Regression Integrated Moving Average (ARIMA), and Convolutional Neural Network (CNN) Auto-encoders are among the main aspects. The methods presented here were applied to a given data set from an actual tunnelling operation in Germany to locate the location of some concrete slabs in a relatively homogeneous ground. The obtained results agree well with the exact location of anomalies. The performance of various methods is evaluated through error quantification measures.

Keywords Unsupervised machine learning · Anomaly detection · Time series analysis

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1 Introduction

Preventing damage to ground structures is always a top priority for any urban tunnelling project. A detailed 3D model of the excavation process that takes into account all the interactions between the TBM and the surrounding soil would be essential. However, the geological profile of a construction site is mostly driven by primary geotechnical investigations, which include a limited number of boreholes and some in-site and lab measurements, and cannot be regarded as an accurate representation. This profile should be changed during excavation by conducting more explorations and collecting data from multiple sources that project the tunnelling-induced changes in the surroundings. A tunnel boring machine (TBM), which is a highly automated operation, consecutively excavates the earth and installs the tunnel liner in mechanized tunnelling. Here, abrupt geological changes can jeopardize tunnelling, resulting in unforeseen surface settlements, TBM damage, or cutting tool wear. TBM damage results in construction delays, which can increase ongoing expenditures (e.g. personnel costs). Early detection of geological changes gives the chance to start countermeasures, such as modifying the speed of excavation, the type of cutting instruments used, or the face pressure.

Seismic exploration provides approaches suitable for exploring the space directly in front of the tunnel face. In terms of precision, a seismic methodology known as full waveform inversion can provide a significant improvement over state-of-the-art seismic methods [18]. The monitoring campaign can be expanded to incorporate above-ground structural monitoring as well as terrestrial and satellite data to track displacements of existing infrastructure induced by tunnelling. Furthermore, ground conditions can be evaluated by analyzing data gathered during excavation via settlement and pore water pressure sensors [14]. Another approach of exploration is to continuously monitor TBM sensors and utilize this data to detect disturbances with pattern recognition, and machine learning techniques [5]. This research mainly focuses on the latter approach, by comparing various available data analysis methods.

Nowadays, the anomaly detection domain is also getting popular with the classification problem in the machine learning regime. Finding outliers in data is a crucial problem in a variety of contexts, from financial applications to healthcare monitoring to manufacturing operations [19]. Here, the outliers in the data are the observations in data that do not follow the norm. For every anomaly detection technique, the basic assumptions are that the anomalies do not occur often and that the outlier features are significantly different from the normal observations. While detecting the anomalies, we mostly never have labels of the anomalies; hence, anomaly detection is usually done using unsupervised machine learning techniques [1].

This paper majorly focuses on applying anomaly detection techniques to time series data. Time series data is the set of observations measured in a sequential, timely manner. Anomalies in a time series data are of three types; i) Point anomalies, ii) Contextual anomalies, and iii) Collective anomalies. The point anomalies are the observations in the time series data which are outside the entire set of data observations in the time series. On the contrary, contextual anomalies are observations that are not outliers when seen individually but are an outlier in some contexts. Lastly, the collective anomalies are the set of observations that are outliers as a collection of observations but are not anomalous when considered individually in a global sense.

Often detecting global outliers is not challenging as they deviate significantly in the global sense of the time series data. But on the contrary, it is quite challenging to detect contextual and collective anomalies. The state-of-the-art anomaly detection approaches can be subdivided into the various domain approaches, namely, statistical, machine learning and neural networks approach [4]. In the statistical approaches, mainly fundamentals of the statistics regime are used, and these approaches include Auto Regression (AR), Moving Average (MA), Auto Regression Integrated Moving Average (ARIMA), etc. (the reader is advised to see [11] for more details). Various approaches in unsupervised learning techniques include kMeans clustering, a modified version of kMeans clustering for the time series data viz. kMeans Sequential Time Series Clustering (kMeans STSC), Density-Based Spatial Clustering of Applications with Noise (DBSCAN), Isolation Forest, One-Class Support Vector Machines (OC-SVM), etc. Finally, the neural network approaches include various approaches like Multiple Layer Perceptron (MLP), Residual Neural Network (ResNet), Long Short Term Memory (LSTM) network, Autoencoder, etc.

After applying different efficient algorithms of the anomaly detection regimes to detect anomalies in the time series data of the tunnelling project, comparing the performance of the methods using the $F1$ score metric will take place. The research methodology incorporated in this research article is as shown in Fig. 1.

This paper starts with the illustration of the present research in the domain of tunnelling and how various machine learning approaches are implemented in the domain. Later, the data used for the implementation of various anomaly detection techniques are described, and the pre-processing step is explained briefly. Further, various modelling approaches implemented in this paper are explained briefly, and

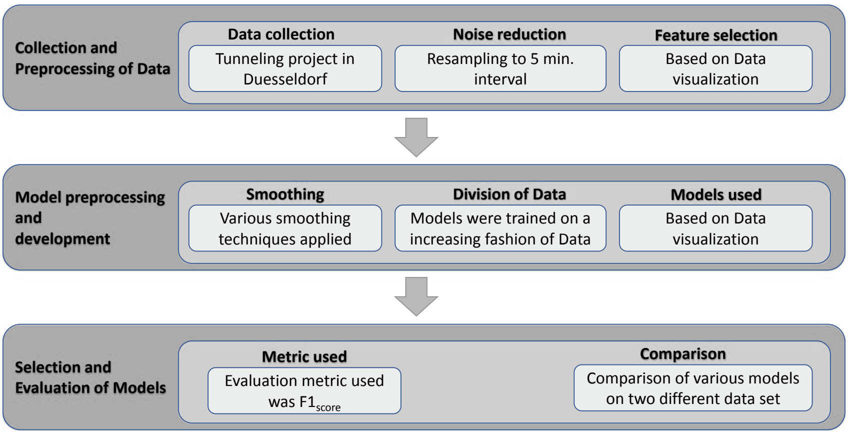

Fig. 1 Research methodology

the results obtained by the application of the models are compared. Henceforth, the insights of the possible future work are proposed.

2 Related Works

The field of anomaly detection in mechanized tunnelling is an emerging field that is currently being heavily researched. The need for anomaly detection is to get early warnings before the performance of TBM is imperilled. One can predict anomalies in ground conditions using various state-of-the-art approaches with anomaly detection methodologies. This section devotes to the present and related research in the field of anomaly detection and prediction of ground conditions in the mechanized tunnelling domain.

For anomaly detection, one of the recent promising approaches was used by Maes et al. [13], where they used principal component analysis to detect early warning signals in mechanized tunnelling. The deformations and the temperatures monitored for a period of over a year were used to identify minor changes in the tunnel response. To ensure the safety and reliability of a geotechnical project Zou et al. [29] proposed a meta-learning anomaly detection method which improves the accuracy of detection by averaging the parameters of the same type of algorithm. The approach achieved a 96.41% accuracy, which is way higher than current outlier detection approaches. Another approach for outlier detection was proposed by Zheng et al. [27] which implemented a probabilistic Bayesian learning manner to detect outliers in multivariate sparse data. As Mahalanobis distance was used as a measure to compute outlier probability, this method is immune to the swamping effect, viz. misidentifying regular data as an outlier. In micro tunelling, Sheil et al. [20] proposed a comparison of various clustering- and regression-based methods to detect anomalies using jacking force. It is further described in the paper how the detected anomalies help to decrease unplanned downtimes and operation costs of the project.

Determination of geotechnical parameters requires traditional approaches some testing which is difficult to conduct every time. Hence, another promising domain in the geotechnical regime is predicting the ground conditions beforehand using the Machine learning approaches. The recent approach for the same was proposed by Yang et al. [24] where he used the canopy clustering method to find beforehand roughly the centres of the clusters and then used K-Means clustering on the clusters obtained previously. Then these clusters of the ground conditions were used to classify the ground conditions using various methods. Gradient Boosting Decision Tree (GBDT) gave the best performance among all the methods. The investigation of evaluating geological conditions was also performed by BaiXue et al. [3]. In the research published by Tang and Na [21], various machine learning approaches such as Support Vector Machines (SVM), Random Forest (RF), Back propagation Neural network (BPNN) and Deep Neural Network (DNN) were used to predict ground settlement prediction. The results were further supported by performing sensitivity analysis. Another prediction-based approach using the Bi-directional Gated Recurrent Unit (GRU) Attention (Att) model was described by Zhang et al. [26]. It has been concluded that this model has stronger learning and prediction capabilities.

Fu et al. [9] proposed a method to estimate TBM performance in soft soils. For cluster analysis Shared Nearest Neighbour (SNN) DBSCAN was used, and for prediction, Random Forest (RF) approach was utilized. Wu et al. [23] attempted to predict rock mass information from tunnelling data. The method first involved cluster analysis and then DNN in predicting the rock mass behaviour. An attempt to recognize geological type on the In-Situ data of the Earth Pressure Balance (EPB) Tunnel Boring Machine (TBM) in [25]. A chi-square test is performed for feature selection, and four machine learning approaches, viz. K-Nearest Neighbour (KNN), Classification and Regression Tree (CART), SVM and Artificial neural networks (ANN). Armaghani et al. [2] estimated the TBM advance rate using two hybrid methods, viz. Particle Swarm Optimization (PSO) ANN and Imperialist Competitive Algorithm (ICA) ANN. Complex Network (CN) theory was implemented by Zhou et al. [28] to spectral cluster in the shield monitoring data. The safety factor of the retaining walls is also one of the important parameters and Ghaleini et al. [10] proposed a method to approximate the factor with an approach of combination of ANN and Artificial Bee Colony (ABC). Erharter et al., [8] used an ensemble of ANN to classify the rock mass behaviour on different input features. Chen et al. [6] proposed water inflow quantification from rock tunnel faces as a way of emulating the human inspection process. It is crucial to get water inflow information to assess the rock mass rating, and they proposed a method of classification and segmentation using CNN for the water inflow evaluation. They also proposed how the method reduced the ergodic damage segmentation procedure significantly.

The current state of digitalization in the domain of tunnelling is described by Marcher et al. [15]. The application of machine learning in various tunnelling domains is explained briefly in the article, and it also emphasises how it can be used to increase the safety and comfort of underground workers by withdrawing workers from the most hazardous zones in the active areas of tunnelling. The capabilities and challenges of the application of Neural networks and Machine learning are also elaborated in [7, 16].

It seems that machine learning approaches are recently developing exponentially in the domain of geotechnique and the transition to digitalization in the aforementioned regime. This article majorly focuses on the anomaly detection of the walls in a tunnelling project. As mentioned before, an attempt is made to detect various sensor data anomalies using various approaches. We aim to provide readers with a baseline idea of various approaches available currently for detecting anomalies in tunnelling sensor data and illustrate a comparison between the approaches.

3 Data

The tunnelling project data was taken from 342 TBM sensors that were employed to excavate a tunnel under the city of Dusseldorf, Germany. The TBM excavated through a depth of approximately 12 to 16 m [5]. The data observations were taken from the sensors every 10 to 15 s. The tunnel includes two various Metro lines. The South line data comprised of 868 rings from ring No. 0 to Ring No. 867. The East line TBM sensor data includes 637 rings from Ring No. 1000 to Ring No. 1636 [17].

3.1 Data Summary and Preprocessing

To reduce the involved noise in the recorded data with intervals of 10 to 15 s, a re-sampling to 5 min intervals is performed. The descriptions of abbreviations used in the tables are described in Table 1. Table 2 provide an overview of all the sensor data collected from the East line.

Figure 2 and 3 show a comparison between the noisy data of turning moment and the contact pressure cutting wheel displacement collected from the sensors and their re-sampled data (with 5-minute interval), respectively. As seen in the figure the noise is removed to a great extent.

Table 1 Abbreviations

Abbr.	Description	Abbr.	Description
Mom	Moment	Press_A	Advance pressure Group A
Pen	Penetration	Press_B	Advance pressure Group B
Dist	Distance SR/advance	Press_C	Advance pressure Group C
Speed	Speed of cutting wheel	Press_D	Advance pressure Group D
Vol_soil	Conveyed soil	Press_E	Advance pressure Group E
Strok	Total number of strokes mortar compression	Press_F	Advance pressure Group F
Tar_flow	Target value of conveyed material Flow	Press_J	Jacking pressure force
Tar_TBM	Target value of material TBM	Press	Cutting wheel displacement pressing force
Prog_cyl	Progress of jacking cylinder	Vol	Volume mortar compression
Pow	Power input cutter wheel	Vol_{Mor}	Target volume mortar

3.2 Relevant Data Selection and Data Transformation

After data visualization, the important sensor data relevant for detecting anomalies were moment (Mom), power consumption of cutting wheel (Pow) and Contact pres-

Table 2 Summary of the sensor data for East line

Attr.	**Mom**	Pen	Dist	Strok	Vol_soil	Tar_flow	Tar_TBM	Prog_cyl	**Pow**	Press_A
unit	MNm	mm/min	km	Imp.	m^3	m^3	m^3	mm	kW	bar
mean	0.82	26.11	1.07	415.03	42.25	41.59	52.49	742.06	58.89	67.72
std	0.50	7.89	0.84	318.99	28.69	26.68	33.00	466.49	74.08	20.07
min	0.00	0.00	0.00	0.00	−7.62	0.00	0.00	0.00	0.04	1.14
25%	0.47	24.72	0.44	163.26	17.78	18.00	22.94	324.36	18.20	54.73
50%	0.65	30.00	0.95	368.82	40.73	41.16	52.52	742.44	39.86	65.95
75%	0.97	30.07	1.48	603.00	64.20	63.68	81.14	1147.20	67.37	76.61
max	3.36	58.67	9.44	2413.00	191.20	124.25	123.57	1747.03	820.53	229.74

Attr.	Press_C	Press_B	Press_E	Press_F	Press_D	Press_J	Speed	Vol	Vol_{Mor}	**Press**
unit	bar	bar	bar	bar	bar	kN	1/min	m^3	m^3	kN
mean	131.66	111.73	105.44	65.01	127.44	18192.70	1.26	4.96	4.14	2284.15
std	24.68	36.61	37.33	20.64	24.95	3630.41	0.27	8.93	2.72	790.32
min	8.33	23.54	0.58	0.04	20.26	3861.28	0.00	0.00	0.00	−586.36
25%	114.65	84.15	76.91	50.58	110.30	15734.29	1.05	1.85	1.67	1820.28
50%	129.70	108.01	103.53	63.35	125.02	17815.12	1.22	4.20	4.11	2058.65
75%	145.92	135.41	131.43	75.78	142.07	20392.03	1.44	6.89	6.51	2559.08
max	284.03	263.73	251.38	186.39	273.38	40751.49	2.62	456.72	10.13	7417.90

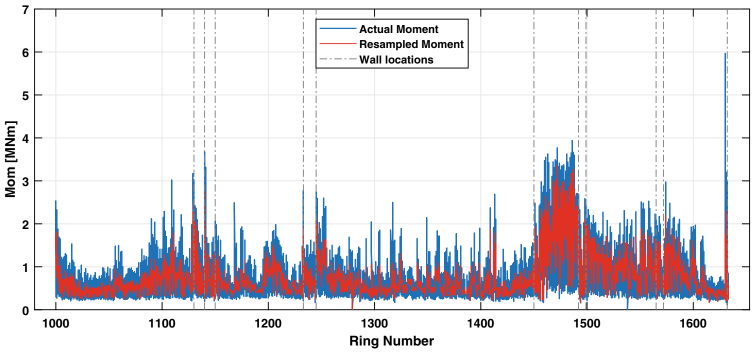

Fig. 2 Noisy data vs. Re-sampled data of Moment

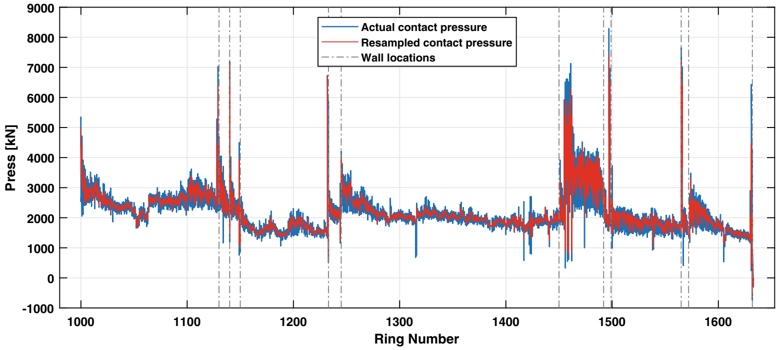

Fig. 3 Noisy data vs. Re-sampled data of Contact pressure Cutting wheel displacement

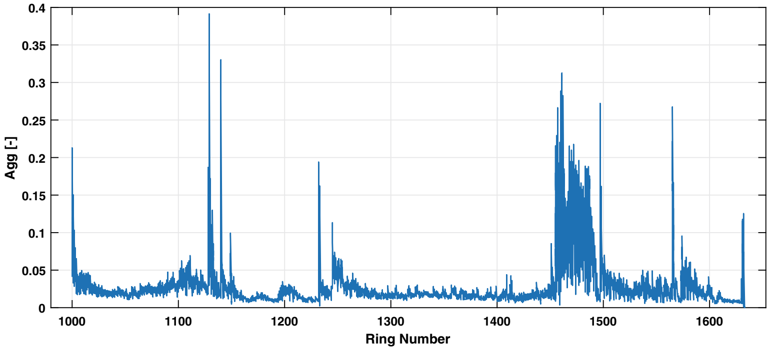

Fig. 4 Time series plot for Agg data for East Line data

sure Cutting wheel (Press). As this paper focuses mainly on a univariate time series analysis, in order to incorporate the importance of all the features/relevant sensor data, a new normalized aggregate feature (Agg).

Agg was introduced whose formula is as shown in Eq. 1 and the time series plot is as shown in Fig. 4 and 5.

$$Agg = \left[\frac{1}{3}\left(\frac{0.5 \cdot \text{Mom}}{max(\text{Mom})} + \frac{\text{Pow}}{max(\text{Pow})} + \frac{\text{Press}}{max(\text{Press})}\right)\right]^2 \tag{1}$$

The frequency distribution of various relevant sensors as Moment and Contact pressure sensors is illustrated in Fig. 6 along with the box plots of each sensor.

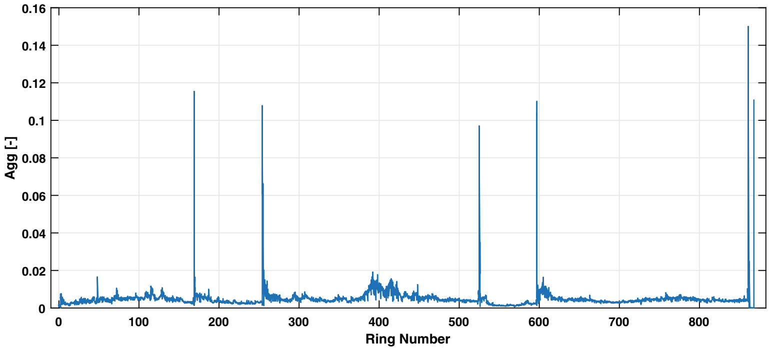

Fig. 5 Time series plot for Agg data for South Line data

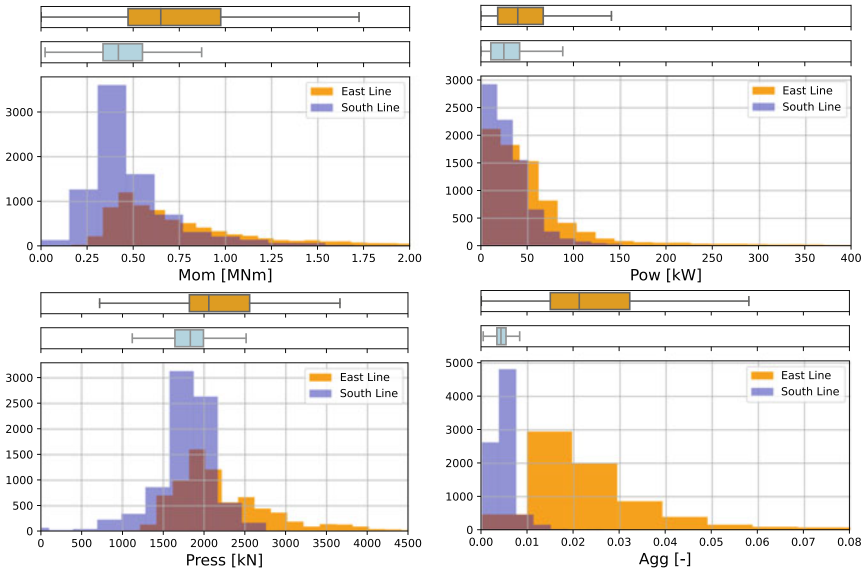

Fig. 6 Frequency distributions and Box plots for all the relevant sensors

4 Methodology

After a comprehensive literature review of the available methods to analyse our data, the following algorithms were chosen to be investigated in detail, and later their performance is compared.

4.1 Isolation Forest

Isolation forest finds anomalies by isolating the observations. This method considers points with shorter path lengths to be likely an anomaly.

The anomaly score for each observation is computed, and the threshold is computed by the required level of contamination given by the user. The anomaly score $S(x, m)$, where x is the data observation and m is the sample size, is computed as in Eq. 2 [4].

$$S(x, m) = 2^{\frac{-\mathbb{E}(h(x))}{c(m)}} \tag{2}$$

where $-\mathbb{E}(h(x))$ is the average search height of x for iTrees (Isolation trees) and $c(m)$ is the average of h(x).

The hyperparameter used for the algorithm was contamination = 4% i.e. 0.04.

4.2 kMeans and kMeans STSC

kMeans finds k-centroids in the time series and detects anomalies based on the distance of the observations to the centroids. The difference between kMeans and kMeans STSC (Sequential Time Series Clustering) is that instead of individual data observations, time series clusters of window length are employed to find the cluster centroids [4].

In kMeans clustering algorithm, a sliding window approach is used which means that the time series $\{X_N\} = (x_0, x_1, ..., x_N)$ and window length w and a sliding length γ, the time series $\{X_N\}$ results in a set of subsequences $S =\subseteq \mathbb{R}^{(N-w)\times w}$:

$$S = \{(x_0, x_1, ..., x_w)^T, (x_{0+\gamma}, x_{1+\gamma}, ..., x_{w+\gamma})^T, (x_{N-w}, x_{N-w+1}, ..., x_N)^T\} \tag{3}$$

The pseudo algorithm of the kMeans STSC algorithm is shown in Algorithm 1.

The hyper-parameters used for kMeans were $k = 5$, and for kMeans STSC, $k = 5$, window length: $w = 10$, sliding length: $\gamma = 1$.

4.3 ARIMA

ARIMA stands for Auto-Regression Integrated Moving Average, the algorithm comprises three components: autoregression applied to lag p, moving average applied to lag q, and differencing d [12].

Algorithm 1. An algorithm for kMeans STSC

Require: $\{X_N\} \leftarrow (x_0, x_1, ..., x_N), w, \gamma, k(centroids)$
$S \leftarrow \{(x_0, x_1, ..., x_w)^T, (x_{0+\gamma}, x_{1+\gamma}, ..., x_{w+\gamma})^T, (x_{N-w}, x_{N-w+1}, ..., x_N)^T\}$
$C \leftarrow k - centroids$ computed on $\{X_N\}$
$\epsilon \leftarrow (e_0, e_1, ..., e_{|S|})$
where e_i for $i \in \{0, ..., |S|\} is : e_i = \min_{\forall c \in C}(d(s_i - c))$
Set threshold e^* based on the contamination level set by the user.
$i \leftarrow 0$
while $i \leq N - w$ **do**
  if $e_i \geq e^*$ **then**
    The sequence i is an anomalous sequence.
  else
    The sequence i is not an anomalous sequence.
  end if
end while

$$X_t = \mu_t + \epsilon_t + \sum_{i=1}^{p} \phi_i X_{t-i} + \sum_{i=1}^{q} \theta_i \epsilon_{t-i}. \tag{4}$$

where in Eq. 4, X_i is obtained by d^{th} order differencing of observations y_i.

Equation 4 represents the ARIMA approach where μ_t and ϵ_t are mean and error, respectively. p and q are the observations and forecast error lags used for Auto regression and Moving average respectively.

Python computed the hyperparameters p, d, and q with the Auto Arima library. The time window to find the error's mean and standard deviation is evaluated to be equal to 40% of the forecast.

4.4 CNN Autoencoder

A traditional autoencoder includes an encoding part that reduces the dimension of the input data, and a decoder part reconstructs the input dimension, as shown in Fig. 7. The main assumption about the distribution of data is that the normal and the anomalous data are significantly different in the reduced dimension space. Due to the encoding function ψ and decoding function ϕ, there is a reconstruction error, and this error is used for detecting anomalies [22]. The pseudo algorithm of the Autoencoder approach is shown in Algorithm 2.

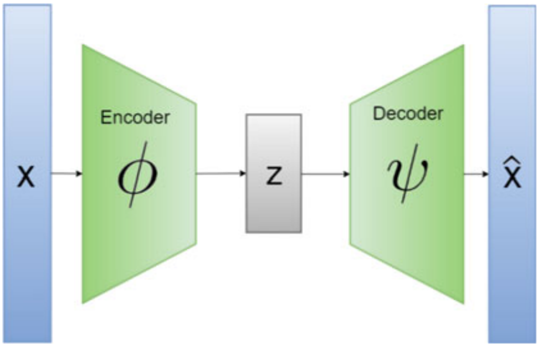

Fig. 7 Autoencoder: The encoding function maps x to reduced space z and the decoding function ψ maps z back to original dimension space $\hat{x}$ [4]

Algorithm 2. An algorithm for CNN Autoencoder

Require: $\{X_N\} \leftarrow (x_0, x_1, ..., x_N), w$
$S \leftarrow \{(x_0, x_1, ..., x_w)^T, (x_1, x_2, ..., x_{1+w})^T, (x_{N-w}, x_{N-w+1}, ..., x_N)^T\}$
$\hat{X} \leftarrow \psi(\phi(X))$
$\epsilon \leftarrow (e_0, e_1, ..., e_{|S|})$
where e_i for $i \in \{0, ..., |S|\} is : e_i = mean((X_i - \hat{X}_i)^2)$
Set threshold e^* based on the maximum value of e_i in ϵ with some weight.
$i \leftarrow 0$
while $i \leq N - w$ **do**
  if $e_i \geq e^*$ **then**
    The sequence i is an anomalous sequence.
  else
    The sequence i is not an anomalous sequence.
  end if
end while

5 Results

Figures 8, 9, 10, 11 and 12 compare various methods's performance by the evaluated $F1$ score metric as formulated in Eq. 5. True Positives (TP), in the anomaly detection regime, are the actual anomalies which are also detected efficiently by the algorithm. Similarly, False Positives (FP) are the wrongly detected anomalies, and False Negatives (FN) are the actual anomalies which were not detected by the anomalies.

$$F_1 = \frac{2 \cdot Precision \cdot Recall}{Precision + Recall} \tag{5}$$

Here Precision and Recall are calculated as shown in the Eq. 6.

$$Precision = \frac{TP}{TP + FP}, \qquad Recall = \frac{TP}{TP + FN} \tag{6}$$

However, in TBM excavation data, early detected anomalies are very beneficial, while this can help change the TBM excavation parameters, consequently decreasing downtime. Hence the early detected anomalies (if detected at least before five walls) before the actual location) are considered to be TP and not FP.

The comparison between the noisy sensor data (row data) and two smoothed versions of the data namely, Trailing Moving Average (TMA) data with lags = 20 and Exponential moving average (EMA) with $\alpha = 0.3$ was performed. The models are trained on increasing data to imitate the actual real-time behaviour.

To visualise various methods further, the bar chart plot below shows the comparison between the various methods.

Figure 8 compares the Isolation Forest algorithm with various sensor data used on row data (data without any averaging), TMA and exponential moving average. The best $F1$ score for East Line data was with the Agg. sensor data (which is given by the Eq. 1) - row data and for South Line data was with Press and Agg. sensor data with TMA smoothing Eq. 1. The best $F1$ score found was 0.6667 for both the East and South Line data.

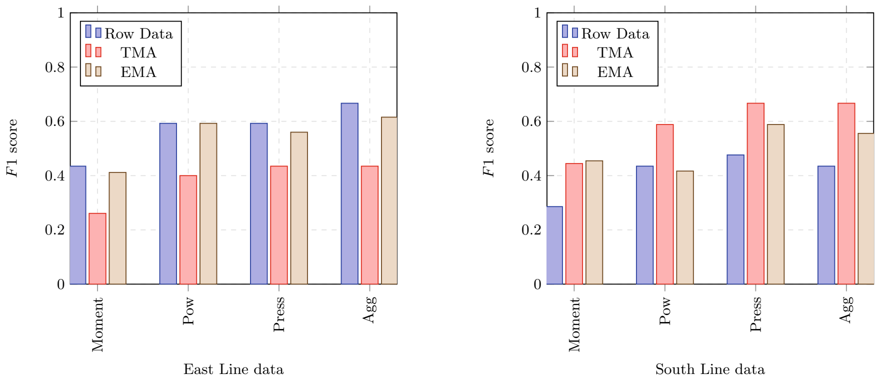

Fig. 8 Comparison of $F1$ scores for Isolation Forest model

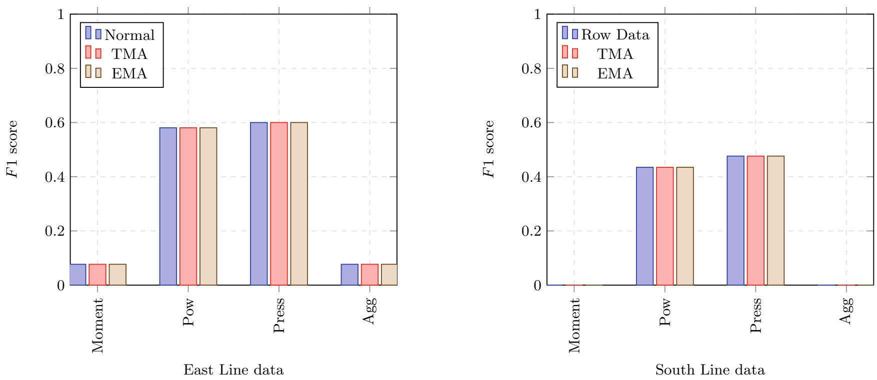

Fig. 9 Comparison of $F1$ scores for kMeans model

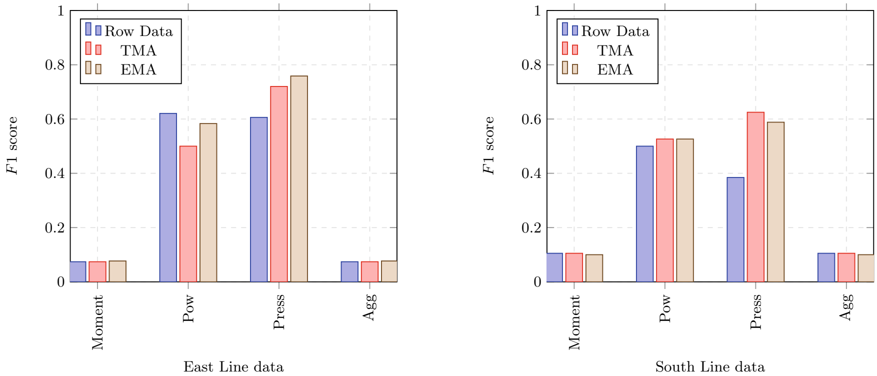

Fig. 10 Comparison of $F1$ scores for kMeans STSC model

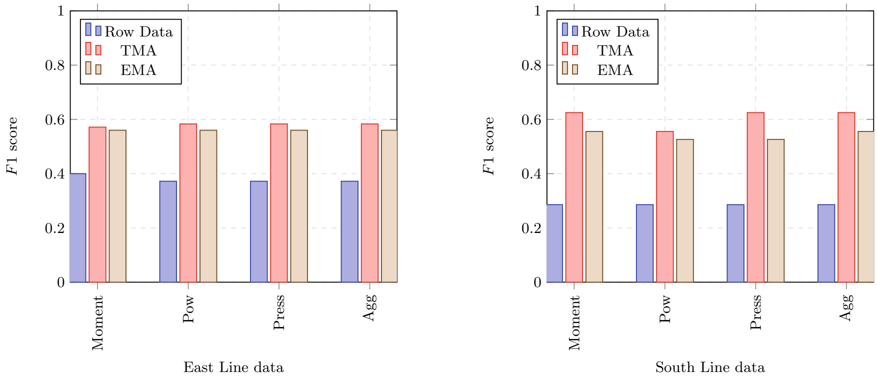

Fig. 11 Comparison of $F1$ scores for ARIMA model

Figure 9 shows a similar comparison for the kMeans algorithm. The best $F1$ score for East and South Line was with the Press sensor data - (row data, TMA and EMA gave the same $F1$ scores). The best $F1$ score equal to 0.6000 is evaluated for the East Line data and 0.4762 for the South Line data.

Figure 10 shows the comparison for the kMeans STSC algorithm. The best $F1$ score for East and South Line data was with the Press sensor data - (EMA for East and TMA for South Line data). The best $F1$ score found was 0.7586 for the East Line data and 0.6249 for the South Line data. The $F1$ score of 0 represents the method's predicted irrelevant anomalies hence the value is not relevant and hence, set to 0.

Figure 11 shows the comparison for the ARIMA algorithm. The best $F1$ score for East Line data was with the Pow, Press and Agg sensor data with TMA smoothing. For South Line data, the best $F1$ score was Moment, Press and Agg sensor data with TMA smoothing. The best $F1$ score found was 0.5834 for the East Line data and 0.6249 for South Line data.

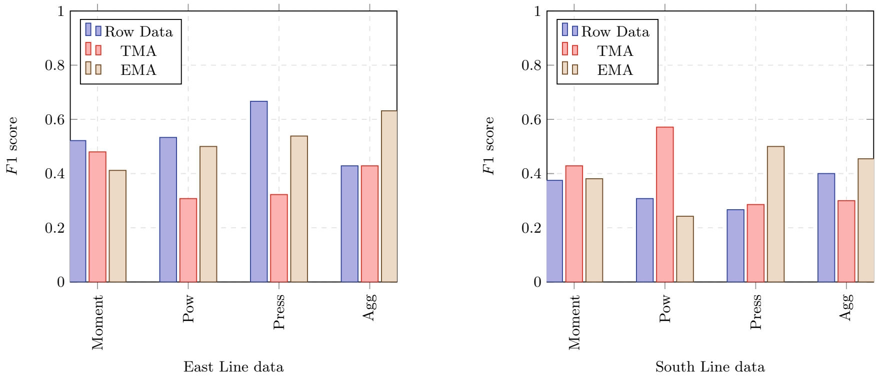

Fig. 12 Comparison of $F1$ scores for CNN Autoencoders model

Fig. 13 Comparison of the best $F1$ score models

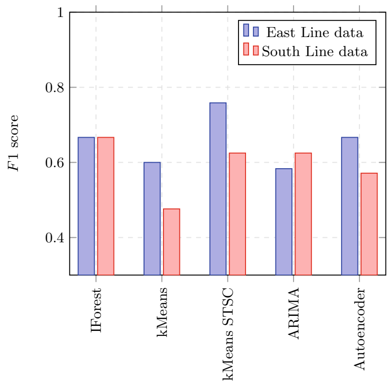

Figure 12 shows the comparison for the CNN Autoencoder algorithm. The best $F1$ score was evaluated as 0.6667 for the East Line data and 0.5714 for South Line data.

The results discussed above were the best $F1$ scores for every algorithm, in order to compare every algorithm with each other in Fig. 13. For East Line data, the algorithm which gave the best $F1$ score of 0.7586 was the kMeans STSC algorithm with Press sensor data and EMA smoothing. For South Line data, the algorithm which gave the best $F1$ score of 0.6667 was isolation forest with Pow and Press sensor data and TMA smoothing. For South Line data, the Isolation Forest performed efficiently because the anomalies in the south line data were mostly pointed anomalies and Isolation Forest is one of the efficient methods to detect point anomalies. kMeans STSC (Press sensor TMA smoothing) and ARIMA (Moment, Pow, Agg sensor data with TMA smoothing) also performed well in the South line data with an $F1$ score of 0.6249.

6 Conclusion and Remarks

In the present study, various statistical and machine learning approaches were applied to detect anomalies in a TBM excavation process on real data. The data were gathered by multiple sensors on a TBM throughout two lines of excavation. After performing pre-processing on the noisy data, they have been used in various implemented anomaly detection methods to indicate the location of anomalies. The TBM was running in an almost homogeneous subsoil, therefore, existing concrete slabs, constructed for the stations, were considered as anomalies. After comparing different methods, we may conclude that in general anomaly detection of the concrete slabs, the kMeans STSC approach delivered a more promising prediction, and for detecting point anomalies, Isolation Forest proved to be the most effective. This can however be the case because of the sensor data itself. As previously stated, early identification of severe changes in the TBM's surroundings might be regarded as early warnings to trigger appropriate adjustments in either the pace of excavation or some other steering parameter to prevent possible consequences. This can help to reduce tunnelling delays due to TBM damage to a great extent.

This paper focuses mainly on univariate time series data, which imposed the limitation on investigating the influence of different sensors together. Hence, an effort was made to empirically create a variable, which incorporates the influence of various sensor data. However, this does not overcome the disadvantages of using the univariate data later. Ongoing research by the authors addresses this issue to investigate the domain of multivariate time series for detecting anomalies.

Although the methodologies implemented in this paper are validated through a severe material change (subsoil to concrete), they can be extended further to improve the performance of detecting any material changes in the tunnelling project and modify the geological profile.

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Towards Multicriterial Scan Planning in Complex 3D Environments

Florian Noichl and André Borrmann

Abstract As-is geometry of existing structures in the built environment can be captured with high accuracy using laser scanning. Frequent measurements and automation of data processing steps allow digital representations of physical assets to be kept up to date at a justifiable cost, even if they are subject to frequent changes. Before operators can execute stationary laser scanning, scan planning has to be performed to estimate the required effort and choose equipment, settings, and locations. In contrast to the conventional, expert-based method usually conducted as an assessment in the field, automated offline approaches aim to solve this task exclusively with pre-existing data describing the scene. These methods are more efficient, add transparency to the existing process landscape, and are a prerequisite for sensible implementation of robotic automation, enabling actual repeatability. The novel method proposed in this paper works in complex 3D environments while considering multiple criteria relevant to the feasibility of acquisition and the quality of acquired datasets. The proposed method introduces the scene as a triangulated mesh within which viewpoint candidates are automatically generated. This mesh is further used in a deterministic approach for visibility and coverage analysis between scene and viewpoint candidates. Based on this analysis, viewpoints are selected to form a solution set that fulfils all pre-defined requirements regarding surface coverage in the scene using a greedy algorithm. Connectivity in the solution is enforced to ensure the captured data will allow targetless registration. The objective function used for evaluating potential solutions allows for consideration of all necessary objectives and constraints in the greedy algorithm while retaining flexibility for applying other solution heuristics and optimization methods.

Keywords Scan planning · Planning for scanning · P4S · Terrestrial laser scanning · TLS · Greedy algorithm

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1 Introduction

As the digitization of the built environment progresses, methods for managing physical assets using their digital representations are evolving, and applicable solutions are penetrating the market. With a majority of projects within the domain of Architecture, Engineering and Construction (AEC) happening in the context of the existing building stock, an increasing focus lies on the challenge of keeping the digital models up to date. Capturing technology is rapidly developing in various aspects, ranging from sensor precision and acquisition speed to easy applicability; first attempts are made to perform acquisition tasks fully autonomously with the help of robotic platforms to further lower costs and enable regular updates. Furthermore, these platforms can be deployed under conditions that would make it difficult or impossible for a surveyor to perform the acquisition. For any reality capture mission to be successful, it needs to be properly planned. In the context of construction sites or industrial facilities, changes in geometry happen regularly and are of high relevance for those in charge of their management and monitoring progress. A conceptual overview of this repetitive process is depicted in Fig. 1 to introduce the context. The conventional method of scan planning is expert-based and often conducted in the field only- in some cases, supported by pre-existing information, such as floorplans of the area to be scanned, which helps to ensure proper data quality in the resulting point cloud. Automating the scan planning process helps save time, approximate the required time for capture and assure sufficient quality in the resulting data in each repetition.

Most existing approaches that develop scan plans based on prior knowledge of the scene are based on 2D scene representations and therefore lack specific precision in geometrically complex environments. Some use actual 3D representations as input but use heavy simplifications or simulations to proceed, often leading to impractical or not generally applicable results.

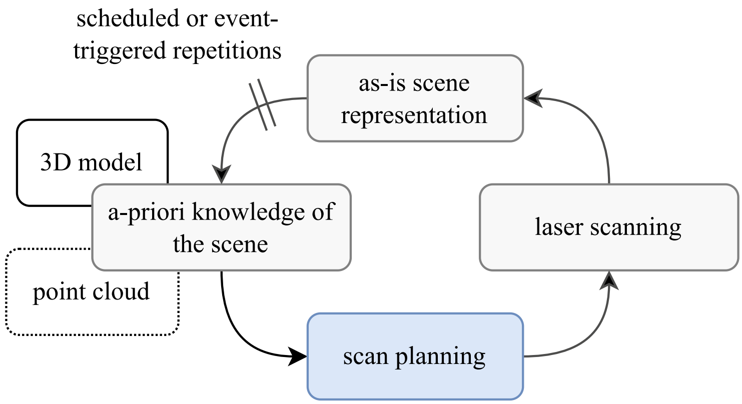


Fig. 1 Conceptual, repetitive process to keep geometric as-is scene representations updated on a regular basis; this paper introduces a novel method for scan planning

To overcome these limitations, the method presented in this paper can process the scene in a full 3D representation instead of a simplifying abstraction- while taking into account multiple aspects of recording quality and equipment requirements for scan planning using a simple heuristic. Thus, this method can achieve a technically comprehensive and feasible scan plan ready for deployment in the scene.

2 Related Work

In scan planning, automated approaches can generally be separated into model-based and non-model-based approaches. Non-model-based approaches perform decision-making on the go with no prior knowledge of the scene, while model-based methods are informed by prior knowledge. While model-based approaches can provide solutions for the scene in its entirety, the actual quality of the proposed strategy is limited to the closeness to the reality of the input model. Non-model-based solutions generally aim for local optimality in consecutive acquisition steps; they are therefore well suited for those cases where no reliable prior knowledge of the scene is available. Either paradigm poses specific challenges that have been faced with various technical solutions. In this work, we focus on model-based scan planning; the related works are therefore selected accordingly. For a comprehensive review of relevant aspects and approaches, the reader is referred to the pertinent overview publications in the field [1, 14].

Model-based methods for scan planning are classically treated as variations of the Art Gallery Problem. In this, an art gallery needs to be equipped with a minimum amount of guards such that the entirety of the gallery, represented by a wall polygon, can be observed [7]. In the context of scan planning, the same logic can be applied for finding optimal locations for scanner placement that minimize effort while ensuring sufficient surface coverage in the scene [11]. Amongst others, the problem has been referred to with *viewpoint planning* [11, 15], *scanning network design* [10] and *planning for scanning (P4S)* [1]; for the sake of clarity and to emphasize the application reference, we refer to it with *scan planning* like the majority of researchers in the field [3, 5, 13, 17].

Proposed solutions for the scan planning problem are largely focused on 2D floorplans as input to achieve 100 % wall coverage- predominantly using variations of the greedy algorithm [10, 16], in comparison with other optimization methods [9]. In 3D, solution approaches include the use of laser scan simulation [2, 6], or specific, repeating geometric features of the scene [12] to solve the problem. Beyond coverage alone, scan planning should consider other constraints- one important aspect to consider for terrestrial laser scanning is the acquired data's readiness for registration [15]. [10] proposed a solution for target-based registration based on a 2D floorplan representation of the scene; towards 3D, [4] includes the floor area in addition to the wall polygon and proposes an approach to assure connectivity between scanning locations through sufficient overlap.

After potential scanning locations have been evaluated with regard to the defined evaluation criteria, a selection needs to be made to form a set of points that is able to fulfil the overall requirements. [10] uses the well-known greedy best-first approach; [9] in comparison with evolutionary optimization methods, [4] define the candidates on a scanning graph and use mixed integer linear programming to find optimal solutions.

Based on this, we identify a research gap in a robust scan planning method that is versatile in terms of 3D input, works in full consideration of this 3D environment and can take into account multiple constraints. We investigated a deterministic approach to face this problem in 3D without simulation and analysed the performance of two single-criterion greedy algorithms in [13]. This paper extends the well-known greedy approach to work on multiple criteria using a graph-based objective function. This allows us to take more criteria into account- which we showcase by introducing pairwise overlap while assuring set-wide connectivity.

3 Method

In the context of construction sites or industrial facilities, changes in geometry happen regularly and are of high relevance for those in charge of their management and monitoring progress. The presented method is model-based and therefore especially suited for the context of repeated inspections, updating and extending the digital as-is representation of the scene, as introduced in Fig. 1. The necessary individual steps of the scan planning method are automated and get introduced in more detail in the following sections; three main steps can be distinguished, Fig. 2 provides an overview.

3.1 Viewpoint Candidate and Scene Preparation

In the scene, a 3D viewpoint candidate grid is initiated based on model areas suitable for setting up laser scanners. First, the user needs to identify planes in the model that are suitable locations to place the scanner, which is the only remaining step that requires manual intervention. Three parameters are then used to create the candidate grid:

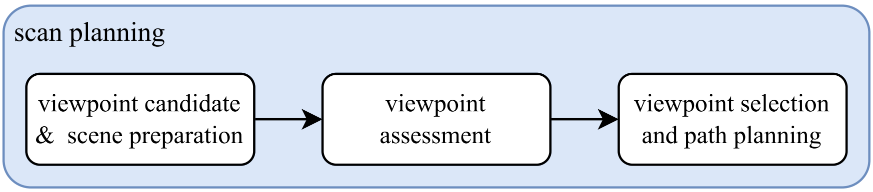


Fig. 2 Subsequent steps of the scan planning method

- r_{scene}: voxel size scene
- r_{grid}: viewpoint candidate grid resolution in the x-y-plane
- t_z: options for height adjustments on the z-axis

Points are sampled on a regular grid with grid size r_{grid} on the identified planes to create a regular-spaced grid of candidate points; the scene mesh scene is transformed into an occupancy grid with voxel sizes r_{scene}. The candidate grid points are translated along the z-axis to the first element of t_z- if there are multiple height options for the equipment, the initial grid is copied in the direction of the z-axis for each entry of t_z accordingly. An inlier test is then performed between all elements of the resulting 3D candidate grid and the occupancy voxel grid depicting the scene to filter candidate points that either collide with or lie in direct proximity of the triangulated scene. The remaining points are valid viewpoint candidates and are further processed into a viewpoint candidate graph $G_{cand} = (V_{cand}, E_{cand})$, connecting all valid viewpoints with their immediate neighbours leveraging the pre-defined parameters of grid resolution as thresholds in the respective coordinate directions; The respective edges graph are weighted with the euclidean distance between the nodes they connect to create a weighted graph that is suited for path planning. Using this method, edges in this graph will naturally not connect nodes whose direct connection is obstructed by objects in the scene, thus allowing meaningful path planning directly within the viewpoint candidate graph.

The scene is considered in the form of a triangulated mesh. For meaningful investigation of occlusions caused by obstructions of the line of sight, triangles in the mesh should have consistent, limited sizes. To create such evenly sized faces of a limited extent, the triangulated mesh is refined by subdivision of edges such that all edges in the mesh are shorter than a pre-defined threshold value l_{max}. Using this method, the integrity of the original geometry is insured, as additional nodes are only created on existing edges; additional edges will always lie within existing faces.

3.2 Viewpoint Assessment

Raycasting is performed from all candidate viewpoints to all triangle midpoints of the faces in the scene. This way, visibility between each viewpoint candidate and the scene is evaluated on a deterministic basis and independent of equipment resolution. Each ray's first intersection with the scene is stored, and the intersected face ID is stored as visible from the ray-emitting viewpoint candidate. The full visibility information is stored in the initial, binary visibility table

$$\mathbf{V}_{0_{i,j}} \text{ with } v_{i,j} = \begin{cases} 1 & \text{face } j \text{ visible from viewpoint } i \\ 0 & \text{face } j \text{ occluded from viewpoint } i. \end{cases} \tag{1}$$

The visibility table is further filtered according to the defined framework conditions:

1. equipment-specific
   - field of view
     - horizontal assumed to be 360°, negligible
     - vertical restrictions: user-defined ($\leq 180°$)
   - depth of field: minimum and maximum distance
   - minimum incidence angle
2. technical requirements
   - maximum distance
   - minimum local point density LPD

$$LPD = \frac{1}{LPS_{90}} \times \frac{1}{LPS_{\alpha}} \tag{2}$$

with $LPS_{90} = SPS \times d$ for the orthogonal case and $LPS_{\alpha} = LPS_{90} \div \sin\alpha$ for any incidence angle; SPS denotes the distance-specific point spacing, d the scanning distance, and α the local incidence angle.

The visible faces that also comply with these requirements are collected in the initial coverage table

$$\mathbf{C}_{0_{i,j}} \text{ with } c_{i,j} = \begin{cases} 1 & \text{visible and within requirements} \\ 0 & \text{occluded or visible and violating requirements.} \end{cases} \tag{3}$$

After the initial mesh subdivision step, triangle face areas are similar but not equal. Therefore, the coverage table needs to consider the individual areas of all faces, denoted with a_j:

$$\mathbf{C}_{i,j} = \mathbf{C}_{0_{i,j}} \circ a_j \tag{4}$$

The evaluation of potential strategies is conducted over three levels of granularity between individual viewpoints (micro) and a full set of viewpoints forming a scan plan (macro).

Micro: Viewpoint Coverage. Based on the qualified coverage-based visibility table, the coverage can be calculated per viewpoint i as the sum of all qualified visible face areas.

$$c_i = \sum_{j=1}^{n} \mathbf{C_i} \tag{5}$$

Meso: Pairwise Overlap. An overlap index matrix is calculated based on the visibility lists per point for the complete candidate set as $\mathbf{O}_{\text{ind}_{i,j}}$ with $o_{i,j} = \{\text{ind}_i\} \cap \{\text{ind}_j\}$ with ind denoting the list of row indices of visible faces in $\mathbf{V}$ and thus the faces' ID in the model; it should be noted that in this and the following equations, j is reassigned: here, indices i, j refer to viewpoint indices. For each pair of candidate viewpoints, the overlap is determined as their intersection. The respective set of face IDs can be directly accessed in the overlap table $\mathbf{O}_{\text{ind},i,j}$ using the viewpoints' indices. The relative area overlap is calculated as the area of intersection over union for all pairings of viewpoint candidates in the candidate set with intersection indices $o_{i,j}$ and union indices $p_{i,j} = \{\text{ind}_i\} \cup \{\text{ind}_j\}$.

$$\mathbf{O}_{\text{rel}_{i,j}} \text{ with } o_{\text{rel}_{i,j}} = \frac{\sum_{k \in o_{i,j}} a_k}{\sum_{l \in p_{i,j}} a_l} \tag{6}$$

Macro: Set-Wise Connectivity. Sufficient overlap must be ensured on the level of the set of viewpoints chosen as a strategy, which is evaluated in its graph representation. A complete graph $G_{sel} = (V_{sel}, E_{sel})$ is built from the selected viewpoints V_{sel} as nodes, and the adjacency matrix of $E_{sel} = \mathbf{O}_{\text{sel},i,j}$, populated from $\mathbf{O}_{\text{rel},i,j}$. The best connectivity network of viewpoints is established as the maximum spanning tree $T = (V_{set}, E_{tree})$ of this fully connected weighted graph. The quality of cloud-to-cloud registration is evaluated by the best pairwise overlap, represented by the weighted edges in the graph. The critical overlap in the set can be quantified in the final result as the minimum weighted edge in E_{tree}.

$$o_{crit} = \min_{w} (E_{tree}) \tag{7}$$

3.3 Viewpoint Selection and Path Planning

A greedy algorithm is applied to select viewpoints to form a suitable scan strategy. The choice for the next viewpoint is made based on an evaluation of all options successively, and at each step, the option scoring the highest value is selected for the strategy. Beyond the variables introduced above, c_{min} denotes the overall required coverage, o_{min} the minimum required pairwise overlap. S denotes the score used to make the greedy choice as follows:

Algorithm 1: Greedy algorithm for viewpoint selection

$VP_{select} := \emptyset$
while $\sum_j \mathbf{C}_{i=VP_{select},j} < c_{min}$ **do**
  calculate S_i // calculate score per candidate
  VP_{select}.append($\max_S VP_i$) // append best candidate
  $\mathbf{C}_{i,j} = 0 \ \forall \ \mathbf{C}_{i=VP_{select},j} \neq 0$ // delete covered faces from C
  if *greedy weighted* **then**
    $\mathbf{C}_{i,j} = \mathbf{C}_{i,j} \circ W$ // update coverage table with weight

The applied variations of the greedy algorithm differ in candidate evaluations. In the *standard greedy*, evaluation is performed directly on the sum of the covered areas.

$$S_{greedy,i} = \sum_j \mathbf{C}_{i,j} \tag{8}$$

In the proposed method, an objective function is used to evaluate the score per candidate; This approach can be directly applied in the context of other optimization methods as it allows to evaluate complete solutions in terms of coverage while taking into account the adherence to the overlapping requirement by penalizing its violation with penalty value p:

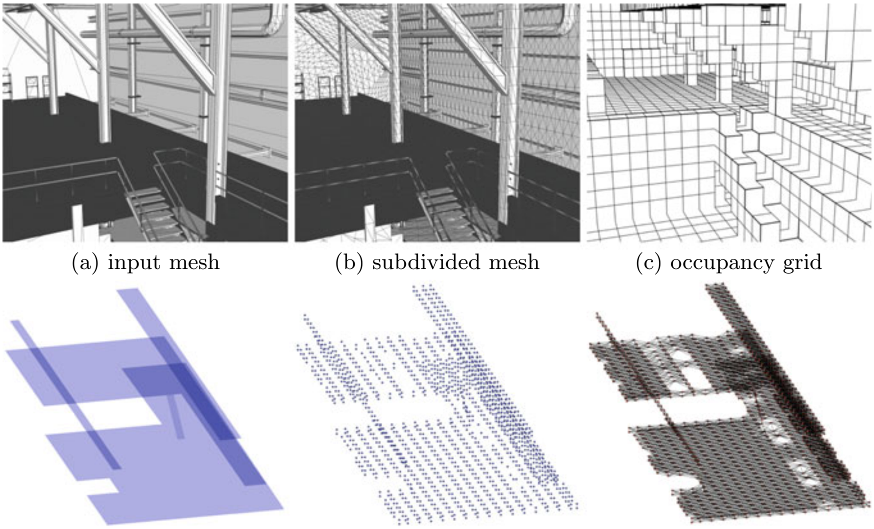
$$S_{objective} = S_{greedy,i} + f_o \text{ with } f_o = \begin{cases} 0 & o \geq \min o_{min} \\ p & \text{otherwise} \end{cases} \tag{9}$$

After a set of viewpoints is established, a suitable sequence of execution in a loop and an actual path through the scene is found using the initially created candidate graph $G_{candidate}$ by approximating a solution for the Traveling Salesman Problem (TSP) for the selected nodes V_{sel} within $G_{candidate}$. This path is inherently limited to the candidates' immediate neighbours and thus passable in the scene. Path planning is performed using existing libraries without adaption in this contribution and is not further introduced as part of the method.

4 Experiment

4.1 Setup

The evaluation of the proposed method is performed using the 3D model of an industrial facility, including several levels of steel structures, pipe and duct systems, shelves, and some clutter. The original triangulated model (overview depicted



(a) input mesh (b) subdivided mesh (c) occupancy grid

(d) candidate areas (e) viewpoint candidates (f) candidate graph G_{cand}

Fig. 3 Experiment setup: Model input and intermediate processing results

in Fig. 3a, 89 000 faces and 62 000 vertices) was processed by subdivision with a threshold of max. 1 m edge length; resulting in a model with 1 030 000 faces and 530 000 vertices (Fig. 3b). After suitable viewpoint areas have been identified (Fig. 3d), candidate viewpoints are generated and filtered by inclusion testing with the occupancy voxel grid derived from the triangulated scene input (Fig. 3c); 1730 candidate viewpoints (Fig. 3e) are identified as valid input for further processing ($r_{scene} = 0.5$ m, $r_{grid} = 2.0$ m, $t_z = [1.0$ m, 2.0 m$]$). Due to the model's incompleteness in terms of level connectivity, some candidate areas are disconnected, and the initial graph is not fully connected. To allow automated processing end-to-end, the disconnected parts are joined automatically to their respective nearest neighbour in the remaining point set. The resulting set of viewpoint candidates is connected to immediate neighbours in 3D, forming the viewpoint candidate graph, as depicted in Fig. 3f. The implementation used in this experiment makes use of Open3D [18] for geometric functionalities such as raycasting and NetworkX [8] for graph processing.

4.2 Results

For all experiments, scanning equipment has a full horizontal field of view, a vertical range of 30–180°. In the first experiment, requirements are set to overall coverage of min. 75% of the coverable surface, the minimum local required point density is set to 2500 pts/sqm, and the required overlap between two viewpoints to ensure targetless registration is assumed to be 20%. In the objective function, a violation of

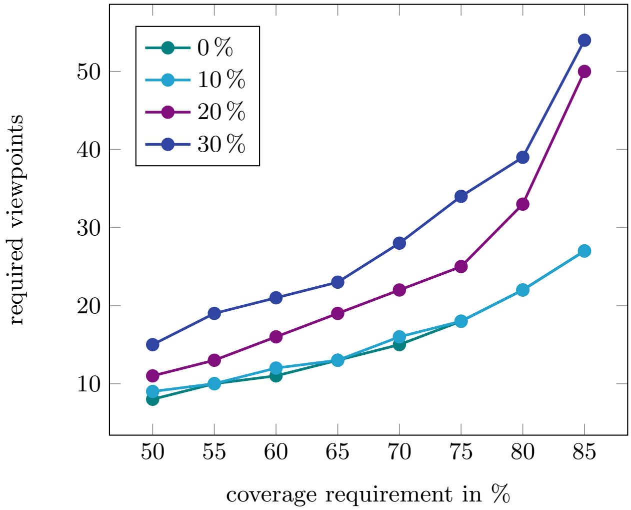


Fig. 4 Experiment results for varying overlap requirements (legend) and coverage requirements

this overlap constraint is penalized with $p = 100$, to make the overlap objective a limiting constraint.

The experiment is performed using a straightforward, non-constrained greedy heuristic in comparison with the greedy approach using the introduced objective function. Without objective function, the resulting strategy is able to cover the required surface with 18 viewpoints, including the constraint for sufficient overlap 25 viewpoints are required (full results depicted in Fig. 5). However, cloud-to-cloud registration with our defined parameters is impossible in the former result; 10 out of 24 pairwise connections do not have sufficient coverage with any other point in the strategy.

To investigate the influence of varying overlap requirements, the experiment was repeated for a range of relative overlaps from 0 % to 30 %. The results are summarized in Fig. 4 and indicate an exponential growth in the number of viewpoints required to meet the requirements. Although an investigation of the impact of such relative overlaps in terms of targetless registerability of individual point clouds is beyond the scope of this work, it has been shown that they can be accounted for within the presented scan planning methodology and have a significant impact on its results.

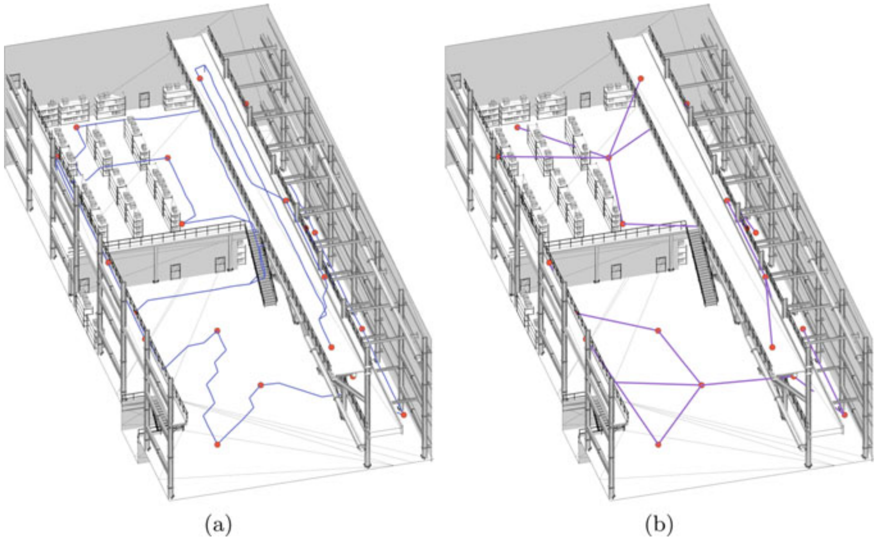


Fig. 5 Aspects of scan planning results in the context of the original experiment scene (before subdivision, two walls and roof structure removed for visualization): **a** selected scan points with shortest path visiting all selected points, **b** connectivity graph indicating best pairwise overlaps

5 Discussion and Outlook

This paper introduces a method for model-based scan planning in complex 3D environments. Beyond existing approaches, it is able to work directly with a standard 3D representation of the scene, in which the input viewpoint candidate grid is generated as a 3D graph automatically with minimal required user input. In the method, three granularities of quality metrics are considered to choose a set of viewpoints forming a scan plan, including the shortest round trip through the candidate graph as a proposed scanning sequence. With coverage and point density, local and global point cloud quality considerations are taken into account while ensuring sufficient overlap for targetless registration of the resulting point clouds. The competing objectives of this setup are considered as constraints and part of the objective function used for decision-making in the greedy heuristic. In a short experiment, it is shown how this method performs in an exemplary industrial scenario.

As the underlying computation is static and performed as an initial step, it is quite computationally expensive in its current implementation. Through the static and comprehensive basis, however, it provides a robust basis for further investigations of alternative methods for optimized viewpoint selection- which is a promising outlook, especially for more complex scenarios of competing goals.

Going forward, sensible extensions of this work are therefore identified in a) the extension of constraints and criteria to achieve more specific industry-relevant solutions along with b) the investigation of methods that are eventually able to consider all these criteria in finding suitable solutions.

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Image Segmentation on Concrete Damage for Augmented Reality Supported Inspection Tasks

Firdes Çelik, Patrick Herbers, and Markus König

Abstract The building inspection process is an important step in the maintenance phase of a building. However, human resources are limited, and the inspection process is still predominantly a manual process: Damage is documented on paper, recorded with cameras, and manually entered into databases. Digital tools could improve this process, making it more time and work efficient. Continuous advancements in Machine Learning (ML) and Augmented Reality (AR) can support inspectors during damage documentation tasks, allowing for combined capture and documentation of damage.

This paper presents an approach to damage documentation with the Microsoft HoloLens 2 (HL2), a head-mounted optical see-through augmented reality device. To this end, we train and review image segmentation models based on over 5,500 images and deploy the best-performing model on the HL2. The segmentation model is trained to distinguish four concrete damage types. Model inference time is compared between the deployment of the ML model on the HL2 and a compute server. The application is tested on-site for a bridge inspection task, investigating the feasibility of the developed AR-ML-based sub-concept for damage documentation.

Keywords Concrete Damage Segmentation · Damage Detection · Crack Detection · Machine Learning · Augmented Reality

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1 Introduction

Maintenance becomes an ever more critical part of a structure's life cycle as buildings and infrastructure age. Regular inspections are vital to detect damage to a structure early and prevent critical failure. To this day, these inspections are performed primarily using paper-based processes. With the increasing importance of digitization, the inspection process should be elevated to the standards of the digital age. One approach is using technology which aids the maintenance personnel in the laborious parts of their work and provides them with sufficient data to focus on the bigger picture.

Machine Learning (ML) is a key concept that can fulfil this role. Automatically marking, labelling, and analyzing data on structure damage would increase maintenance missions' efficiency, accuracy, consistency, and prediction power. A neural network could categorize and measure damage found on a structure. This kind of data enrichment may improve our understanding of building and aging infrastructure.

In addition, the maintenance personnel requires technology that can help visualize past and present data without obstructing regular inspection tasks. Augmented Reality (AR) may be suitable for this goal. Maintenance is usually performed in

Fig. 1 Damage segmentation with the help of the HoloLens 2 on a bridge inspection mission.

unpredictable conditions, and workers need to climb and get close to a building element to record damage. Thus, devices that can be operated hands-free, e.g. head-mounted AR devices, are suitable for a safe working environment. Devices like the Microsoft HoloLens 2 (HL2) already employ see-through optical lenses and gesture control, which requires neither dedicated input devices nor vision-obstructing displays. Being able to visualize past and present damage directly on-site may add a more responsive and holistic layer to the maintenance process.

An AR application using ML for recording and visualizing concrete damage is the first step to an entirely digitized workflow for infrastructure inspection tasks (see Fig. 1). The combination of these technologies would allow a maintenance worker to connect and interact with a digital twin on site. Such technologies may pave the way for more frequent, fully autonomous inspections of infrastructure and buildings with the help of drones and robotics. Letting users see and interact with the results of an ML model is central when bridging artificial intelligence (AI) and the engineering sciences.

This paper presents the results of ML-based segmentation models that were trained on a large concrete damage data set with over 5,500 high-resolution images. This data set was manually segmented for four concrete damage types: Cracks, spalling, corrosion, and honeycomb. The distribution of the damage types regarding occurrence and size is shown and explained with a data set analysis.

Multiple semantic segmentation networks are trained on this data set. The networks are based on Feature Pyramid Network (FPN) [10] and differ by the backbone network. The feasibility of on-device (HL2) deployment of semantic segmentation models is examined, and the deployment challenges are elaborated. Additionally, the performance of the segmentation model is tested on the HL2. An HL2 application was programmed for this test that visualizes the damage segmentation mask as a holographic overlay and displays damage type and quantity information. This application is the first step to interaction with the damage results.

2 Related Work

Using AI for damage recognition, especially crack recognition, has been a topic for ML since early on. Kim et al. [8] use an R-CNN in combination with traditional computer vision to mask concrete damage on bridges using a UAV. To identify regions of interest, a bounding box regression network was trained on 384 crack images with size 256×256 pixels. Cracks inside of regions of interest are then marked using Sobel filters. The researchers also present a crack size evaluation method through a reference marker, which has to be present in the picture.

AR in the engineering sciences has been a central area of research in the last decade [3]. Annotation tools, such as presented by Bae et al. [1], were the first applications of AR in maintenance. Later, the connection between AR applications and building data was expanded, and processes were evaluated closely. For example, Kim et al. [9] utilize AR for post-disaster damage assessment by providing 3D building models to a mobile device. Users can overlay the 3D model using a map, and compare the damaged building to the model. Neges and Koch [11] use AR to visualize and feed back data into a Product Lifecycle Management system. John Samuel et al. [6] developed a hand-held AR application. It can show historical damage information on 3d bridge models and capture damage more accurately and objectively. These approaches are mainly based on hand-held AR, e.g. through a tablet or smartphone. Smith et al. [12] propose a possible interface design for head-mounted AR devices to be used in the bridge inspection workflow, which is evaluated on a Virtual Reality prototype. In these examples, the damage is still identified and recorded manually.

In recent research, a combination of AR and AI was identified as beneficial. Karaaslan et al. [7] use a similar approach of combining ML-based damage segmentation and AR with the head-mounted HoloLens. The damage is segmented using a two-step approach to provide real-time damage segmentation. Damage instances are then displayed using an image overlay, and an evaluation of damage severity is given based on the size of the damage. Similarly, Wang et al. [14] developed a head-mounted AR inspection application that includes bounding box detection of corrosion and cracks using Mask-R-CNN.

3 Methodology

The proposed system is an ML-based concrete damage segmentation model supported by an AR application. Section 3.1 describes the data and the training process of the segmentation network. Section 3.2 shows how the network was deployed and visualized on an AR device, specifically the HL2.

3.1 ML-based Damage Segmentation

To recognize damage with the HL2, an ML-based segmentation model is needed. In our concept, an end-to-end segmentation network is chosen. This is a different approach to the two-step method proposed in Karaaslan et al. [7]. There, the damage is first captured by a detection model, and afterward, a segmentation network is applied to the previously detected bounding boxes. We opted against a two-step method. Firstly, two models must be trained, i.e. a detection and a segmentation model. Secondly, the majority of segmentation models only accept one pre-defined image size. This means the detected bounding boxes must be resized to one specific size. However, damage comes in a variety of shapes. For example, spalling and honeycomb usually have a compact form, i.e. they have a low difference in aspect ratio. Cracks, on the other hand, have an elongated shape, i.e. they have a high contrast in aspect ratio. Barring the possible significant differences in bounding box sizes, rescaling bounding boxes to an equal aspect ratio poses problems regarding image quality, especially for crack images.

Next to the ML-based segmentation architecture, a necessary and more important condition for a well-performing segmentation model is the availability of a large data set covering the high variability and complexity of concrete damage. A large data set was prepared to fulfil this condition.

Training Data. The data set to train the segmentation models consists of 5, 575 high-quality images. The image width varies between 733 and 6641 pixels and the image height is between 453 and 4137 pixels. Over 81% of the images have a resolution larger than 2048 × 2048 pixels. The images were taken with smartphone cameras by student assistants. They were instructed to take images of the damage types spalling, crack, corrosion, and honeycomb from a variety of concrete structures. Due to low availability and accessibility of bridges and for a fast data collection, the images were not only taken from bridges but also from parking garages, walls, buildings and floors. To add more variability and complexity in the data set, the image collection was extended from Germany to multiple other countries: Albania, Bosnia and Herzegovina, Netherlands, Serbia, Turkey, and the United States (Florida). Students labelled the data set manually by using the label tool COCO Annotator [2]. The labeling includes the drawing of polygons along the contours of the damage and the damage type assignment. To ensure high quality labeling, the annotations were reviewed and corrected by the authors. After the labelling, all images were resized to size 512 × 512 pixels.

In Fig. 2, the percentage of images containing a specific damage type are shown. Spalling and cracks appear in the majority of the images with a share of 61.73% and 61.41% in the data set. Corrosion is found in 33.57% of the images, followed by honeycomb, which is in 28.42% of the images. It can be observed that there is an imbalance in the damage type representation, where corrosion and honeycomb appear 50% less than spalling and cracks when measured by availability on images.

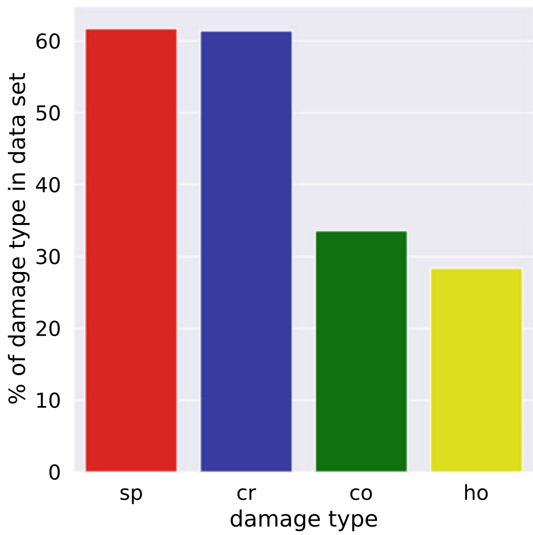

Fig. 2 Percentage of images in the data set containing specific damage types. The damage types are abbreviated as 'sp' for spalling, 'cr' for crack, 'co' for corrosion, and 'ho' for honeycomb.

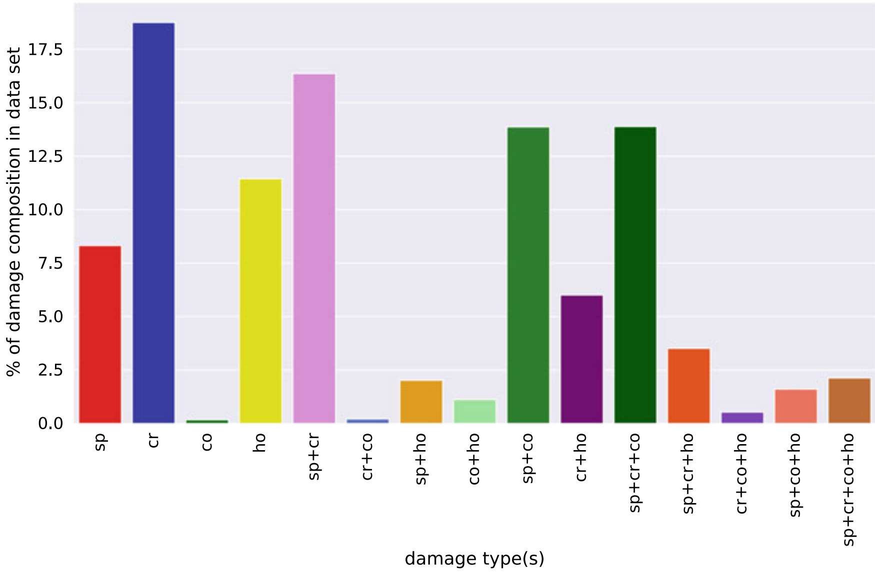

Fig. 3 Percentage of images in the data set containing specific combinations of damage types. The damage types are abbreviated as 'sp' for spalling, 'cr' for crack, 'co' for corrosion, and 'ho' for honeycomb.

A more detailed view of the damage distribution in the data set is provided in Fig. 3. There, the damage composition in the images is given. More than 38% of the images contain one damage type. Most images, i.e. 18.75%, contain only cracks. This means that almost one-third of images containing cracks contain no other damage types. This ratio also applies to honeycomb, which is the second most frequent exclusively appearing damage type with 11.45% share in the data set. 8.32% of the images contain only spalling. A very small amount of images, i.e. 0.18%, contain only corrosion.

Spalling is the damage type that appears most frequently in combination with other damage types: 16.36% of the data set are images that exclusively contain spalling and crack. The combination spalling+crack+corrosion is the second most frequent spalling combination, with a share of 13.89% in the data set. This combination is closely followed by the combination spalling+corrosion with a share of 13.87%. Considering the percentage of further combinations of spalling with corrosion, i.e. spalling+corrosion+honeycomb and spalling+crack+corrosion+ honeycomb, it is noticeable that almost 95% of images containing corrosion also contain spalling.

Further frequent combinations are crack+honeycomb with a share of 6.01% and spalling+honeycomb with a share of 2.02%. The combinations with the lowest frequency are crack+corrosion with 0.22% and crack+corrosion+honeycomb with 0.54%.

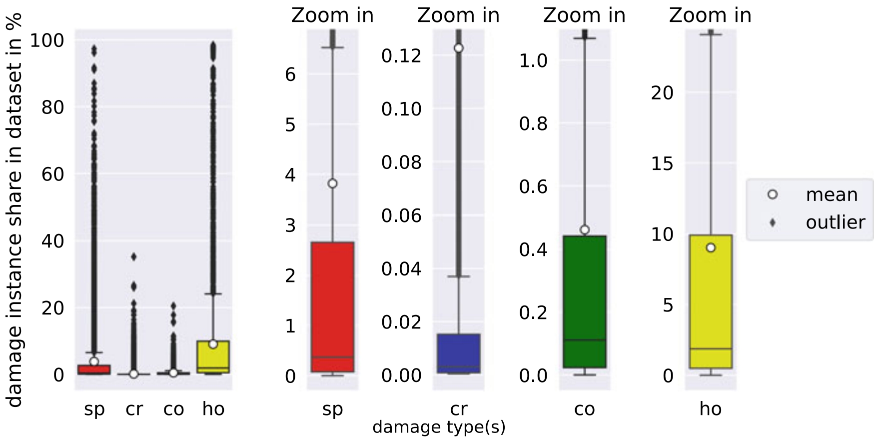

Fig. 4 Size of damage instances in an image in percent. The damage types are abbreviated as 'sp' for spalling, 'cr' for crack, 'co' for corrosion, and 'ho' for honeycomb.

Next to the distribution of damage types in the data set, the size of damage instances gives further insights into the data set. In Fig. 4, the distribution of the damage instance shares in images according to damage types is shown. The left box plot shows the distributions with outliers for all damage types. It is noticeable that spalling and honeycomb instances have more varying sizes than crack and corrosion instances. The spalling and honeycomb instances have sizes ranging from 0.0003% to 97.3% and 98.44%, respectively, whereas crack and corrosion instances have sizes ranging from 0.0003% to 35.22% and 20.47%.

However, the high instance size shares in the images are outlier values. The large majority of the damage instances cover smaller areas. Zoom-in plots of the individual damage types to the right of Fig. 4 provide a closer look at the pixel share distribution. Honeycomb instances have the largest image share. The mean image share is 9.03%, and the standard deviation lies at 16.55%. 75% of the instances have a lower share than 9.98%. Spalling instances have the second-largest image share. The mean image share is 3.82%. The standard deviation is 9.01%. 75% of the spalling instances have an image share less than 2.65%. The image share of corrosion instances is one order smaller than spalling and honeycomb instances. The mean is 0.46% and the standard deviation is 1.03%. 75% of the instances are smaller than 0.44%. Crack instances have the smallest image share with a mean value of 0.12%, a standard deviation of 0.75%, and with 75% of the image shares less than 0.44%.

Cracks are fine structures that are challenging to segment. A sufficient amount of crack samples with complex and fine structures helps ML models to recognize cracks well and capture their structure fully. In Figs. 2, 3 and 4, it was shown that a relatively large amount of images contains cracks and that their image share is very low. However, the maximum width of the crack instances also plays an important role in the data's representativeness. According to the German guideline for the documentation of the results of bridge inspections (*RI-EBW-PRÜF*), cracks with a maximum width of 0.1 mm and upwards have to be documented. Therefore, in Fig. 5, the maximum crack width distribution of all available crack instances in the data is visualized. However, the distribution is not given in real scale but in pixels. To measure the crack width, the distance transform function in the OpenCV library was applied to the binary crack masks. The distance transform is an operator that maps the pixels of a mask to intensity values that quantify the distance of the pixels to the closest mask border. The mathematical formulation reads: Let B be a pixel-based image and P a set of pixels such that $P \subseteq B$. In our application case, P is the set of crack mask pixels. The distance map $\mathcal{D}$ is calculated as follows

$$\mathcal{D}_P(p) = \min_{q \in P} \operatorname{dist}(p, q),$$

where $p \in B \setminus P$. The function $\operatorname{dist}(\cdot, \cdot)$ denotes a function for calculating the distance between the pixels p and q. The pixel with the largest intensity value in $\mathcal{D}_P$ is the pixel where the maximum width of the crack is located. If an inner-mask circle were to be drawn, the pixel with the highest-intensity would be the center, and the intensity value is the radius of the inner circle. As a result, the maximum crack width can be computed as the diameter of this circle. The crack width is measured in L_2 norm units and not in real length units.

Analyzing the crack width box plot in Fig. 5, it can be seen that the mean width is 3.5 units. The minimum value, the first quartile and the median are the same and are 1.91 units. 75% of the instances have a value less than 2.73 units. The crack instances in the data set also have many outliers, ranging from 4 units to 84.04 units.

Even with some data imbalance problems regarding honeycombs and corrosion, it is assumed that this data set, especially with its small damage objects, provides a reasonable basis for a well-performing segmentation model.

Segmentation Model Training. Feature Pyramid Network (FPN) was chosen as network architecture of the ML models. Multiple ImageNet-pretrained backbone networks were chosen as the encoder of the FPN. The backbone networks are MobileNet [4], DenseNet121 [5], and EfficientNetB0 [13]. The FPN and the backbone networks were chosen by the experience of the authors. The networks either provided best results in previous tasks or have smaller network sizes, as computation time needs to be low for our application. All chosen backbone networks are relatively small models compared to larger networks like Inceptionv3 or EfficientNetBx ($x \in [1, ..., 8]$).

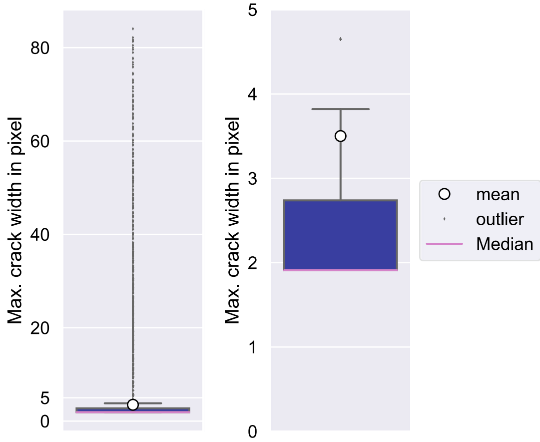

Fig. 5 Maximum crack width per image in pixel.

To evaluate the model performances, we used 5-fold cross-validation. To further improve the data's variability and to make the model robust to possible low-quality image capture during HL2 deployment, a set of data augmentation techniques were applied in a pipeline: the addition of blurring, the addition of rotation, the addition of barrel distortion and the change of brightness. These techniques were each applied with a randomly generated probability $p \in [0, 1]$ ($p < 0.5$ apply, $p \geq 0.5$ do not apply). Once the technique was chosen, another randomly generated probability value chose the degree of change (e.g. brightness degree). With this data augmentation, 26, 754 images were generated and used as the training data set.

The networks were trained with the Adam optimizer. The batch size was four, and the epoch size was set to a maximum of 100 epochs. All networks had an initial learning rate of 10^{-4}, with a learning rate reduction schedule and an early stopping schedule for learning stagnation. None of the backbone layers were frozen during training. All layers were fine-tuned. TensorFlow was used for the implementation of the models.

Results. Table 1 shows the performance of the FPN models measured by Intersection over Union (IoU). The mean IoU (mIoU) value over all damage types and the IoU value for each damage type is given. The FPN model with EfficientNetB0-backbone (FPN-EffB0) outperforms the models with MobileNet-backbone (FPN-MNet) and DenseNet121-backbone (FPN-D121) regarding all damage types. The mIoU value of FPN-EffB0 is 58.72%. All models perform best regarding the segmentation of corrosion. FPN-EffB0 provides an IoU value of 64.3% for corrosion. Considering the previous data distribution analysis and reviewing the data set visually, we assume that the segmentation of corrosion is facilitated due to the strong connection of spalling and corrosion.

Second- and third-best segmentation results are obtained for spalling with 62.57% and honeycomb with 55.62% IoU value. We assume that these results are due to the data imbalance problem given in the data set. Though honeycomb instances are larger (see Fig. 4), they are 33.31% less represented in the data set than spalling (see Fig. 2).

Table 1 Performance of FPN models with different backbone networks (columns). The performance is measured by IoU. The numbers in brackets in the cells of the first row indicate the number of model parameters. The IoU values printed in bold indicate the best results.

	MobileNet (6, 106, 564)	DenseNet121 (9, 915, 204)	EfficientnetB0 (7, 041, 952)
spalling	57.61 ± 1.79	58.34 ± 2.24	$\mathbf{62.57 \pm 2.5}$
crack	48.54 ± 1.36	48.94 ± 1.74	$\mathbf{52.39 \pm 0.3}$
corrosion	59.83 ± 1.61	61.77 ± 2.19	$\mathbf{64.3 \pm 1.23}$
honeycomb	53.25 ± 1.9	53.24 ± 2.65	$\mathbf{55.62 \pm 1.8}$
mean	54.81 ± 1.18	55.57 ± 1.34	$\mathbf{58.72 \pm 1.29}$

There is also an additional challenge in the segmentation of spalling and honeycombs, as there is often a seamless transition from one damage type to the other when both damage types appear in one image.

All models give the lowest IoU value for crack segmentation. FPN-EffB0 achieved an IoU value of 52.39%. As was observed in the previous data distribution Figs. 2–4, cracks are relatively well represented in the data. However, we assume that their fine structure with a maximum width of 2.73 units is challenging for segmentation models.

3.2 HoloLens 2 Deployment

To enable augmented reality supported damage segmentation, the FPN-EffB0 model was deployed on the HL2. The HL2 is a head-mounted AR device which has a see-through display for projecting holograms and a LiDAR sensor for spatial mapping features. The device is powered by a Qualcomm Snapdragon 850 CPU and GPU and has a Kinect sensor for gesture recognition. Also attached is an 8-megapixel camera, which can be used to capture images from the user's view. To comply with safety measures for on-site maintenance missions, the HL2 was acquired with a Trimble XR10 system, which integrates the HoloLens into a helmet and follows the AN-SI/ISEA industry standard for safety.

Quantization Tests. The segmentation model should run on the HL2 without a server connection via the Internet. This way, the bridge inspector would have uninterrupted service in places where network coverage is usually not given, e.g. in box girders. However, high-performance segmentation models are large, and mobile device hardware is generally incapable of real-time inference for large models. This was also confirmed in a segmentation-model test run on the HL2: The latency time for the segmentation of one image was 57.5 s using the HL2 CPU.

To make ML models deployable on mobile devices, TensorFlow provides a library extension called TensorFlow Lite (TF Lite). This library converts TF models to compressed TF Lite format (FlatBuffer). The underlying technique of the compression is quantization. The quantization is an optimization method that reduces the precision of model weights that are of 32-bit precision by standard. For this work, Post-Training Dynamic Range Quantization (DRQ) and Post-Training Float-16 Quantization (F16Q) were applied. The DRQ method quantizes kernels to 8-bit precision wherever it is feasible. The F16Q method converts all kernels to 16-bit precision. Applying both methods to the FPN-EFFB0 model (37.9 MB), a four-times model size reduction to 9.475 MB and a two-time reduction to 18.95 MB was achieved, respectively.

Since HL2 accepts ML models only in ONNX format, the compressed TF Lite models were converted using an ONNX-converter. However, this conversion recovered the initial size of both models. It is assumed that the ONNX format only accepts 32-bit precision numbers. Tests with the originally quantized ONNX models on the HL2 have shown little to no time performance gains. Due to hardware insufficiency, we conclude that the execution of segmentation networks of this complexity is not feasible on the HL2. To test the HL2 for damage recognition, we added a laptop to our tests that was used as a server to outsource the ML computations. The laptop was equipped with the Nvidia GPU GeForce GTX 1080 Ti (running CUDA 11.6, CUDNN 8.4, and onnx-runtime 1.12). The connection between the HL2 and the laptop was ensured through the Wi-Fi hotspot of the laptop.

Damage Segmentation Mask Projection. An application for the HL2 was developed to visualize the result of the damage segmentation model in 3D augmented space. The developed AR application works as follows: The user selects the option for analyzing the current view through a hand gesture. The device's photo camera takes a picture, and the current extrinsic photo camera matrix C_e is stored. The image is sent to an inference client located on the device or an edge device connected through Wi-Fi. The inference client executes the network with the given image and returns a mask for every damage type. Simultaneously, the extrinsic camera matrix C_e is used for a ray cast onto the current spatial mesh on the HL2. The ray cast's first hit is considered the damage's anchor point. The spatial mesh around the anchor point, consisting of points p_i, is then preserved as a projection space for the mask. Once the inference client has returned the masks of each individual damage type, they are projected onto the saved spatial mesh. This projection is made using a mesh shader and the intrinsic photo camera matrix C_i, which is unique to each photo camera model. To render the mask, all spatial mesh points p_i are transformed into the camera projection space by the shader: $\hat{p}_i = C_i C_e p_i$. The masks are combined to a single texture sampled as normal using the transformed points $\hat{p}_i$. Since the masks are projected onto the spatial mesh, it is possible to accurately display the damage even at high angles, around corners or on non-flat surfaces.

The above procedure, combined with the HL2's hologram stability, results in stable damage overlay pinned to the spatial mesh, as can be seen in Fig. 1. Furthermore, a box with additional information is created at the anchor point. Displayed are the types and number of instances for each damage type segmented. Instances are counted using a contour function of OpenCV. Figure 6 shows the interface of the HL2 application from a user point of view. The recorded damage photos, the masks, and any additional information can then be collected and further processed for the inspection task.

Fig. 6 Interface of the HoloLens 2 application. The functions for recording ('Aufnahme') and sending damage instances ('Senden') can be controlled through gestures and virtual interfaces. The crack in the concrete slab has been marked by the segmentation network in red.

3.3 Outdoor Experiments and Results

For on-site experiments, two bridges and a public parking structure were chosen. To simulate the bridge inspection process, one author put on the helmet with the HL2, and the other carried the laptop. Image captures were made of damage, but also of structures that look like damage but are not. The non-damage images were captured to test the robustness of the segmentation models. Figures 7 to 10 present some of the damage segmentation results. All figures, except for Fig. 10, show relatively good results. Spalling, crack, corrosion and honeycomb objects are segmented well, even in relatively far distances, as can be seen with spalling and corrosion instances in Fig. 7. However, false positive and false negative instances can also be observed. In Fig. 8, damp spots on the concrete (e.g. left instance) are wrongly segmented as spalling. On the right side, the shadow of a corroded hanging-out reinforcement bar is wrongly segmented as a crack. The corroded reinforcement bar was not segmented as corrosion, though it is a corrosion object. Large parts of the cracks in Fig. 9 are correctly predicted as cracks, even though the surface of the concrete is complex due to irregular textures, graffiti, and plants. However, smaller cracks in darker areas are not segmented, and parts of a plant stalk are wrongly detected as cracks. It was also observed that parts of plants or trees were mistakenly detected as cracks. A repaired concrete surface can be seen in Fig. 10. Concrete layers from the repair work are visible on the right and left parts of the figure. The ML model wrongly predicts parts of the concrete layer contours as cracks. The layer contours are very similar to cracks. However, they are distinguishable from cracks.

Fig. 7 Segmentation results with the FPN-Effb0 model. Red color masks are spalling predictions and green color masks are corrosion predictions.

Fig. 8 Segmentation results with the FPN-Effb0 model. Red color masks are spalling predictions, blue color masks are crack predictions, and green color masks are corrosion predictions.

Fig. 9 Segmentation results with the FPN-Effb0 model. Blue color masks are crack predictions.

Fig. 10 False positive crack results with the FPN-Effb0 model. Blue color masks are crack predictions.

4 Conclusion

This paper has examined the segmentation performance of the FPN architecture trained on a large concrete damage data set and the deployment of such an end-to-end model on the HL2. Good segmentation results were obtained in the on-site tests. However, there are still too many false predictions that are easily differentiated by the human eye. Although the data set is very large and diverse compared to other data sets used in damage segmentation research, it becomes evident that even more data and better image preparation techniques are needed to obtain more reliable results. This is mainly due to the complex building environment. Focusing on negative examples, like more images with plants and trees, can improve the segmentation.

During the segmentation model deployment on the HL2, many obstacles were encountered. On the one hand, segmentation models are generally too large for mobile devices. Real-time capable models were suggested in previous publications. However, these models ask for an accuracy-time-trade-off, favoring time performance over accuracy. Considering complex bridge environments, these models will predict more false positive and false negative damage instances. For digital documentation, this means that falsely predicted cases have to be filtered out by the HL2 user. This will likely affect the user experience and decrease the acceptance of this technology. Generally, state-of-the-art ML-based computer vision models are many orders larger than the FPN-EffB0 model suggested here. So, the ML research tends to utilize huge ML models to solve complex tasks. However, research in small real-time capable models is still ongoing. Also, different offline HL2 concepts can make the real-time capable models obsolete. On the other hand, the HL2 software needs to adapt the available infrastructure, like quantization, to make large models deployable. Regarding the HL2 computation hardware, further studies must be conducted. In this work, the segmentation model was deployed on the CPU. In continuing work, the GPU will be tested regarding real-time segmentation. Future developments of the HL can ease the use of ML, especially considering the benefits and development of edge computing.

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Modelling Sustainable Transportation Systems by Applying Supervised Machine Learning Techniques

Thembani Moyo and Innocent Musonda

Abstract Public transportation has been reeling under the coronavirus pandemic. To curb the spread of Covid-19 national governments-imposed lockdown regulations at various scales. The transport industry in developing countries bore the initial brunt of lockdowns leading to the grounding of fleets. Ostensibly, very little has been documented on the mechanisms adopted and implemented to develop sustainable mobility solutions in developing countries during the pandemic. Consequently, using the city of Johannesburg as a case study this paper adopted a quantitative research approach to investigate commuters' perceptions and expectations of the quality of service during the Covid-19 pandemic. Using Supervised Machine Learning techniques, a quality-of-service model was developed to assess the quality of service and inform approaches for sustainable increasing public transport ridership. The results show that there was an increase in retail and recreation-based trips and a decline in work-based trips. This was due to an increase in telework (working from home) during the Covid-19 pandemic. The finding also reveals machine learning techniques can be used to understand commuters' cognitive decisions or their final outcomes. The trip duration was the most influential feature of the city of Johannesburg also experiments using information gain reveal that increased investment to improve other public transportation features such as reliability and accessibility leads to an increase in public transport ridership. In conclusion, the paper calls for intensified investment in innovative approaches to plan for sustainable public transportation post the Covid-19 pandemic. This can be achieved through upscaling existing uses of technology such as using machine learning in scenario planning.

Keywords Machine Learning · Quality of Service · Johannesburg · Public transport · Sustainable

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1 Introduction

Contemporary we are in the age of digital transformation. This has led to a growth in research to assess big data [1, 2] and the internet of things [3, 4]. Globally these emerging data analytic approaches seek to support decision-making and policy development. In Europe, Asia, and the United States there are several studies that have used classifiers using supervised and unsupervised learning algorithms to assess the quality of service of public transport systems [3–5]. Clustering algorithms have the merit of partitioning data into a certain number of clusters [6]. Such data analysis plays a major role in machine learning when the learning algorithm is utilized to discover and learn knowledge from learned experience.

In developing countries, there exist limited data analytic approaches. This has led to several public transportation systems being left reeling under the coronavirus pandemic. To curb the spread of Covid-19 national governments-imposed lockdown regulations at various scales. The transport industry in developing countries bore the initial brunt of lockdowns leading to the grounding of fleets. Ostensibly, very little has been documented on the mechanisms adopted and implemented to develop sustainable mobility solutions in developing countries during the pandemic. Consequently, the aim of the study was to investigate commuters' perceptions and expectations of the quality of service during the Covid-19 pandemic. Section 2 presented literature related to the study. Section 3 outlines the methodological approach adopted. While Section 4 presents the findings. Lastly, Section 4 presents the implications of the study before providing the concluding remarks.

2 Related Work

In developing countries, the debate on how to ensure the sustainability of public transport systems continues unabated. Literature from the past decade reveals the assessment of Quality of Service (*QoS*) as a viable solution to increase public transportation ridership [5]. This approach will ensure improved commuters' satisfaction [9]. The United Nations have also articulated through SDG 11 the need for smart cities that cater to the need of citizens through the provision of smart sustainable public transport services [7].

Over the years, variables for assessing QoS have been identified as tools to classify commuters' experiences and identify their commuting needs [3, 5]. This has resulted in the reduction of negative externalities such as noise and vibrations from public transportation [8]. Assessment of QoS has also been promoted as a practical societal service designed to educate and inform authorities and commuters on a variety of issues namely economic, social and educational [8, 9]. This has led to the systematic planning for QoS for different commuter needs. Given the growth in emerging data analytics approaches, machine learning algorithms have proven a viable solution

Table 1 Machine learning algorithms

Algorithm	Application Areas	Approach	Source
Decision Trees	Quality Assessment	Assessment of linearly inseparable data	[10, 11]
Random Forests	Object detection	Offers explanation and visualization of output without parameter inputs	[1, 10, 12]
Bayesian Network	Data classification	Able to interpret data in terms of the structural relationships among predictors	[13, 14]
Logistic Regression	Cluster classification	Output interpreted as the probability	[4]
SVM	Text classification	Avoids overfitting	[15]

that caters to multi-disciplinary research. Table 1 outlines advantages of machine learning algorithms.

Literature reveals machine learning algorithms can handle large-scale empirical comparisons namely supervised learning methods such as: SVMs, neural nets, logistic regression, naive Bayes, memory-based learning, random forests, decision trees, bagged trees, boosted trees, and boosted stumps. [5, 6]. Scholars have also attempted to address the interesting problem where documents remain unclassified, by introducing a machine learning algorithm that combines several parameters and meta-data of a research article [5, 7]. Building from the above-mentioned case studies on the use of machine learning techniques, this study utilizes supervised machine learning techniques to assess the QoS of public transport services within a developing city context.

3 Methodology

A mixed method approach utilised the spatial and qualitative methods of data collection and analysis. In this study using the city of Johannesburg as a case study, this paper adopted a quantitative research approach to investigate commuters' perceptions and expectations of the quality of service during the Covid-19 pandemic. The city of Johannesburg is the economic hub of the wealthiest province, Gauteng in South Africa. Due to these economic activities, many people traverse this city on a daily basis which has led to major freeways and roads experiencing high levels of congestion. The study focused on commuters of the Gaubus an innovative bus rapid transit system that serves as an extension of the Gautrain, a rapid railway system [1, 2]. To collect data the study relied on a questionnaire-based survey that was administered to 200 Gaubus commuters. The questionnaire was administered physically at the various Gaubus stops to obtain a good response rate (see Fig. 1).

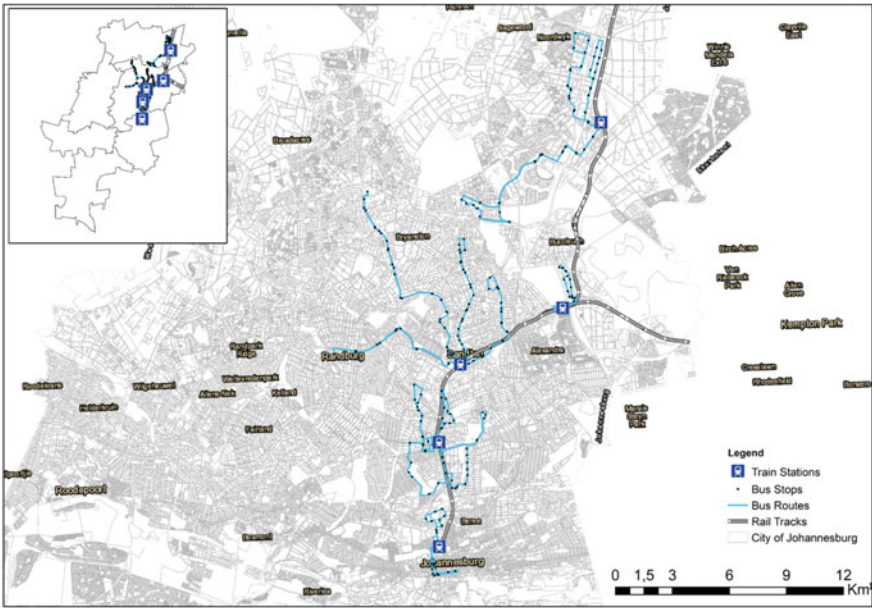

Fig. 1 Study Area

The data was collected through questionnaires, individuals of different gender, ages, occupations, and education were asked to give a score between 1 and 10 on 9 attributes and then an overall score of their satisfaction with Gaubus service was determined. The respondents were chosen using a cluster sampling technique. This study notes that the traveling patterns for public transport users vary throughout the day so data will be collected during the morning, afternoon, and evening peak hours to rule out bias that may be caused by sampling time. The questionnaire had both closed and open-ended questions that were centered on the following themes:

- Average Travel Speed
- Level of Service
- Trip Comfort
- Affordability
- Average Travel Time
- State of road infrastructure
- Information dissemination
- Convenience of Routes
- Trip duration

Table 2 Attributes of spatial dataset

Column ID	Column Name	Unit	Interpretation
1	Longitude	Degree	Longitude reference of infrastructure data
2	Latitude	Degree	Latitude reference of infrastructure data
3	Format	Polygon or Point	Route or Station
4	Source	Gaubus stop Name	Name of stop/station
5	Source	Gaubus Route Name	Name of route
7	Time last data modified	YYYYMMDD	Date, month and year of last data modification

In addition to the questionnaire, the study collected spatial data on urban public transport infrastructures in shapefile format from their service providers (Gautrain Management Agency) and the city of Johannesburg). The data gathered were used to visualize the spatial trend maps using a geographic information application (ArcGIS Pro software) to inform the analysis and discussion of spatial patterns. Table 2 below summarizes, the spatial datasets gathered.

4 Model

This section describes the supervised clustering algorithm. Using supervised machine learning techniques, a quality-of-service model was developed to assess the quality of service and inform approaches for sustainable increasing public transport ridership. In the supervised clustering model, the researchers held the clustering algorithm constant and modify the quality-of-service measure to ensure the clustering algorithm produces desirable clusters. The *QoSw*, parameterized by w, maps pairs of items to response from the questionnaire indicating the *QoS*. To define the three intervals for the score: High (above 8), Low (below 5) and Medium (between 5 and 7), the researchers use supervised clustering system. The mapping of the intervals from the set of responses … to a set finite set of discrete class labels *y ε1,…C* $y \in 1, \ldots C$, where C is the total number of class typology, modelled in terms of the function *QoS = QoS(x,w)*, $QoS = QoS(x, w)$ where x are the responses. For the cluster method, the responses were grouped into Low Score Occurrence (LSO), Medium Score Occurrence (MSO) and High Score Occurrence. The values of these parameters were then optimised through an inductive learning algorithm, to minimise empirical risk functional on data set input–output.

5 Findings and Discussion

To test the approach, an initial training data set of 75 instances was randomly generated with a uniform distribution from 1 to 10. As outlined earlier values refer to the score given by the respondents. The data set consists of 9 columns to determine overall *QoS*. For each classifier class, Table 3 represents the trained algorithms.

Considering the results from the training and the overall accuracy of the classified algorithms the best algorithm is the DA with an accuracy of 96.0 to define the *QoS* level and the lowest misclassification cost of 2. While the quadratic SVM algorithm produced the highest accuracy. After training the algorithm the dataset from the Gaubus commuters was analysed. From the literature review, using a learning model

Table 3 Results from trained algorithms

Classifier Class	Classifier Algorithm	Overall Accuracy	Misclassified Variable	Training Time (sec)
Decision Trees	Fine Tree	87.6%	8	5.6
	Medium Tree	87.6%	8	5.0
	Coarse Tree	85.3%	10	6.3
	Boosted Trees	67.8%	34	9.9
	RUSBoosted Trees	89.0%	9	6.4
	Bagged Trees	88.0%	10	11.7
NB	Gaussian NB	87.3%	8	14.3
	Kernel NB	88.7%	9	8.8
SVM	Linear SVM	93.7%	4	9.5
	Quadratic SVM	94.8%	2	5.1
	Cubic SVM	94.8%	3	9.9
	Fine Gaussian SVM	78.7%	17	8.9
	Medium Gaussian SVM	93.3%	4	8.7
	Coarse Gaussian SVM	76.1%	15	8.9
KNN	Fine KNN	83.7%	10	9.6
	Medium KNN	81.0%	14	9.3
	Coarse KNN	54.2%	36	9.6
	Cosine KNN	72.3%	17	10.3
	Weighted KNN	86.0%	13	16.6
	Subspace KNN	79.6%	14	9.3
DA	Linear DA	96.0%	2	8.7
	Quadratic DA	78.0%	3	6.4
	Subspace DA	74.3%	3	13.8

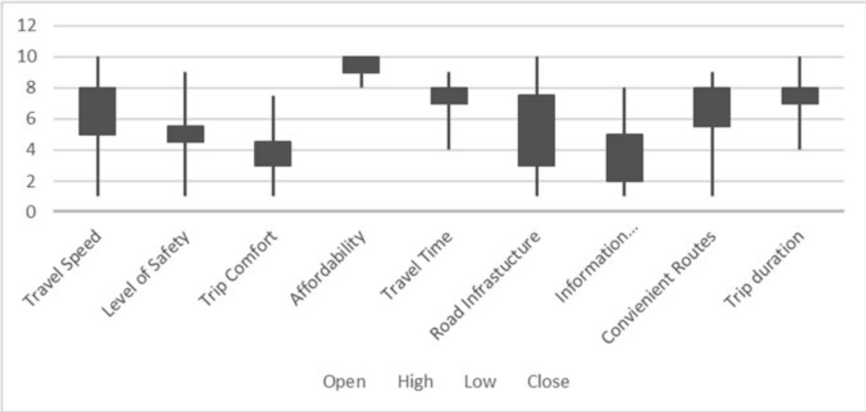

Fig. 2 Satisfied cluster for the Gaubus commuters

allows for the development of clusters and predictions of the model. Figure 2 presents the satisfied cluster for the Gaubus commuters.

Every learning algorithm will tend to suit the research problem to be addressed better than others, and typically requires training to ensure parameters and configurations are adjusted to the research problem. The quadratic SVM was used to develop the cluster as it required the least training time while ensuring high accuracy. From the clusters travel speed was scored the highest by the respondents. This is aligned to previous studies, that have noted commuter preference to utilize public transport over private vehicle has a strong correlation with overall travel speed [1]. Other noteworthy emerging clusters were convenient routes, affordability and information dissemination.

The results also reveal that there was an increase in retail and recreation-based trips and a decline in work-based trips. This was due to an increase in telework (working from home) during the Covid-19 pandemic. The finding also reveals machine learning techniques can be used to understand commuters' cognitive decisions or their final outcomes. The trip duration was the most influential feature of the city of Johannesburg also experiments using information gain reveal that increased investment to improve other public transportation features such as reliability and accessibility leads to an increase in public transport ridership. The overall impact of each attribute was then assessed using a decision tree algorithm (see Fig. 3). As outlined in literature decision trees have the merit to map observations about a variable to conclusions about the variables' target value [2].

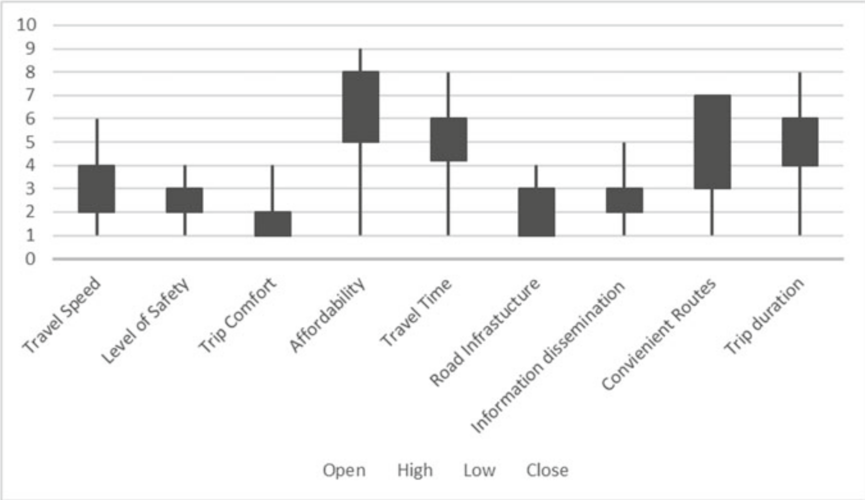

Fig. 3 Impact of evaluated attributes

Considering the spatial network of the Gaubus (see Fig. 1), the Gaubus connects commuters to locations of economic nodes in the city of Johannesburg. As such the convenience of the routes to connect commuters of several points of interest was the most influential variable. Other influence variables included affordability, trip duration and travel time. Trip comfort and road infrastructure scored the least. The decision tree results also revealed that age and gender have no significant influence on satisfactions level of the Gaubus commuters.

6 Conclusion

In conclusion, the study has several implications for policy and infrastructure development. The proposed approach to utilize machine learning algorithms to assess *QoS* can be adapted to inform operational interventions aimed at improving public transport services in developing cities such as Johannesburg, particularly metropolitan cities. The study also calls for intensified investment in emerging databased approaches to inform decision making and policy development. A close reflection of emerging urban mobility modes such as the Gaubus reveals that contemporary public transport services need to be highly flexible and demand-responsive. Consequently, the understanding of determinates of *QoS* would lead to better scenario planning to build on efforts to improve commuters' travel experience. To this end, future studies should utilize unsupervised learning to assess *QoS* of several public transportation systems.

innovative approaches to planning for sustainable public transportation post the Covid-19 pandemic. This can be achieved through upscaling existing uses of technology such as using machine learning in scenario planning.

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Machine Learning Algorithm Application in the Construction Industry – A Review

Samuel Adeniyi Adekunle, A. Onatayo Damilola, Obinna C. Madubuike, Clinton Aigbavboa, and Obuks Ejohwomu

Abstract Industries like manufacturing use Machine Learning (ML) algorithms to conceive and produce excellent consumer goods. This achievement has persuaded other economic sectors, including the construction sector, to attempt and incorporate intelligent algorithms. The most recent developments in ML algorithms have made it possible to automate those non-trivial jobs that were thought unsolvable years back. Early involvement of Construction researchers in the ML process is necessary to ensure that they have sufficient awareness of the advantages and disadvantages. It is worthy of note that construction organisations have concerns due to the peculiarity of the sector. As such, adopting machine learning (ML) for profitability predictions or cost-saving results can be challenging. Construction industry stakeholders are eager to discover how ML may help improve operations, and the benefits of ML algorithms, among others, before adopting these algorithms for decision-making. To assist construction industry stakeholders in the adoption of ML algorithms, the study adopted a systematic literature review. The study helps in the proper identification of the uses of ML algorithms to improve the construction industry processes and product.

Keywords Construction digitisation · Construction industry · Emerging technologies · Machine algorithm

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1 Introduction

In today's world, industries like manufacturing use Machine Learning (ML) algorithms to conceive and produce excellent consumer goods [28]. This achievement has persuaded other economic sectors, including the construction sector, to incorporate intelligence algorithms into their activities [27]. The most recent developments in ML algorithms have made it possible to automate those non-trivial jobs that were thought unsolvable a decade ago [9]. This technology significantly impacts many aspects of construction project management, including risk assessment and mitigation, site safety management, cost estimating and forecasting, schedule management, and forecasting building energy use. However, for many tasks, it is unrealistic to expect these algorithms to perform at human levels [28].

Machine Learning algorithms can be classified into supervised, unsupervised, and reinforcement learning [14, 19]. Supervised learning uses a dataset with assigned labels. Most prediction tasks involve guessing the expected output from a given input when the input data has already been provided with the desired outputs and inputs. Among the most widely used supervised learning algorithms are Linear Regression, Logistic Regression, Support Vector Machines (SVMs), Decision Trees, and Random Forests [20]. Unsupervised learning makes use of unlabeled data provided to the algorithm. The computer tries to learn from the input without being given the desired outcome. The most popular algorithms employed in the unsupervised learning approach are clustering methods like K-Means and Hierarchical Cluster Analysis (HCA); anomaly and novelty detection algorithms like One-class SVM and Isolation Forest [20].

A general definition of reinforcement learning is an action-reward system. In the reinforcement learning process, the training and test stages are coupled. User input is obtained for each assumption or action taken during the learning process [32]. The algorithm seeks to develop a self-learning strategy to maximise reward from its action cases [19].

Simply starting ML projects without understanding the benefits and drawbacks of ML algorithms frequently results in failures [28]. Without a well-defined strategy, even simple ML activities become challenging. When seemingly flawless ML models fail in use, investments are lost, distrust rises, and future support is lost. Many construction companies are starting ML-incorporated projects out of reaction rather than understanding what it entails. ML, as advertised by tech companies, has not yet produced the results that were anticipated in reality. Whatever ML offers, construction companies are urged to take advantage of it for a competitive advantage.

The construction industry must have faith in ML models' capabilities because most ML solutions either automate or simplify the decision-making process [16]. To train dependable, transparent, and trusted models, it is necessary to have a broad understanding of the domain, the data, and ML algorithms. Early involvement of Construction researchers in the ML process is necessary to ensure that they have sufficient awareness of the advantages and disadvantages of algorithms. Construction companies have concerns, so it can be challenging to persuade them to adopt machine learning (ML) for profitability predictions or another cost-saving solution. While they are eager to discover how ML may help them with their operations, they typically want to know more about the advantages and disadvantages of ML algorithms before they trust or allow these algorithms to affect their decision-making [25].

ML algorithms play a critical role in analysing vast amounts of data and building highly accurate prediction models. The construction sector already has a track record for consuming innovative technology in moderation [28]. Techniques such as classification analysis, regression, data clustering, feature engineering and dimensionality reduction, association rule learning, or reinforcement learning are available in machine learning algorithms to efficiently construct data-driven systems [22]. The artificial neural network, which is a member of a larger family of machine learning techniques that may be used to evaluate data intelligently, is also where deep learning originated [39]. So it can be challenging to choose a learning algorithm appropriate for the construction industry's target application.

The reason is that different learning algorithms serve different purposes, and even the results of different learning algorithms in the same category can change depending on the qualities of the data [21]. It is crucial to comprehend the fundamentals of different machine learning algorithms and how they can be used in different practical applications in construction management. To determine their current use and trend, it is necessary to explore various Machine learning algorithms and their application in the construction industry.

According to recent findings, machine learning techniques are among the most widely used tools. Research on the construction ML algorithm applications has been conducted using a variety of machine-learning techniques, including Random Forest, Decision Tree [35], Support Vector Machine [42], K-Nearest Neighbour [5], Artificial neural network [7], and Adaptive Boosting [13].

A thorough overview of the many machine learning algorithms that can be used to improve intelligence in construction management and capabilities is required, given the significance and promise of "Machine Learning" in construction.

2 Method

The study adopted a qualitative approach which also includes systematically analysing relevant papers selected for the study. The qualitative approach employed includes a literature review which helped to develop an understanding of the research topic in its entirety, identifying the strengths and weaknesses of the study [15]. The literature review was used to address the research questions, including (1) what construction activities can be improved using ML algorithms? and (2) what ML algorithms can be used to improve intelligence in construction management.

To effectively address the research question and purpose of the paper, related and relevant articles were sourced from reputable sources such as Web of Science (managed by Clarivate Analytics), Scopus, and Google Scholar (managed by Google). The related articles in ML were sourced using the input TI (Title = TI =

Machine Learning). A total of 5,453,404 articles were sourced from Web of Science, Scopus, and Google Scholars combined. A breakdown of the results showed that articles related to ML were 352 on Web of Science, 103,053 on Scopus, and 5,350,000 on Google Scholar. The vast amount of articles on ML shows the growing interest and applications from various researchers and innovators. Various researchers have also adopted these databases for research in the built environment [1–4, 12, 18]

The search further streamlined the ML-related articles to TI = Machine Learning in Construction to ensure that only relevant articles to construction were selected. The following outputs were obtained from the selected sources: **536** from Web of Science, **85** from Scopus, and **3,700,000** from Google Scholar. The number of articles obtained from the Web of Science, even after the streamlining, was larger than the previous finding. This is attributed to the fact that the Web of Science provided results that showed articles on Machine Learning, Machine Learning and Construction, and Construction, only related articles separately. The search was further limited to the title of this article, 'Machine Learning Algorithm Application in the Construction Industry', which yielded '0' result in all sources. These findings help to show the relevance of this article and that, given the vast application of ML in other industries, the construction industry should also take advantage of the benefits of ML. The systematic literature review method was previously adopted by [31] in reviewing Digital Twin applications in the construction industry. the analysis of findings was done using a thematic approach.

3 Discussion of Findings

3.1 Process Optimisation and Prediction

It takes several decisions to accomplish short-, medium-, and long-term objectives in the complicated building process, from planning and management to minor corrective measures. Decisions that must be made quickly—within a few hours—are frequently referred to as daily construction process optimisation. By optimising the numerous factors that affect the construction process, they often aim to maximise construction costs.

Today, the construction managers in charge of the process are typically the ones who carry out the daily process optimisation. The construction process is affected in one way or another by a huge number of controllable parameters throughout this immensely challenging optimisation effort. A machine learning-based technique takes on a lot of appeal in this situation to determine the optimal possible combination of all factors. The construction managers' optimisation is mainly based on their expertise, which they amass over time as they gain proficiency in managing the construction process. This ability to learn from previous experience is exactly what is so intriguing about machine learning. Machine learning is exciting because it can learn from prior experience. The algorithms may learn to grasp complicated relationships between the different elements and their impact on the construction lifecycle by evaluating enormous quantities of previous data from construction activities, sensors, productivity output, safety concerns, and material cost.

In theory, the algorithms' ability to learn from experience is similar to how project managers pick up process control. In contrast to construction managers, machine learning algorithms have no trouble studying the complete historical datasets for hundreds of variables over the course of many years. Unlike human brains, they have an infinite capacity for experience accumulation. When it detects a possibility for increased productivity, a machine learning-based optimisation algorithm may operate on real-time data flowing from construction operations and give recommendations to the construction manager. Poh et al. (2018) used five well-known ML algorithms to forecast accident severity and frequency on construction sites in Singapore, while Zou & Ergan (2019) relied on three Ml algorithms to forecast how construction projects would affect the urban quality of life. Also, using only one ML model and three ML models, respectively, Arditi & Pulket (2005); Mahfouz & Kandil (2012) forecasted construction litigation outcomes all in the USA.

3.2 Data Handling and Deep Learning for Intelligent Systems

With data modeling, one may replace cognitive bias and false assumptions with fact-based understandings of the statistical likelihood of a project's success. Analytics may evaluate the likelihood of project outcomes by examining past data such as labor and contractual arrangements categories, regional spending trends, and project size. These will therefore allow teams to assess a project's attractiveness more accurately, realign the portfolio away from work that frequently performs poorly, and determine the appropriate amount of contingency to add to a bid.

Construction companies can create a dashboard of risk factors that could impact project profits using the findings from the analysis. Suppose a project is in an area with a history of low-margin projects or involves dealing with a public-sector owner with different criteria than usual private-sector partners. In that case, the system can develop a scorecard that indicates possible risks based on prior trends. Teams use this data during pre-bid meetings to estimate costs, determine the size of the contingency to include in the bid, and determine whether the project is sufficiently appealing to submit a bid.

3.3 Accident Prediction

In the literature on construction safety, binary categorisation is extremely popular. Based on information gathered from the US OHSA, [35] employed decision tree analyses using the C5.0 and CHAID algorithms. The researchers used the C5.0 method in binary classification to predict the outcomes of fall accidents involving roofers (i.e., injury and death). They discovered a negative correlation between the probability of fatalities and the employees' participation in safety training programs. Like this, [13] established a prediction model for categorising injury and mortality outcomes in construction accidents based on four widely used ML algorithms. When the data was subjected to the RF algorithm, the prediction rate was assessed at its greatest level. It was also shown that the month and employment size were the most causing factors in this respect.

Another area that needs considerable study is accident classification. Goh & Ubeynarayana, (2017) examined the results of the SVM, LR, RF, KNN, and NB algorithms to categorise construction accidents into 11 categories, including explosion, electrocution, and exposure to chemicals. The pre-processing of the machine learning models was done using word stemming, while parameter optimisation was done using grid search algorithms. Based on data gathered from the US OHSA, it was discovered that SVM with unigram tokenisation performed better than other models in terms of the F1 score, where electrocution was the instance that had been most accurately diagnosed. [43] suggested an ensemble prediction model based on SVM, LR, KNN, DT, and NB algorithms utilising the dataset from the same data source.

The researchers optimised the weights of standalone ML models using a sequential quadratic programming approach, which enhanced prediction performance compared to the average weighted F1 score. The RF algorithm for construction accident-type prediction was the main topic of [25] study. To address the issue of class imbalance, the researchers eliminated classes with enrollments of less than 10% and utilised random under-sampling (RUS). Assailing materials and original-cause materials were the two most important factors in the RF algorithm's prediction accuracy, which was 71.3%.

[7] used the ANN technique for accident severity classification after completing the latent class clustering analysis for dimension reduction. Researchers found that applying fuzzy set theory enhanced prediction accuracy concerning at-risk behavior and severity levels of lost workday situations. [5] examined the performances of ANN, DT, KNN, and SVM to anticipate uncomfortable working postures based on data obtained from a wearable insole pressure system. According to the cross-validation data, SVM has the greatest accuracy rating. Using random forest and SGTB algorithms, Tixier et al. (2016) created a prediction model for injury type, energy type, body part, and injury severity categories. They discovered that SGBT performed better than the random forest method across all classes based on the 470 contractors' reports of injuries sustained during construction.

3.4 Feature Engineering

The process of creating, building, and filtering features to improve the efficiency of a data analysis task is known as feature engineering [17]. Due to the enormous rise in data across many scientific disciplines, including structural engineering and genetic analysis [23], it has drawn more and more attention in research [41]. By maximising the relevance and redundancy of the data, feature engineering has been shown to increase ML models' computational efficiency and learning performance [37]. Due to the limited dimensionality of the data, feature engineering did not initially receive enough attention in data-driven building construction (Energy-based) prediction. However, the amount of data accessible for construction process prediction has dramatically grown thanks to the rapid development of sensor technologies [30].

4 Conclusion

The construction industry is traditionally known to be less productive and efficient. It has been observed that the industry operates less than its potential and is thus less productive compared to other sectors. Another characteristic of the industry is its late adoption of technology. Meanwhile, the realisation of its full potential has been linked to the adoption of technology. In the present age of fast technological adoption, diverse technologies are emerging and have the potential to change the construction industry. This study explores the adoption of a machine learning algorithm for the construction industry through a literature review. This study's outcomes are important to the construction industry stakeholders in adopting ML as the various benefits and potentials for the construction industry were identified and explained. This provides a profound insight for the construction industry stakeholders and helps them increase productivity and efficiency through the adoption of ML. The study thus contributes to the existing body of knowledge on technology adoption in the construction industry y highlighting the relevant applications of AI.

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Identifying Risky Zones in Water Distribution Networks Using Node Burst Indices

Christopher Dzuwa, German Nkhonjera, Innocent Musonda, and Adetayo Onososen

Abstract This study presents an algorithm for identifying potential points of failure (leakage) in water distribution systems by evaluating the risk of pipe burst at each node. The algorithm calculates a burst index for each node using burst factors derived from the average District Metered Area (DMA) burst pressure and relevant parameters such as pipe length, age, and thickness. A sensitivity analysis based on pressure observations at the nodes under different leakage scenarios is conducted to identify deviations from the no-leak scenario. DMAs are then ranked according to their total burst risk, and nodes are partitioned based on their average DMA burst pressure. Although this algorithm may generate a larger number of candidate nodes than necessary due to the lack of optimization, its output can be used as input for sensor location optimization algorithms, reducing the search space for these algorithms.

Keywords Water network · Risk assessment · District Metered Area · Hydraulic Simulation · EPANET · Leakage

1 Introduction

Sustainability in urban water distribution systems is still a major challenge due to the huge amount of water lost annually. The global average volume of water lost annually is 126 billion cubic metres [1]. It is well known that 70% of the lost water is due to leakages [2]. A lot of research has been conducted to understand how leakages in water distribution networks behave under varying network parameters (pipe size, pipe material, internal pressure, wall thickness, etc.), [3–6]. Understanding leakages

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not only helps practitioners predict the outcome of a burst event but also aids in identifying risky network areas before any further leakages occur. Network risk assessment has been approached as an optimization problem, mainly to deal with sensor placement for leak detection. Forconi et al. [7] employed three different risk-based functions to determine optimal sensor locations in water distribution networks. Their work considered the leak hazard, leak hazard and its impact, and leak impact and network vulnerability. Hu et al. [8] also argued that it is impossible to detect all leakage events in a distribution system, as such, priority should be given to locations with higher importance. To quantify this importance, risk-based functions were defined based on how leakage on each node affected the number of nodes with pressure drop, water demand, pressure drop in pipes, increase in pipe flow rate, and joint impact of the mentioned parameters in the network. Although sensor placement in water distribution network has been achieved through other means as, evolutionary algorithms [9, 10] entropy [11, 12] among others, the risk-based approach looks promising since leak events are not common to all the nodes/links in a distribution network. As such, simply considering the structure of the network and operating pressures can be misleading. The aim of this study was therefore to develop a risk-based algorithm for the identification of potential leakage areas in a water distribution network considering network structure and parameters (pipe length, pipe diameter, pipe age, nodal pressure, pipe material, and installation depth). The procedure developed in this study is then verified by a case study of the C-TOWN Network.

2 Methodology

2.1 Calculation of Burst Indices

For a sub-network shown in Fig. 1, the first step involves the calculation of the node burst index (NBI). The assumption is that not all pipes in a water distribution network have the same chance of breaking. Several factors such as burst frequency, pipe size (length, wall thickness, and length), pipe age, installation depth, and inline pressure are taken into consideration.

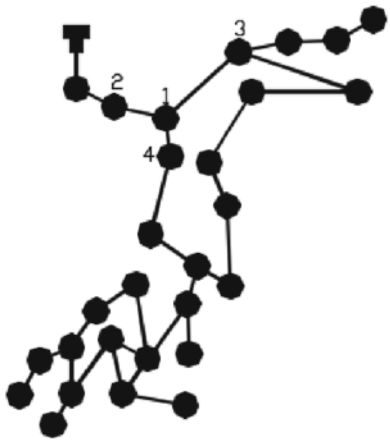
The node burst index is computed using the formula

$$\gamma_k = \rho_k + \zeta_k \tag{1}$$

where ρ_k is the nodal pressure burst index, and the second term is a sum of link (pipe) burst indices for N pipes connected to node k, i.e.

$$\zeta_k = \alpha_{DMA} \sum_{i=1}^{N} \sum_{j=1}^{M} \beta_{ij} \tag{2}$$

Fig. 1 Sub-network of the C-Town Network



α represents the average DMA burst factor value, and β is the ratio of the actual network parameter and the value of the studied DMA parameter at average burst pressure. M represents the total number of leakage factors considered. γ_k is calculated for the worst-case scenario. In this paper, ζ values are calculated for peak demand period.

The NBI value for node 1 in Fig. 1 can be calculated using $link_{12}$, $link_{13}$, $link_{14}$, and $node_1$ as reference.

Burst factors can be arbitrary or can be calculated based on the scheme given in appendix A. For this study, the burst factors are arbitrary and depend on the researcher's knowledge of how each factor influences leakages in water distribution.

2.2 *Risk Calculation*

If only the risk associated with each DMA is required, the weighted average of DMA indices for all the considered parameters (nodal pressure, pipe length, pipe age, etc.) is computed. The weighted average is given by the formula:

$$r_{DMA} = \frac{\sum_{k=1}^{N} \gamma_k}{N\gamma_{DMA}} \tag{3}$$

where r_{DMA} is the weighted average of DMA indices, γ_{DMA} is the average DMA burst index calculated from real leakage events. If no leak events exist in a DMA, a global average from all network DMAs is used.

N is the total number of DMA nodes included in the analysis.

The DMAs can then be ranked using the computed r values, and the needed attention can be directed based on the level of risk.

However, if the actual risk associated with each node is desired, leakage simulations are run to determine node sensitivity. The simulations are run on a calibrated hydraulic model, and pressure changes on each node are recorded for each leak scenario in the network. Leaks are modelled using the power equation.

$$q_l = Ch^e \tag{4}$$

where q_l is the leakage flowrate in m^3/s, C is the discharge coefficient in $m^3/s/m^e$ and e (unitless) is the pressure exponent.

Hydraulic simulations are run, noting the pressure differences in all the nodes, apart from tanks and reservoirs.

This is then followed by the calculation of actual risk associated with each node which is given by:

$$R_k = \gamma_k \sum_{i=1}^{N} |\Delta P_i| \tag{5}$$

where R_k is the total risk associated with node k for a total of N leakage events. γ_k is the NBI for node k. ΔP is the change in pressure at node k for event i.

2.3 Node Categorisation

Finally, network nodes are categorised as either low, medium or high risk. Since DMAs are hydrologically separated, conditions causing leakage in one DMA will eventually be different from another. For instance, the same amount of pressure can cause a leakage in one DMA and completely leave another DMA unaffected. Due to this, consideration of critical nodes should be done at DMA level. For each DMA, the split criteria are as follows:

i) For DMAs with known burst events, use the DMA NBI. Average DMA NBI values can be used for new DMAs or DMAs without leak events
ii) Partitioning is done using the following criteria:
   a) Low risk nodes: $NB < \gamma_{DMA} - \sigma_{DMA}$
   b) Medium risk nodes: $\gamma_{DMA} - \sigma_{DMA} \leq NB \leq \gamma_{DMA} + \sigma_{DMA}$
   c) High risk nodes: $NB > \gamma_{DMA} + \sigma_{DMA}$

   where γ_{DMA} is defined in Eq. (3) and σ_{DMA} is the standard deviation obtained from the same dataset as γ_{DMA}.
iii) Add DMA partitions to global categories for final risk map generation

The flow chart for the algorithm is shown in Fig. 2:

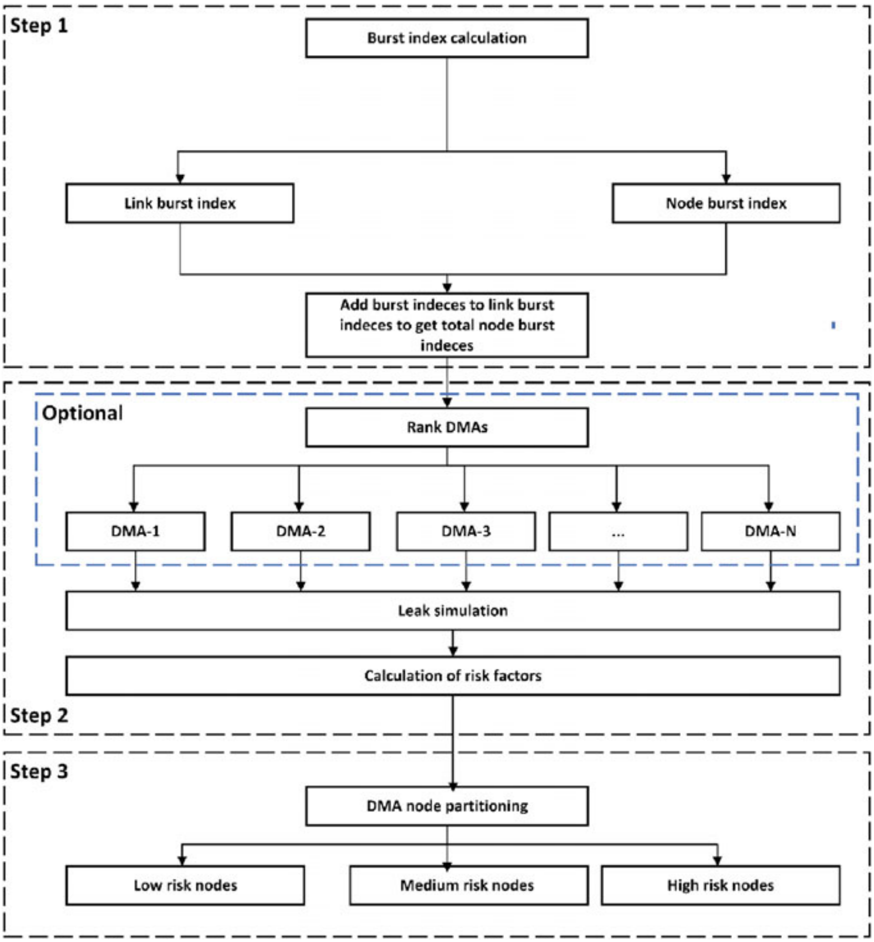


Fig. 2 Algorithm for node categorisation

3 Case Study

The network used in this study is a virtual city with 5 distinct District Metered Areas distinguished by varying topographical regions. The network has 388 nodes, seven water tanks, one reservoir, and 11 pumps. The lowest and highest elevations among nodes are 3.48 and 113.08 m, respectively. Leakages are introduced at the middle of each pipe section, except valves and pumps). The emitter coefficient and emitter exponent are taken from [13] and are 13×10^{-4} and 0.5071 respectively. Hydraulic simulation was done using the EPANET 2.2 engine based on the pressure drive demand model. The simulation was only run for the peak hour. This study is based on a numerical experiment, and field data are not used for validation of the model. It is assumed the hydraulic model is calibrated and represents the conditions of the C-Town system. Since this study does not attempt to generate a risk map for the DMAs, data which is not very specific (defined at DMA level) is not used. This automatically rules out age (Fig. 3).

The results obtained in Fig. 5 use arbitrary factors shown in Table 1. It was assumed that the DMA conditions were the same as such same burst factors are used across all DMAs. However, the calculation of β uses the ratio of the DMA mean parameter values and actual network parameter. For β, the assumption was that burst pressures for all parameters happened at their average values. This study only considered 2 factors: pipe length, diameter. For simplicity, the algorithm was only run for a single simulation.

The distribution of NBI values for each DMA is shown in Fig. 4. As can be seen from the distribution curves, each DMA has a different set of NBI values and operating conditions.

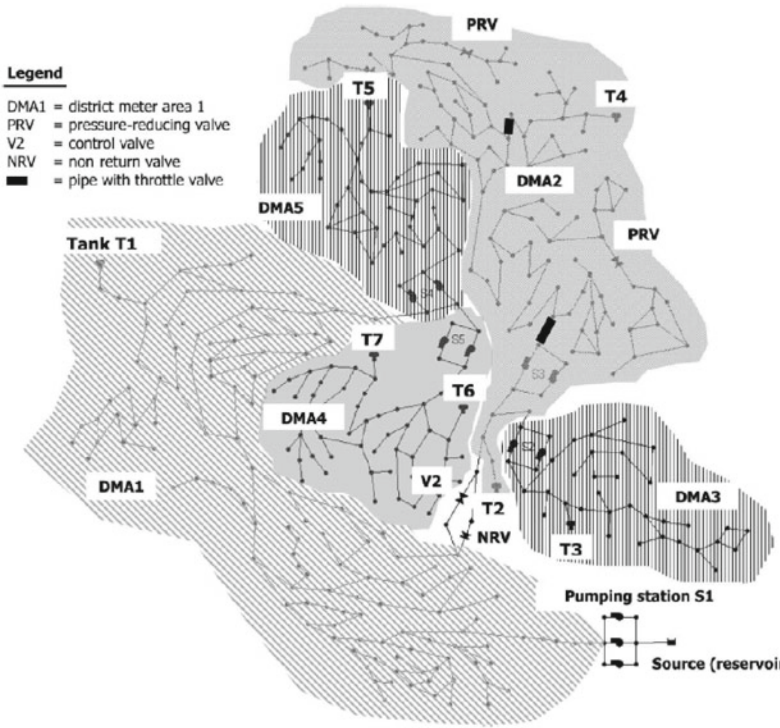


Fig. 3 C-TOWN Layout, [14]

Table 1 Assumed burst factors

Parameter	Risk factor
Length	0.7
Diameter	0.3

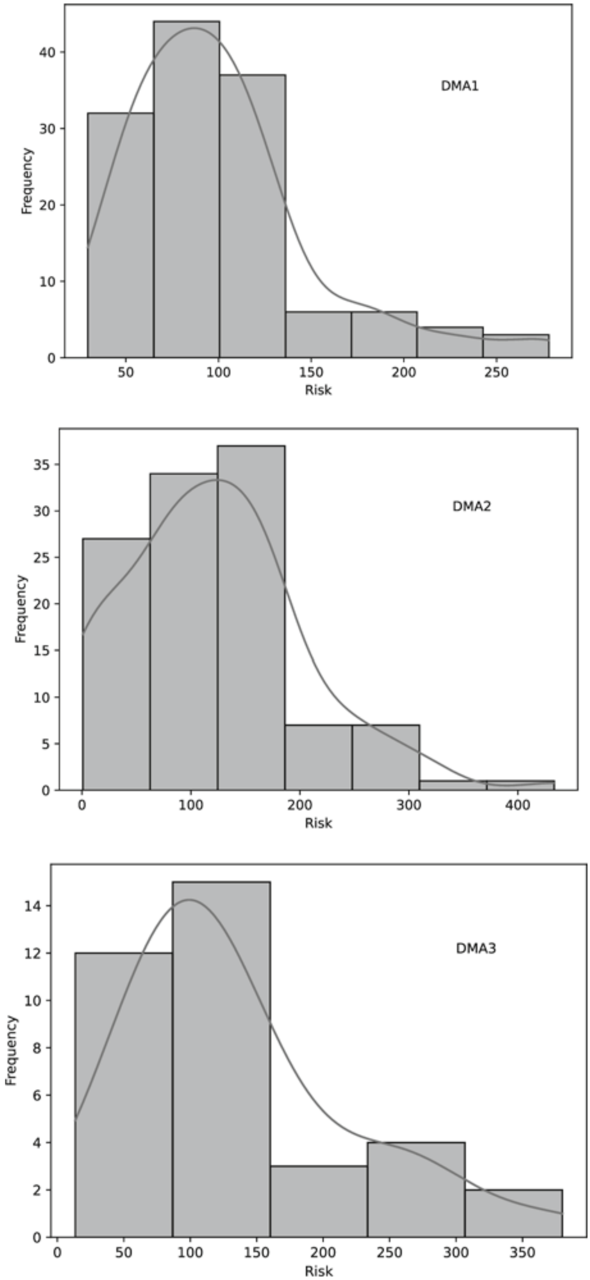


Fig. 4 Distribution of CNBI values in each DMA

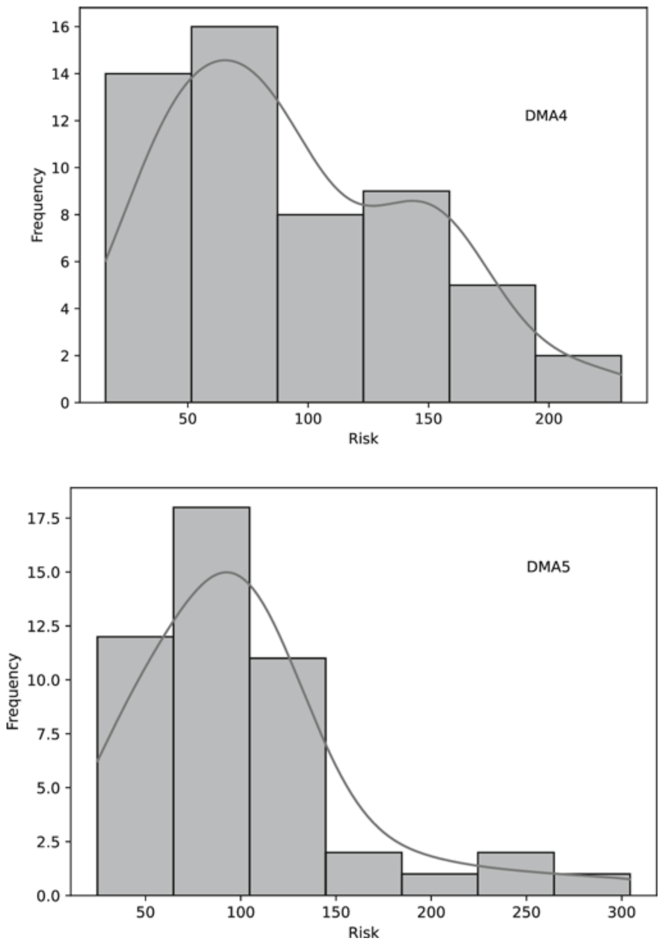


Fig. 4 (continued)

In this study, the average DMA NBI values are used to categorise the nodes as shown in Fig. 4. 14.39% of the nodes are low risk nodes, 68.69% medium risk, and 13.64% high risk nodes. The remaining 3.28% (grey) were not included in the analysis as they do not belong to any DMA (see Fig. 5) and some of them are tanks and reservoirs.

After filtering the low and medium risk nodes, the distribution of high-risk nodes in the distribution system is as shown in Fig. 6.

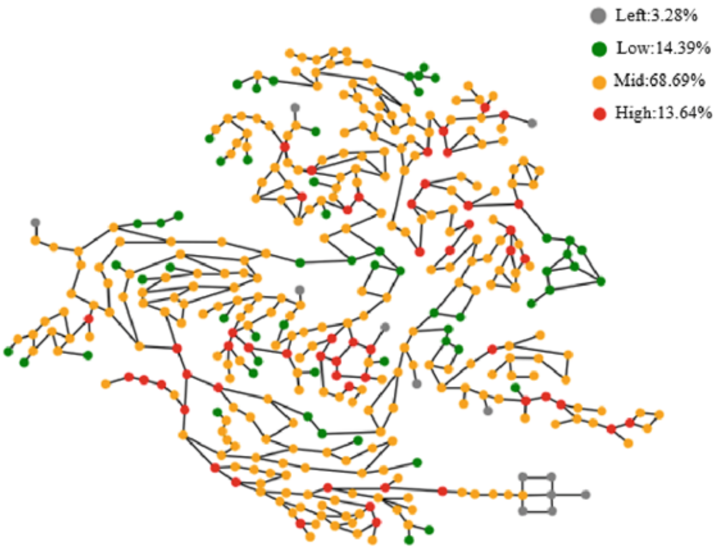


Fig. 5 Categorised node map

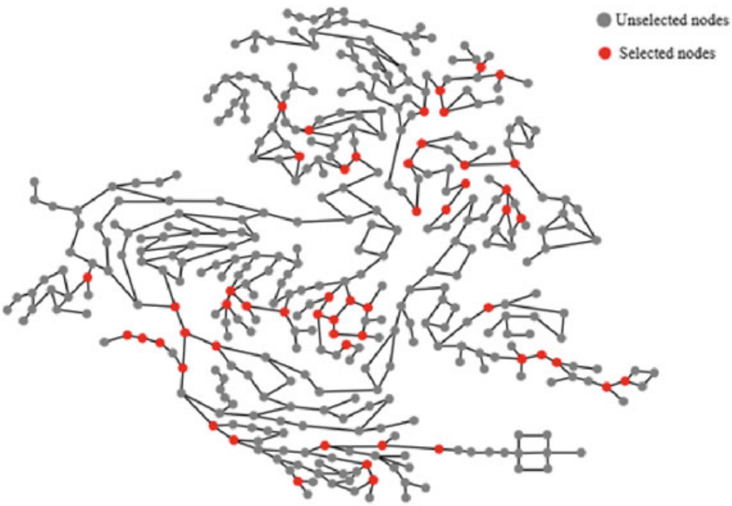


Fig. 6 Selected nodes (High Risk)

4 Limitations

It is very challenging to know the actual burst pressure for a leakage event in a water distribution system. For new leaks, this can easily be estimated based on the hydraulic state of the network prior to the leakage. The assumption here is that the leakage might be younger than a week old. But in the event where a leak has remained undetected for several detection periods, it is usually hard to estimate the burst pressure. In such situations, approach by [15] can be used. The burst pressure at the onset of the leak is then calculated based on the hydraulic state of the distribution system at that time. Furthermore, only the worst-case (peak hour) scenario is used. Future studies should consider adapting the algorithm to extended simulations.

5 Conclusion

Risk assessment of water distribution is key to meeting customer demands. This ensures that proper attention is given to risky areas so that leakage events are identified in time to allow for timely response. However, most of the available methods which deal with leak localization in distribution systems do not consider main risk issues associated with these distribution systems, such as frequency of burst, age of pipes, material strength, etc. Without the intrinsic knowledge of the distribution network, every node is a potential risk. This study therefore attempted to close that gap by introducing a novel approach that quantifies node risk using network parameters (pipe length, pipe age, nodal pressure, pipe material, etc.). The algorithm can enable water utilities to identify risky areas in their network and thus direct the needed attention to them. Furthermore, since the algorithm classifies risks as either being low, medium or high risk, if the low-risk nodes are filtered out, the other nodes can be used as candidate nodes for other risk optimization algorithms, hence reducing the search space. The search space is further reduced if only high-risk nodes are considered. The algorithm developed in this study is also adaptive in the sense that new factors for different parameters can be introduced provided the right definition is attached to them. For instance, [7] defined risk considering nearby affected areas during a leakage event.

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Annex A

Estimation of Burst Factors

Burst factors are estimated using burst pressure curves. These curves are plotted for each factor responsible for leakage while neglecting the rest. Thus, if a curve is plotted for pipe length, the assumption is that the only factor responsible for leakage in the pipeline is pipe length. Once the curve is plotted, the average burst pressure is computed, and its associated pipe length is read on the x-axis. This process is repeated for all the factors until the associated parameter values are found. Following this, the estimated contribution of each factor is calculated using the formula:

$$\alpha_{DMA} = \frac{BP_{j,avg} - \overline{BP}_{DMA}}{\sum_{j=1}^{N}\left(BP_{j,avg} - \overline{BP}_{DMA}\right)} \tag{A.1}$$

where α is the proportion contribution of factor j in the DMA, $BP_{j,avg}$ is the average burst pressure considering factor j, $\overline{BP}_{DMA}$ is the average DMA burst pressure. N is the total number of factors included. Note, the N factors considered in Eq. (A.1) should have $BP_{j,avg} - \overline{BP}_{DMA} > 0$. Otherwise, the parameter should be dropped.

For each factor and leak event, the value at BP_{avg} is noted together with the shape of curve. For parameters with a curve as shown in Fig. A.1, β is therefore given by:

$$\beta_{ij} = \frac{f_{BP_{avg},j}}{f_{ij}} \tag{A.2}$$

where $f_{BP_{avg},j}$ is the j th parameter value at average burst pressure, and f_{ij} is the actual network value.i is a unique leakage event.

However, for parameters with a curve shape as the one shown in Fig. A.2, β is given by:

$$\beta_{ij} = \frac{f_{ij}}{f_{BP_{avg},j}} \tag{A.3}$$

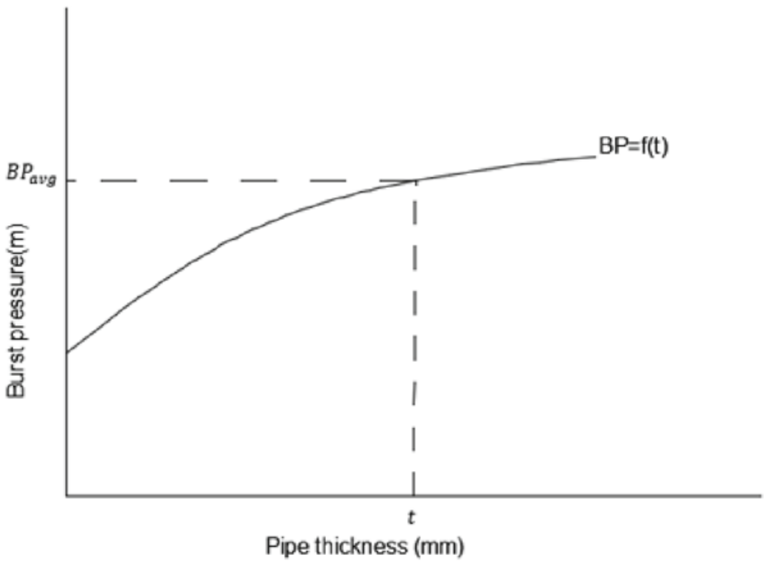

Fig. A.1 Increasing factor curve

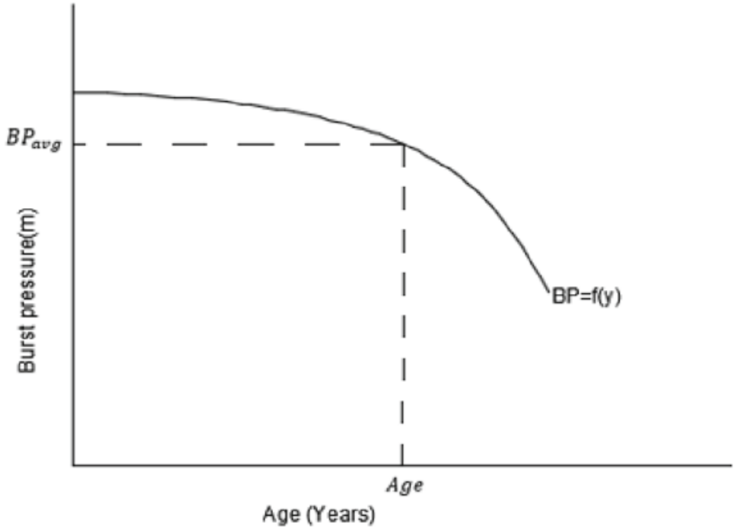

Fig. A.2 Decreasing factor curve

Thus, Eq. (1) can therefore be expanded to incorporate both decreasing and increasing functions and can be rewritten as:

$$\gamma_k = \rho_k + \alpha_{DMA}\left(\sum_{i=1}^{N}\sum_{j=1}^{L}\frac{f_{BP_{avg},j}}{f_{ij}} + \sum_{i=1}^{N}\sum_{j=L+1}^{M-L}\frac{f_{ij}}{f_{BP_{avg},j}}\right) \tag{A.4}$$

where M is the total number of factors included in the analysis, L is the number of factors which follow the curve in Fig. A.1, and

$$\rho_k = \frac{P_k}{\overline{BP}_{DMA}} \tag{A.5}$$

where $\overline{BP}_{DMA}$ is defined in Eq. (A.1). P_k is the pressure at node k.

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Structural Engineering and Materials Modelling

Structural Performance of Metal Sheeting versus Tiled Roofs under Extreme Winds

M. Lukusa Tshimpumpu, Abdolhossein Naghizadeh, and Jeffrey Mahachi

Abstract Houses, the most constructed structures all over the world, can be exposed to extreme winds that may damage their roofs. Generally, roofs are the most vulnerable parts of houses against wind pressure rather than the other elements. Most housing roofs in South Africa are constructed with metal sheeting or tiles as covers, while these systems can exhibit different performance upon their exposure to extreme wind events. The present study is aimed to provide an assessment on the structural behaviour of housing roofs comprising metal and tiled systems under strong winds. Fluid dynamics, wind codes and computational fluid dynamics (CFD) have been employed to analyse and quantify wind loads. Combined wind and dead loads at ultimate limit state served as quasistatic forces acting on roof samples during laboratory experiments. Findings show that cover-to-truss connections are being pulled-out as the sheet deflects under uplift wind forces, even to the removal of batten-to-truss nails when there are no clips. Tiles are cracked gradually till they break as the whole system deflects under wind forces. It can be concluded that the performance of metal sheeting roofs depends on the resistance of cover-to-truss connections against wind pressures, whereas that of tiled roofs depends on the individual resistance of each tile, their interlocking forces, their ability to act as a system, and their attachments' resistance at the edges.

Keywords Extreme Winds · Fluid Dynamics · Metal Sheeting Roofs · Tiled Roofs · Wind Codes

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1 Introduction

Houses in South Africa are constructed following the contemporary South African architectural style introduced since 1980 [1]. Houses serve as shelter to humankind, to protect them against adverse weather conditions such as winds, rains, snow, heat, cold, etc. [2]. A typical example of buildings is a single-story house, composed of metal sheeting or tiled roofs, masonry walls, reinforced concrete floor slab and foundation as structural elements [3, 4]. Typically, a roof and walls serve as building envelope to protect its residents against severe weather conditions, and the foundation supports the envelope, transmitting its load to the ground, while withstanding ground movements [3–5]. During strong wind events such as hurricanes and tornadoes, the roof is the most vulnerable part of a building, where it can be easily damaged [6, 7].

Housing roofs designed and built to standard are generally composed of timber trusses and metallic or tiled covers as structural components, which have been assembled with nails [4, 5]. Most wind post-damage investigations have revealed that roofing components that are easily destructed are the cover, purlins or battens and rafters or trusses' top chords [8]. As such, these components assembled, have been used as samples for laboratory experiments [8].

Winds are moving masses of air which create forces of pressure when in contact with any physical body [9]. Typically, design codes [10–15], categorize winds based on their fundamental speeds, which generate peak gust pressures, in which the excess can lead to roofs' damage. These speeds are referred to the extreme mean wind speeds, while they do not account for a turbulent component [16]. Harper *et al.* [17] states that the World Meteorological Organization (WMO) considers extreme or strong the winds with a minimum of 17 m/s (≥61.2 km/h) speed. Speeds provisioned for in wind codes can be exceeded during extreme events such as tornadoes and hurricanes [9, 18]. Vortical winds are stronger than turbulent winds, and are not included in wind codes, while they are mostly used by meteorologists to quantify tornadoes and hurricanes [10–15, 19, 20].

This study has been conducted in two (2) phases, which consisted of quantifying winds on roofs, and assessing structural performances or behaviours of metal sheeting and tiled systems. Wind codes, fluid dynamics and computational fluid dynamics (CFD) have been used for wind quantification, whereas laboratory experiments served for ascertaining structural behaviours of roofing components. Wind codes have helped provide parameters of exposure to extreme winds, whereas fluid dynamics have helped quantifying vortical winds. CFD has been used for simulating flows on house models, in order to compare and validate results obtained from combining codes approach with fluid dynamics.

The performance of housing roofs under extreme winds depends on the ability to quantify winds, which can be considered as a major challenge, due to the limitations of wind codes to straight winds. However, surface forces that resulted from combining codes approach with fluid dynamics, validated by CFD, have been applied on roof samples under laboratory conditions to lead to results in the form of load–deflection curves. The structural performance of metal sheeting and tiled roofs under extreme winds can be defined by applying quantified wind forces on representative samples of typical roofing systems, having set these upside-down as damage is being ascertained by measuring loads against deflections.

2 Methodology

2.1 Materials

This research was based on single storey masonry houses with as roof covers metal sheeting or tiles. Houses' materials were selected to comply with the standards specified in the South African National Building Regulations [5] and in the National Home Builders Registration Council (NHBRC) manual guide [4]. House models depicted dimensions and materials selected for this research, emphasizing on roofing materials which served as laboratory samples. House models helped analyze and quantify winds, whereas roof samples served for assessing structural performances of metal sheeting and tiled systems under laboratory conditions.

2.1.1 House Models and Roof Samples

Six single storey domestic residential masonry houses comprising hipped, gable and parapet flat roofs were selected. These houses measured 14.7 m in length, 6.9 m in width, 0.5 m in depth and 2.5 m in height to the heaves. Flat roof houses measured 1.6 m above the heaves, whereas gable and hipped roof houses both measured 1.1 m. These houses had roofs made of Grade 5 S.A. timber trusses with metal sheeting or tiled cover, and openings representing 19% of the total area of their external walls. Figure 1 shows house models as per roof with their respective cross-sections.

Roof samples are representative sections of roofs which are the most vulnerable upon their exposure to uplift wind forces. Samples represented a typical tributary area of any housing roof under a specific pressure distribution which, in the current study, corresponded to the largest area under uplift. According to Jayasinghe [8], the most vulnerable parts of a roof are the cover, the battens or purlins, and the rafters or trusses' top chords. Twelve (12) roof samples comprising six (6) metal sheeting and six (6) tiled covers, measuring 1.4 m in length and 1 m in width were constructed for laboratory experiments. Three metal sheeting samples were each made of corrugated galvanized iron sheets (3 mm thick, 4.97 kg/m^2), three (3) SA's grade 5 timber purlins (50 mm × 76 mm × 1.1 m) spaced 700 mm centre-to-centre, and two (2) SA's grade 5 timber rafters (114 mm × 38 mm × 1.5 m) spaced 1000 mm centre-to-centre. These were each assembled using twelve (12) purlin-to-truss nails (100 mm × 3.5 mm), fifteen (15) roof nails (125 mm × 4.5 mm) and six (6) hurricane clips which were fitted each with six (6) wire nails (50 mm × 2.8 mm). The three other metal sheeting samples were made of all the components cited above, except for hurricane clips,

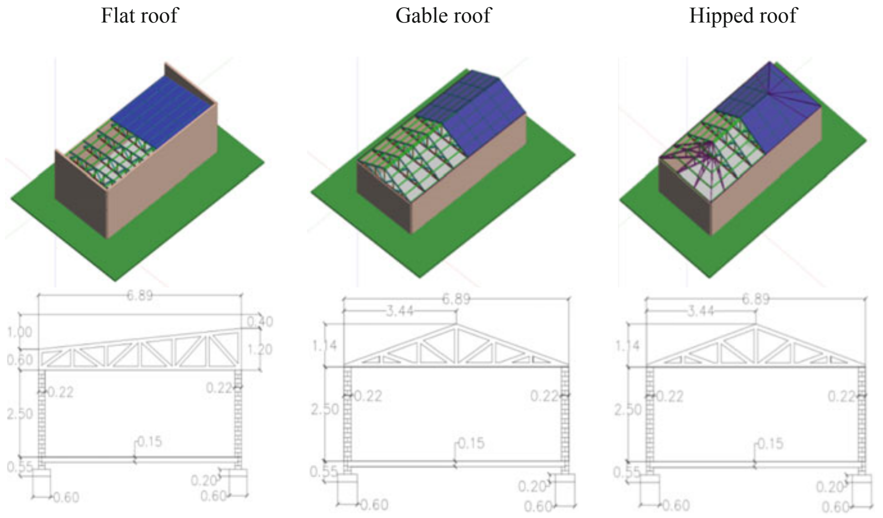

Fig. 1 House models with respective cross-sections

hence the concept of normal connections which differs from hurricane connections. The same applied to tiled roofs, except that they were made each of twelve (12) concrete tiles (320 mm × 420 mm × 15 mm), five (5) battens (38 mm × 38 mm × 1.1 m) spaced 350 mm centre-to-centre, two (2) rafters of the same dimensions and spacing as metal sheeting samples. Three (3) tiled samples were each assembled using ten (10) batten-to-truss nails (100 mm × 3.5 mm) as normal-connections samples, and to the rest of them ten (10) hurricane clips fitted each with six (6) wire nails (50 mm × 2.8 mm) were added as to hurricane connection sample.

The spacing between roof trusses was 1.5 m centre-to-centre, the one between purlins under metal sheeting roofs was 1 m centre-to-centre, and that between battens under tiled roofs was 350 mm centre-to-centre. These dimensions could have been taken as such to construct roof samples 2.1 m long and 1.5 m wide; however, these were all divided by 1.5 to adjust to the loading device's dimensions as shown in Fig. 2. As such, each sample measured in general 1.4 m in length and 1 m in width.

Metal sheeting and tiled roofs samples were categorized in general as normal-connections (NC) and hurricane-connections samples, as this study aimed to establish advantages of using hurricane clips as well. As such, a nomenclature was assigned to metal sheeting roofs (MSR) and tiled roofs (TR) as per the number of samples used for laboratory experiments. Metal sheeting samples were named respectively as MSR1—NC, MSR2—NC, MSR3—NC, MSR4—HC, MSR5—HC and MSR6—HC; whereas tiled roof samples were named as TR1—NC, TR2—NC, TR3—NC, TR4—HC, TR5—HC and TR6—HC.

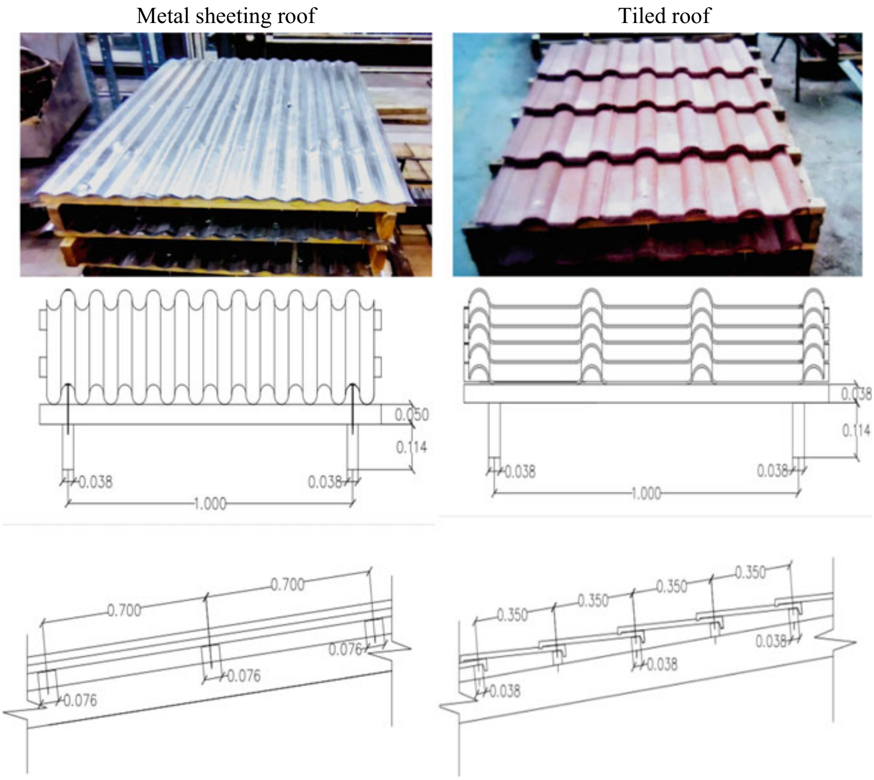

Fig. 2 Metal sheeting and tiled roof samples

2.2 Methods

The structural performance of housing roofs under extreme winds was ascertained by simulating failure of roof samples under the effect of applied surface forces under laboratory conditions. These surface forces resulted from quantifying winds on the largest roof areas under uplift as per geometry. Samples therefore represented roof's tributary areas under a specific uplift pressure distribution, and.

2.2.1 Wind Analysis

Extreme winds needed to be analyzed to be quantified accordingly in terms of velocity and pressure. Fluid dynamics has been utilized to point out different types of extreme winds in terms of flow regimes, to which are linked velocity and pressure formulas. Wind codes [10–15], based on wind-tunnel experiments, wind probabilities, meteorological and geographical features of a given region have been utilized to quantify wind pressures, taking into account every parameter that defines houses exposure to strong winds. CFD served as a tool to simulate different flows around houses, in order to compare and validate pressures obtained based on wind codes and fluid dynamics.

a. Fluid dynamics for extreme winds

Fluid dynamics, the study of fluids in motion and their behaviour when they encounter obstacles comprises three (3) types of flows: straight, turbulent and vortical [21]. These flows can also be encountered during extreme wind events; hence the concept of straight, turbulent and vortical winds [21, 22]. These winds are quantified in terms of velocity and pressure after solving the Navier-Stokes (N-S) equations [22]. Equation (1) represents the general equation for dynamic pressure. This equation varies in velocity with whether the flow is straight, turbulent or vortical.

$$p = \frac{\rho}{2} U^2 \tag{1}$$

ρ is the density, U the velocity and p the pressure.

Turbulent flow is always unsteady and of changing velocity, raising assumptions that its velocity U has a mean and fluctuating components (U_m) and (U_f) such that $U = U_m + U_f$ [21]. The relationship between U_m and U_f has helped introduce the concept of turbulence intensity ($I_v(z)$) [13].

Vortical winds spin into a vortex when they are rotational and into a free-vortex when irrotational [22]. Another component called vorticity ω is added to its velocity (U), causing it to depend on an angular velocity (ω'), a core radius (R) and a changing radius (r), as it is seen in the Rankine combined vortex from Eq. (2) to (5) [19, 20].

$$Velocity\colon U = \omega' r\ (r \leq R);\ U = \omega'^{\frac{R^2}{r}}\ (r > R) \tag{2}$$

$$\text{vorticity: } \omega = 2.\omega' \tag{3}$$

$$Pressure\colon p - \underset{\infty}{p} = -\rho\omega'^2 R^2 + \frac{\rho}{2}\omega'^2 r^2 (r \leq R\colon Inside\ core) \tag{4}$$

$$Pressure\colon \mathrm{p} - \underset{\infty}{\mathrm{p}} = -\frac{\rho}{2}\omega'^2 \frac{\mathrm{R}^4}{\mathrm{r}^2} \cdot (\mathrm{r} > \mathrm{R}\text{: Outside core}) \tag{5}$$

b. Wind codes

South Africa's wind code (SANS 10,160–3:2018) [14] has been utilized to define exposure of house models to extreme winds, and the Eurocodes (EN 1991–1-4:2005) [13, 14] has helped quantify turbulent winds. South Africa's extreme wind map in Fig. 3 shows four (4) main regions of fundamental wind speeds ($U_{b,0}$) recorded regardless of any trajectory and direction, which can be either tangential or angular [15, 23–25]. In this study, the worst case scenario was selected corresponding to a

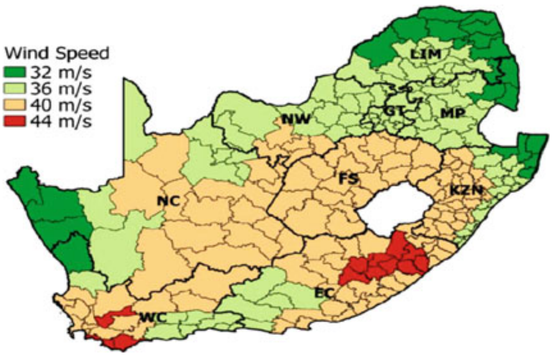

Fig. 3 South Africa's extreme winds map [15, 24]

rural area in the Western Cape (WC) province at an average altitude of 592 m above sea level, under a fundamental speed ($U_{b,0}$) of 44 m/s, giving rise to an air density (ρ) of 1.1 kg/m^3 [15, 24].

Parameters of houses' exposure to strong winds were determined: the probability of occurrence (C_{prob}), the roughness of the terrain ($C_r(z)$) and its topography ($C_o(z)$), the roughness length (z_0) and building height (z), turbulence intensity ($I_v(z)$), and coefficients of pressure distribution on houses (C_p) [14, 15]. These factors have helped adjust fundamental speeds ($U_{b,0}$) to peak wind speeds (U) to determine pressures (p) according to each flow. This pressure was adjusted with distribution coefficients (C_p) to determine uplift forces on roofs. Straight wind speeds were therefore quantified based on Eq. (7) and the corresponding pressures as stated previously in Eq. (1) [14]. According to the Eurocode [14, 15], turbulent wind speeds were quantified based on Eq. (8) and their corresponding pressures based on Eq. (1). Vortical wind velocity (U) depended on angular velocity (ω'), which in this study corresponded to the fundamental wind speed ($U_{b,0}$) as fundamental wind speed is recorded regardless of any direction or trajectory [14]. The core radius (R) of vortical winds was determined by dividing the world's highest speed ever recorded in the history of extreme winds (483 km/h) [8] by the angular velocity (ω'), assuming South Africa might exceed in the future the 321 km/h recorded in 1999 [18]. Velocities and pressures of vortical winds were determined based on Eqs. (2), (4) and (5).

$$U_m = C_{prob.} \cdot U_{b,0} \cdot C_o(z) \cdot C_r(z) \tag{6}$$

$$U = 1.4\, U_{m.} \tag{7}$$

$$\mathrm{U} = (1 + 7 \cdot \mathrm{I_v(z)})^{0.5}\mathrm{Um(z)} \quad and \quad I_v(z) = \frac{1}{ln\left(\frac{zo}{z}\right)} \tag{8}$$

Wind loads (W_k) were determined by multiplying uplift pressures by structural ($c_s \& c_d$) and force factors (c_f), and by the reference tributary area (A_{ref}) [14, 15]. Wind load Eq. (9) has been simplified as structural and force factors were equal to

1.0 [15].

$$W_k = p.Cp.A_{ref} \tag{9}$$

c. CFD

CFD was used to simulate straight, turbulent and vortical wind flows on house models, solving the N-S equations. The CFD software selected for this study was SIMFLOW. The limitation with this software was that house models were represented by boxes such that there were no differences in roof shapes; however these models differed in heights. These simulations did not include parameters of exposure to strong winds as those found in the codes.

Twelve (12) simulations were conducted, comprising four (4) cases under each type of flow, of which three (3) consisted of 0° winds and the fourth of 90° winds. Flat and hipped-roof models were exposed to diverse types of winds flowing at 0° only, whereas gable-roof models were exposed to both 0 and 90° winds.

Material used for every simulation was air of density 1.1 kg/m^3, which defined the nature of the fluid. Houses had no defined material as the software didn't provide any; however, 200,000 meshes were generated for each model after boundary conditions had been defined.

Boundary conditions were not established on the fluid, but rather on the box which was exposed to the wind, which flew in freestream. Boundary conditions of house models consisted of walled bottoms, patched inlets, tops and outlets, and symmetric left and right-hand sides. Inlets, outlets and tops represented respectively windward and leeward sides, and roofs, depending on whether they were exposed to 0 or 90° winds.

Diverse types of wind flows were defined in terms of parameters such as density, velocity and pressure formulas. These winds flew in freestream at directions perpendicular to houses lengths (0°) or parallel to them (90°). Straight, turbulent and vortical winds were respectively defined as laminar transient incompressible, turbulent (RANS) transient incompressible, and RANS turbulent incompressible.

Flow patterns and boundary conditions served as input data prior to running simulations. Simulations were run by causing winds to flow in freestream at 0 or 90°. Results were displayed in 3-D animation in terms of velocities and pressures after N-S equations had been solved. Each simulation lasted at least 18 s, showing that damage would occur over this short period of time.

Ultimate pressures obtained from these simulations were considered as characteristic distributed wind forces acting on different housing roofs. These surface loads were compared to wind loads obtained from combining codes approach and fluid dynamics.

2.2.2 Experimental Method

Roof samples were tested under laboratory conditions to ascertain their structural behaviour under applied uplift wind forces. A hydraulic loading device has been used to apply forces directly to samples covers, while these were set upside down. The device had a hydraulic loading arm mounted at the centre of a steel beam spanning 1.2 m and supported by two (2) steel columns 2.5 m high. Samples were supported along their edges 1.2 m above ground with two (2) steel bars spaced 1.4 m. An IP100 steel load spreader having a 700 mm arm supporting two (2) 800 mm bars has been utilized to distribute the loading arm's point load into a uniformly distributed surface load. Though wind forces are not uniform throughout the roof due to pressure distributions, uniformity can be considered under a particular distribution. Such was the case with each sample as they represented roofs tributary areas under a specific distribution.

a. Experimental loads

Experimental loads (w) were obtained from combining house models uplift wind forces and roofs self-weights at ultimate limit state (ULS). Partial factors of 1.6 and 0.9 multiplied wind and dead loads respectively, while the combined load acted normal to the surface of contact, these expressed in Eq. (10) [26, 27].

$$w = 1.6\,W_k - 0.9G_k cos\,\alpha \tag{10}$$

G_k is the dead load, W_k the wind load and α roof's pitch angle.

Only wind loads obtained based on wind codes and fluid dynamics were used to determine experimental loads, CFD results were only used for comparing and validating wind codes calculations.

b. Laboratory experiment

All metal sheeting and tiled roof samples were of the same dimensions that the difference between flat, gable and hipped roofs was only in terms of pressure distributions or experimental loads. As such, each sample was loaded with combined straight, turbulent and vortical wind and dead loads at ULS, as experimental loads increased from straight to turbulent to vortical winds. The loading arm extended as far as the spreader and forces were applied directly to the cover of each sample that was set upside-down. Each sample's cover, whether metal sheeting or tiled was held by fifteen (15) roof nails (125 mm × 4.5 mm) to prevent downfall when set upside-down. Loads were applied until failure of components was ascertained as they were gradually recorded with their respective deflections (Fig. 4).

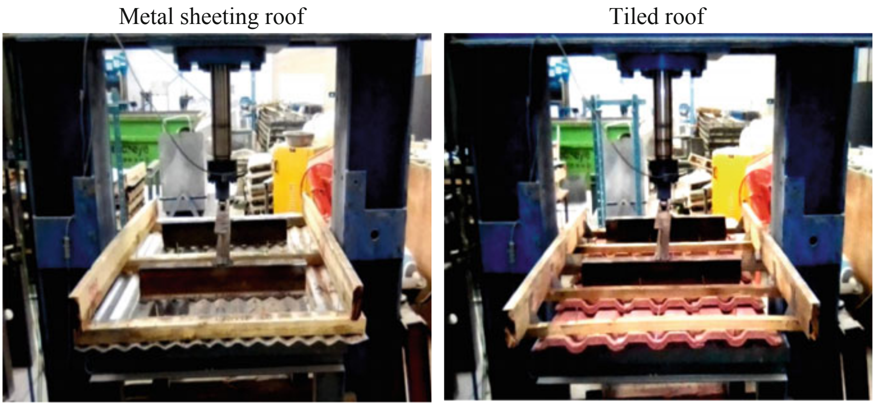

Fig. 4 Laboratory set-up

3 Results

Parameters of houses exposure to strong winds had to be defined according to wind codes as seen in Table 1. Most parameters were obtained from the South African wind code, except for the roughness length and turbulence intensities, which were derived from the Eurocode, due to limitations of the South African code to straight winds. CFD simulations did not include these parameters to analyse different types of flows on house models.

Table 1 Wind codes parameters of houses exposure to strong winds

Features	Flat roof	Gable roof	Hipped roof
Probability factor (C_{prob})	1.0	1.0	1.0
Orographic factor ($C_o(z)$)	1.0	1.0	1.0
Roughness factors ($C_r(z)$)	1.1	1.0	1.0
Roughness length (z_0)	0.05	0.05	0.05
Turbulence intensity ($I_v(z)$)	0.24	0.24	0.24
Pressure coefficients (C_p)	−0.5	−0.6 (0°) −0.9 (90°)	−0.6

3.1 Loadings

3.1.1 Wind and Experimental Loads

a. CFD results

CFD simulations showed how winds were distributed on house models in general, while results were recorded in the form of pressure and velocity curves for each case. Figure 5 shows respectively pressure distribution and pressure and velocity curves generated from a simulation conducted on gable and hipped-roof models exposed to 0° vortical winds. This figure serves as an illustration to how wind pressures or surface loads were obtained from each simulation. Simulations results could not be included in this paper in the form of images and graphs, due to limitation in space. However, results have been condensed in Table 2 as ultimate pressures, which also correspond to ultimate surface wind loads acting on roofs of respective house models. As such, CFD results in Table 2 represent straight, turbulent and vortical wind loads acting on different house models regardless of wind codes parameters of exposure mentioned in Table 1.

Simulation results showed that these extreme winds would distribute around house models and cause damage to their roofs in at least 18 s. As CFD only deals with fluids distributions, the structural behaviour of housing roofs could not be ascertained at this stage. However, CFD results have been compared to wind forces obtained based on codes and fluid dynamics approach. Simulations showed that straight, turbulent and vortical winds gusting at any direction to the houses could not exceed respectively 2, 2 and 7 kN/m^2 in force.

b. Wind loads according to codes and fluid dynamics

Wind loads acting on housing roofs under straight, turbulent and vortical flows have been determined based on different pressure equations mentioned in the methodology, taking into account parameters of exposure as mentioned in Table 1. Distributed pressures have been considered surface loads as they multiplied a tributary area of 1 m^2. Table 3 shows wind forces acting on different house models as per flow.

These results show that straight, turbulent and vortical winds acting on housing roofs could not exceed respectively 2, 3.0 and 10 kN/m^2 in force.

c. Wind codes and fluid dynamics results versus CFD results

Wind forces acting on housing roofs were determined based on wind codes and fluid dynamics, and also based on CFD as seen in Tables 2 and 3. CFD results of seven (7) cases were quite similar to those determined based on wind codes and fluid dynamics approach. The four (5) other cases represented by 0° straight winds and 90° winds on hipped and gable roofs were either smaller by 40% or greater by 45%.

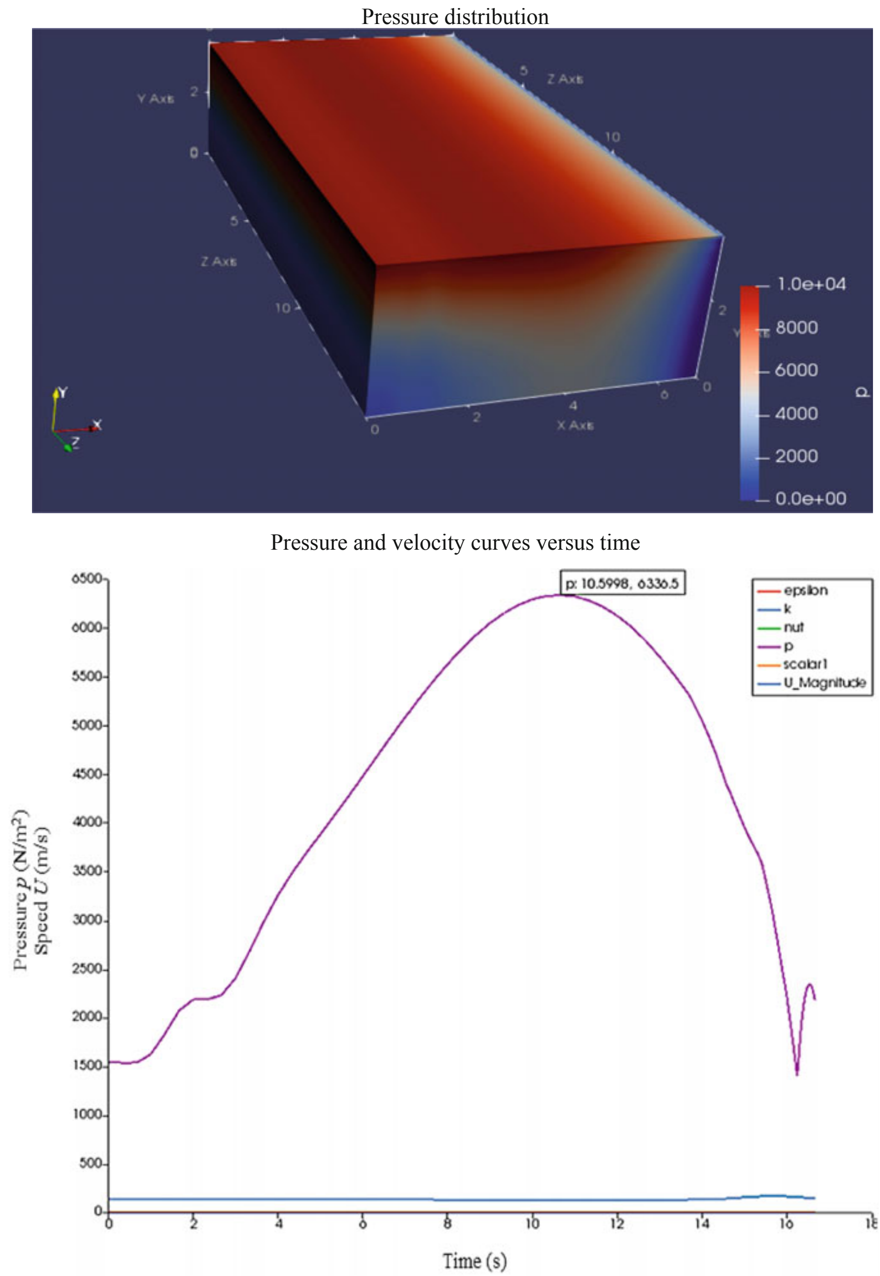

Fig. 5 CFD simulation results of vortical winds acting on gable/hipped-roof models at 0°

Table 2 Extreme wind forces (W_k) based on CFD (SIMFLOW) simulations

Feature	Straight winds (kN/m^2)	Turbulent winds (kN/m^2)	Vortical winds (Tornado) (kN/m^2)
Flat roof (0° winds)	−1.1	−1.8	−4.9 (r = R = 3 m)
Gable roof (0° & 90° winds)	−1.7 (0°) −1.4 (90°)	−1.5 (0°) −1.9 (90°)	−6.3 (0°) (r = R = 3 m) −6.9 (90°) (r = R = 3 m)
Hipped roof (0° & 90° winds)	−1.7	−1.5	−6.3 (r = R = 3 m)

Table 3 Extreme wind forces (Wk) based on wind codes and fluid dynamics

Feature	Straight winds (kN/m^2)	Turbulent winds (kN/m^2)	Vortical winds (Tornado) (kN/m^2)
Flat roof (0° winds)	−1.2	−1.6	−5 (r = R = 3 m) −1.2 (r = 6.2 m)
Gable roof (0° & 90° winds)	−1.2 (0°) −1.9 (90°)	−1.6 (0°) −2.6 (90°)	−5.8 (0°) & −9.3 (90°) (r = R = 3 m) −1.2 (0°) & −1.9 (90°) (r = 6.8 m)
Hipped roof (0° & 90° winds)	−1.2	−1.6	−5.8 (r = R = 3 m) −1.2 (r = 6.8 m)

These differences were due to CFD's limitation in house models geometry, and the accuracy in solving N-S equations in three dimensions (3-D).

d. Experimental loads

Experimental loads varied from one roof type to another and have been categorized as per cover according to Tables 4 and 5. Dead loads (G_k) of metal sheeting and tiled roofs were respectively 0.1 and 0.5 kN/m^2. Tables 4 and 5 represent combined dead and wind loads acting in uplift at ULS on different housing roofs. Experimental loads were applied on samples varying from zero (0) to ultimate combined wind and dead load, depending on whether metal sheeting or tiled roofs. Results show that the ultimate experimental loads of metal sheeting and tiled roofs were respectively 14.9 and 14.8 kN/m^2.

Table 4 Metal sheeting roofs experimental loads (*w*)

Feature	Straight Winds (kN/m^2)	Turbulent Winds (kN/m^2)	Vortical Winds (Tornado) (kN/m^2)
Flat roofs (0° winds)	−1.9	−2.5	−8 (r = R = 3 m) −1.9 (r = 6.2 m)
Gable roofs (0° and 90° winds)	−1.9 (0°) −3.0 (90°)	−2.5 (0°) −4.1 (90°)	−9.3 (0°) & −14.9 (90°) (r = R = 3 m) −1.9 (0°) & −3.0 (90°) (r = 6.8 m)
Hipped roofs (0° and 90° winds)	−1.9	−2.5	−9.3 (r = R = 3 m) −1.9 (r = 6.8 m)

Table 5 Tiled roofs experimental loads (*w*)

Feature	Straight Winds (kN/m^2)	Turbulent Winds (kN/m^2)	Vortical Winds (Tornado) (kN/m^2)
Flat roofs (0° winds)	−1.8	−2.5	−7.9 (r = R = 3 m) −1.8 (r = 6.2 m)
Gable roofs (0° and 90° winds)	−1.8 (0°) −2.9 (90°)	−2.5 (0°) −4.1 (90°)	−9.2 (0°) & −14.8 (90°) (r = R = 3 m) −1.8 (0°) & −2.9 (90°) (r = 6.8 m)
Hipped roofs (0° and 90° winds)	−1.8	−2.5	−9.2 (r = R = 3 m) −1.8 (r = 6.8 m)

3.2 Experimental Results

3.2.1 Structural Performance of Metal Sheeting Roofs

Extreme winds acting on metal sheeting samples damaged their covers, causing them to bulge and deform, while roof nails were being pulled-out as seen in Fig. 6. Uplift wind forces increased from zero (0) to maximum vortical winds (14.9 kN/m^2), while the sheeting underwent strong deflections that caused gradual removal of roof nails and purlin-to-truss nails on normal-connections (NC) samples. Samples with clips or hurricane-connections (HC) samples only experienced pulling-out of roof nails. The average maximum load at which each sample failed was 11.6 kN, which caused a deflection of 55.5 mm corresponding to the average maximum removal length of nails. The structural performance of metal sheeting roofs was determined in terms of load-deflection (L-D) curves that showed in Fig. 7 that the relationship between applied loads and resulting deflections was not linear, but approached a quadratic curve. Figure 7 shows respectively load-deflection curves of

Fig. 6 Nails removal and metal sheets deformation under the effect of applied uplift forces

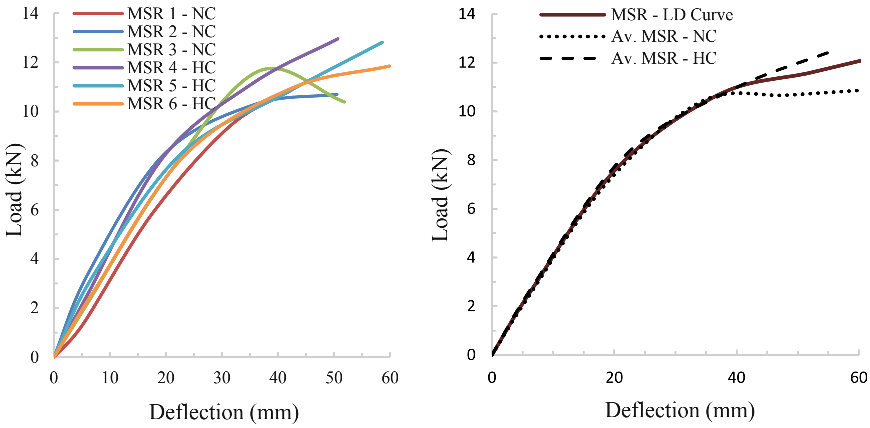

Fig. 7 Load-deflection (L-D) curves of metal sheeting roof (MSR) samples

each individual sample, of normal-connections (MSR—NC) samples, of hurricane-connections samples (MSR—HC) and of metal sheeting roofs (MSR) in general. The structural performance of metal sheeting roofs depends upon the removing strength of roof nails and mechanical properties of the cover.

3.2.2 Structural Performance of Tiled Roofs

Extreme wind forces acting on tiled roofs caused these to break. Interlocking tiles forming the cover were subjected to loads that varied between zero (0) and the ultimate vortical wind (14.8 kN/m^2), causing the whole system to undergo a maximum average deflection of 39 mm, while individual tiles were cracking until they broke at an average maximum load of 3.9 kN (14.8 kN/m^2) and deflection of 13 mm. The structural behaviour of tiled roofs in general was defined by the first row of tiles that was damaged as surface forces spread throughout the system. This row, from which damage was ascertained for each sample, ran parallel to battens and had three (3) tiles which were interlocking. The first tile in the row loaded from zero (0) to breaking load, while those following loaded from interlocking to breaking force. Breaking force or load is the force at which a single tile broke, whereas interlocking force the magnitude of force from which a tile loaded after its precedent tile had broken. Experiments also showed that damage on tiled roofs could spread from one row to another, as tiles on rows that were not damaged first could crack and break randomly as seen in Fig. 7. Figure 8 shows structural performances of each tiled sample, normal-connections samples (TR—NC), hurricane-connections samples (TR—HC), and tiled roofs (TR) in general in terms of load-deflection curves. Load-deflection (L-D) curves of tiled roofs in general show in Fig. 9 a repetition of performance as per tile in a row, with loads starting from zero (0) on the first tile and finishing zeroing on the last tile, as maximum deflection is being reached.

Fig. 8 Roofing tiles cracking and breaking in a row under the effect of applied uplift forces

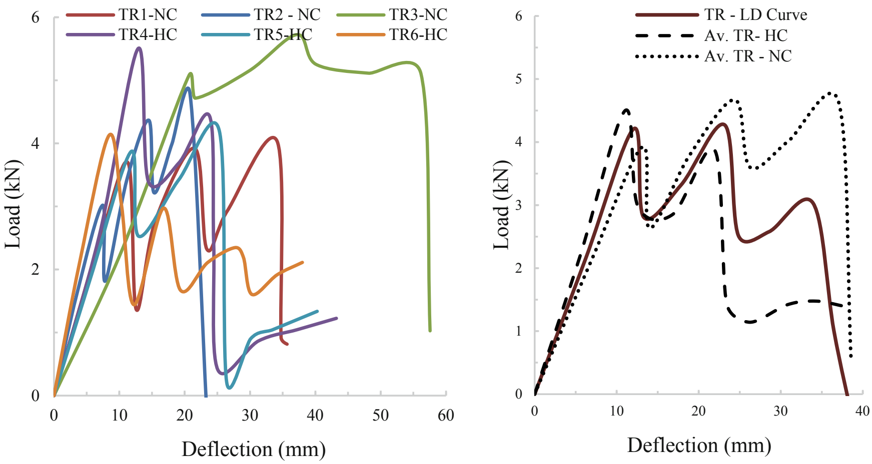

Fig. 9 Load-deflection (L-D) curves of tiled roof (TR) samples

4 Conclusions and Recommendations

Metal sheeting roofs attached with nails built to standards can resist up to 80 m/s of extreme wind speeds. However, any extreme event exceeding this speed, which only includes vortical winds, can damage roofs by removing their nails and causing their covers to overturn under the effect of applied pressures. Tiled roofs built according to regulations can resist up to 63 m/s of extreme wind speeds. However, any speed beyond this threshold, which only includes turbulent and vortical winds, would cause tiles to crack gradually and break, while their attachments at the edges would either be broken or be removed. Hurricane clips improve the resistance of roof trusses to extreme winds as they keep members from being detached while loads are being distributed.

The structural performance of metal sheeting roofs in general depends on the removing strength of roof nails and purlin-to-truss nails. The structural performance of tiled roofs mostly depends on the resistance of individual tiles, and also on their interlocking force and their attachments at the edges. These performances can be defined in terms of load-deflection curves, establishing a relationship between applied wind forces and deflections undergone by the roof till damage has occurred.

Thorough research on including turbulent and vortical winds in most codes would facilitate the analysis and quantification of extreme winds. CFD could be used as a tool for quantifying and analysing strong winds on houses as it gave results approximately equal to those based on wind codes and fluid dynamics approach by almost 60%. However, CFD is rather analytical than experimental in terms of winds quantification. Increasing the resistance of individual tiles and their interlocking ability would increase their performance under extreme winds, as most damage was caused by breaking and dislocating. Strong attachments should be provided at the edges of housing roofs to resist excessive pressures. Cover-to-truss connections stronger than nails could improve the structural performance of metal sheeting roofs under extreme winds. Hurricane clips are recommended to improve the resistance of wooden roofing frames against uplift forces of extreme winds. Effort to research on engineering-based prediction of structural performance of housing roofs under extreme winds should be considered based on experimental load-deflection curves and on mechanics of materials.

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Experimental Testing and Numerical Modelling of Heat Transfer Through a Composite Sandwich Flooring System with Penetrations Exposed to Fire

P. J. Mnanzana, J. Combrinck, R. S. Walls, and G. G. Jacobs

Abstract The designing of structures is an intricate process during which various aspects should be considered, one being fire resistance. Conventional materials such as concrete help structures withstand the effects of a fire. A composite sandwich flooring system, referred to in this paper, is completely void of concrete and has limited inherent fire resistance that is provided. For a flooring system like this, heat transfer will occur more rapidly. Fire-resistant boards are used to protect the system, but the fire rating of these boards is compromised by service holes—which is the focus of this paper. Experiments were conducted to examine the rate of heat flow through a sandwich ceiling system consisting of a Calcium Silicate (CaSi) board on the exposed face, a Voidcon steel sheet in the middle, and a Fibre Cement Board (FCB) on the unexposed face. Various holes, to simulate light and service penetrations, were made in the ceiling system. The experimental results made provision for a 30-minute rating for all the tested samples, with the shortest test taking place over approximately 40 minutes, but this is significantly less than the 60-minute original resistance. The experimental results were compared with simulated results generated using ABAQUS. This paper presents a summary of the comparison between the experimental and simulated results, highlighting important considerations and behaviour.

Keywords FEA modelling · Heat transfer · Perturbance influence · Fire

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1 Introduction

Structural fires are devastating in any economy simply because of the danger to human life and the destruction of infrastructure. Preserving both these entities (humans and structures) as well as safe egress for the occupants is important, thus all possible efforts should be used to ensure enough time during a fire for the safe egress of all occupants.

Over the past decades, the demand for steel as a construction material has grown significantly. Several qualities make steel desirable as a building material. Some of the most popular reasons are its cost-effectiveness, high strength, and reduced construction time. Effectively 70% fewer working hours are required to create a steel structure as opposed to a concrete structure [1]. It has become possible to create skyscrapers from steel without compromising durability [1]. Fire in its nature is destructive, and the aftermath can be devastating if no effort is made to retard or stop the fire in its early stages. Steel is a non-combustible material, and when coated with fire-resistant materials, the extreme heat of a fire can have limited influence on the material properties [2], therefore, protection of the structure can be achieved with the use of ***active*** (limiting the fire development and its effects by some action taken by a person or an automatic device) and ***passive*** (controlling the fire or its effects by systems that are built into the structure or fabric of the building, not requiring specific operation at the time of the fire) systems.

In a building, a fire will burn for as long as there is sufficient fuel or oxygen. The prevalence of either of the products will lead to the determination of whether the fire is fuel- or ventilation-controlled, a topic which is not covered in this paper. Furthermore, in a closed environment, the size and intensity of the fire can increase until all items in the enclosed space are fully engulfed in flames at the time of flashover, which is a transition to the burning period when the peak intensity is maintained while the rate of burning is controlled by the availability of oxygen through ventilation openings [3]. The rate of heat released from a combustion reaction depends on the nature of the burning material, the size of the fire, and the amount of air available, and as such, the rate of heat released typically increases gradually to a peak and then dies out when sufficient fuel has been consumed [3].

The Southern African Institute of Steel Construction (SAISC) has developed a novel lightweight cellular beam structure (CBS) that makes use of a composite sandwich flooring system as shown in Fig. 1. The sandwich flooring system consists of three layers made up of fibre-cement board (FCB), fire-resistant calcium silicate (CaSi) boards and metal sheeting (Fig. 2). The sandwich flooring system serves as a (a) divider of the building levels (compartmentation), (b) load-bearing flooring system, (c) planum for services, and (d) the ceiling of the floor below. What makes this system different from the traditional one is that it is completely devoid of concrete, whereas floor systems like this normally make use of concrete to reduce the effects of elevated temperatures. Those without concrete rely on the thermal properties of composite materials to withstand the effects of the fire.

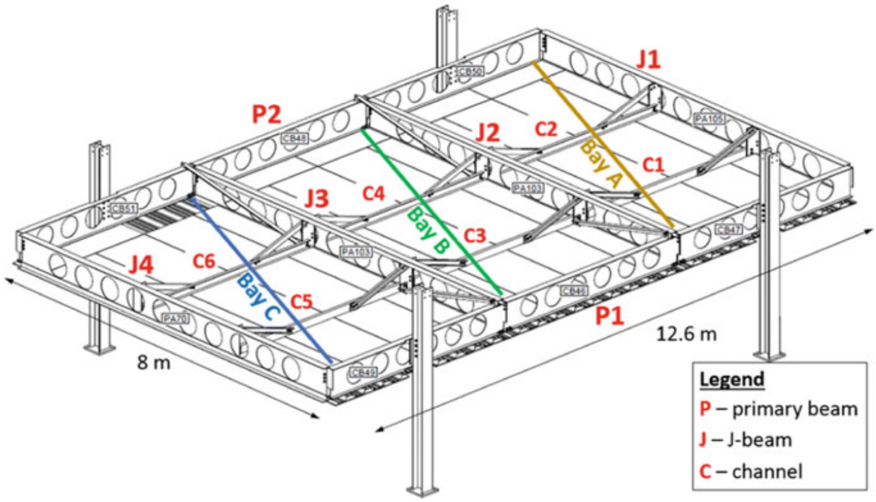


Fig. 1 SAISC modular cellular beam structure (SAISC) [4]

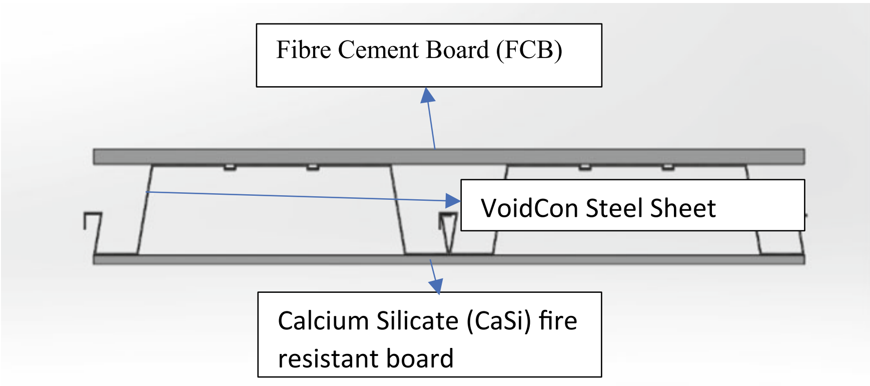


Fig. 2 Sandwich floor system used for protecting the structural system and carrying load. Fire is applied from the bottom of the samples

In the case of a typical fire, the heat transferred from the flames, (which includes radiation and convection), heats the compartment and its boundaries, such as the ceiling. Heat is then conducted through the ceiling board, which is then emitted from the unexposed side to the surrounding surfaces, in this case, the steel decking. The heat continues to be transferred in this manner through the respective material layers, each with its respective thermal properties, such as emissivity and conductivity [5]. The goal here is for the unexposed side of the floor system not to heat up beyond certain temperatures, being that the unexposed side of the specimen should not increase by more than 140 °C above the ambient or the maximum temperature at any one point on the unexposed surface of the specimen should not increase by more than 180 °C or exceed 220 °C regardless of the ambient temperature as dictated by the insulation criteria. Claasen [6] has proven that the flooring systems can obtain a 60-min rating when it has no penetrations. However, when penetrations are added for lights, service ducts, or cables it may compromise the fire rating. Hence, this work seeks to expand previous work looking at the influence of penetrations on the flooring system's fire resistance rating. Experiments and numerical models are developed and presented in the sections that follow.

2 Experimental Setup

The objective of the experiments was to see whether the samples will be able to pass the fire resistance rating criterion, specifically insulation and integrity. The integrity criterion dictates that there should be no flames or smoke through cracks and/or openings in the system, while the insulation criterion has temperature limits on the unexposed face of the system. The focus of this work was on the temperatures on the unexposed face of the system (i.e. on the top of the FCB).

Finite element (FE) modelling can be used to simulate real-life experiments for various testing procedures, with the benefit of reducing the time and costs required for physical tests. Experiments were therefore conducted to; (a) determine the threshold towards which the FE models will perform and (b) compare the results of the samples to those of their corresponding FE models. Should the results from the FE models reflect what was observed during the physical experiments, in terms of the nodal temperatures, then it can be concluded that FEA modelling can be relied upon to predict the results of physical experimentation. Another outcome of the experimentation was to test the ceiling/floor systems that have service holes of different sizes, and locations, on their fire-exposed side to observe how much heat is transferred through each of these samples. In his study, Marx [5] showed that a sandwich floor system with a ceiling board has a better fire performance than the one with no ceiling. This paper seeks to study how rapid the heat transfer to the unexposed face (as a result of the holes on the exposed face) of the system would be when penetrations limited the effectiveness of the ceiling. Samples were prefabricated to the initial size of 2.4 × 1.2 m each. They had to be downsized to fit onto the opening of the furnace that has a fire exposure area of 1.2 × 1.2 m [7].

The sandwich decking floor system consists mainly of three types of materials that are stacked in a three-layer sandwich-like structure and linked together using fixing screws such that they act compositely for load-bearing. Self-tapping screws were used for the reason that they seal tighter around the heads than any other type, and this meant there wouldn't be a considerable influence on the heat transfer. Figure 2 shows the layers of the sandwich decking system. It was constructed of Calcium Silicate (CaSi) fire-resistant board on the exposed face, the VoidCon VP115 or VP50 steel deck in the middle (i.e., either 115 mm or 50 mm deep steel deck) and the Fibre Cement Board (FCB) on the unexposed side. Holes were a requirement for this current paper to see how they (i.e., penetrations represented by holes) would influence heat transfer compared to the samples with solid boards. A total of five samples were tested, however, this paper will only focus on three samples. For Test 1, the sample had no holes on, and it was used to calibrate the furnace and make sure that the furnace temperatures aligned with those of the standard fire curve. Test 5 experienced rapid failure. Hence, these two latter are not the focus of this work. The samples were as described in Table 1 below.

Holes were made on each of the samples, with different sizes and at different locations. The samples layout was as follows:

Test sample 2 had two holes and both holes were made along each length of the flute (also referred to as cavity). The holes were 300 mm from the one (top) edge and 900 mm from the other (bottom) edge and were 600 mm apart and square in shape and 85 × 85 mm^2 each. The hole positions are shown in Fig. 4.

Test sample 3 had two holes, both at the centre of each flute (Fig. 3). The holes are each 80 × 80 mm^2. One hole was concealed using the same CaSi material, and the other was left open and completely exposed to the fire. This was to consider whether a non-combustible light or other services, that were placed at a penetration may influence the heat transfer.

Test sample 4 had three square holes of which two (smaller ones) were situated under the left flute and one (larger one) was situated under the right flute. The smaller

Table 1 Sample sizes with corresponding hole numbers

Test sample number	Number of holes	CaSi thickness (mm)	FCB thickness (mm)	Decking depth (mm)
2	2	9–12	20	115
3	2	9–12	20	115
4	3	9–12	20	115
5	4	9–12	9	50

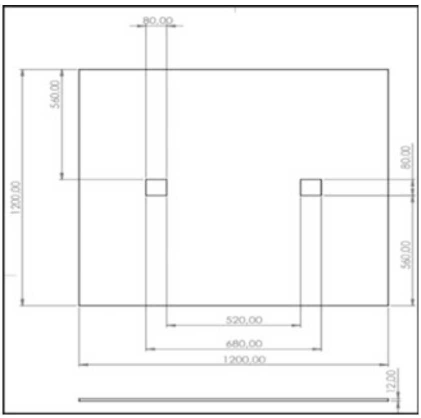
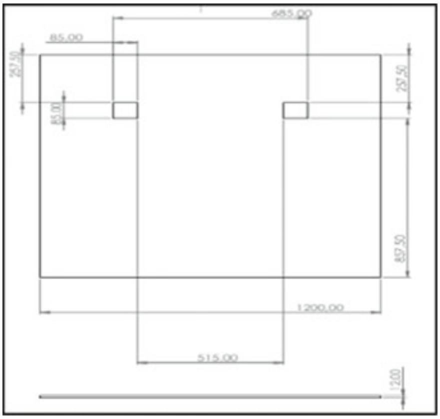


Fig. 3 Hole position for Test Sample 2

Fig. 4 Hole position for Test Sample 3



ones are 80 × 80 mm^2 each and they span 600 mm apart (centre to centre). The larger hole was 200 × 200 mm^2 and was at the centre of the flute below which it was situated. The hole positions are shown in Fig. 5.

Test sample 5, as shown in Fig. 6, had four square hole openings of dimensions 85 × 85 mm^2 each, the hole centres are each 300 mm from the side edges and 300 mm from the top edges, the holes thus span 650 mm from each other's centres.

The focus of this paper will be on Tests 2, 3 and 4, as noted above. Test 5 burned up rapidly and completely failed on the 37^{th} minute of the 60-min test. The samples would fit onto the furnace as shown in Fig. 7(a, b).

All the samples were instrumented with Type K thermocouples (TCs) at different locations to measure the temperatures. Data collection and analyses focussed on insulation requirements because integrity is generally not a problem with composite

Fig. 5 Hole position for Test sample 3

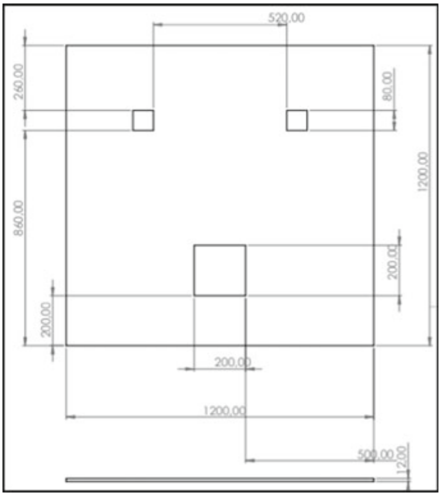


Fig. 6 Hole position for Test Sample 4

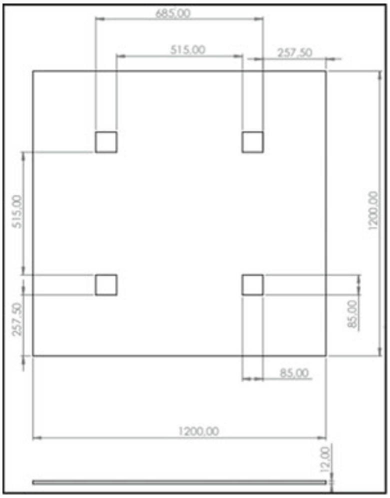


Fig. 7 **a, b** The fitting of the samples onto the furnace opening

slabs since the steel decking prevents any flames or hot gases from passing through the floor system [3] unless the steel decking is compromised from the onset. The TCs were labelled according to these symbols on all the samples: B = Back; C = Centre; R = Right; L = Left.

The furnace used is according to the design in the thesis by Fourie [7]. The furnace has a steel outer frame, steel base, vermiculite lightweight concrete lining, and is lined with a ceramic fibre blanket (Fig. 9) to further reduce the heat transferred to the outside of the furnace and to protect any steel that would be exposed to the heat inside the furnace. The furnace was heated by an LPG burner with a capacity of 200 kW and an additional hand-held burner of 40 kW capacity (Fig. 8). The furnace could be used in either a horizontal or vertical orientation, and to test the ceiling structure, it was used in a vertical orientation. Four plated TCs were placed within the furnace to constantly read the furnace temperature so that the burner could be manually controlled to reach the ISO 834 standard fire curve temperatures. The 0.5 mm diameter Type-K thermocouples were used in these tests due to their robustness and cost-effectiveness [8] and they can measure temperatures of up to 1350 °C [9] and the furnace only needed to heat up to 943 °C for the 60-min test.

Table 2 below depicts a decrease in temperature across all the layers in all the tests, from the hottest surface (furnace side) to the coolest surface (the FCB unexposed face) which was to be expected. The temperatures also increase from Test 2 through to Test 4. With reference to Table 1, the number of holes increases from Test 2 to Test 4, thus the increasing trend observed in Table 2 for the FCB unexposed faces of the samples. Figure 6 shows the trend graphically.

Fig. 8 The furnace and the additional gas burner connection

Fig. 9 Furnace lining with a ceramic blanket

Table 2 Average temperatures for the different levels of the sandwich system after 37 min of exposure

	Furnace temp. avg. (°C)	Flute temp. avg. (°C)	FCB back temp. avg. (°C)
Test 2	694.4	377.8	54.9
Test 3	698.5	423.7	61.9
Test 4	709.7	466.0	123.9
Test 5	727.9	543.9	655.7

Figure 10 depicts a clear increase of temperature on the unexposed faces of the samples from the sample with the least number of holes to the one with the most holes. It is important to note that the holes were not at the same position on all the samples and that their positions had an influence on the performance of the sample. Test 2 has two holes that were on the furthest side from the furnace burner, as opposed to Test sample 3 which had two holes midway through the sample length and one of the holes was loosely covered with the same CaSi material of the same thickness as the one that was on the fireside. The distance of the holes from the hottest point within the furnace (which is closer to the burner) is seen to have played an important role in the final unexposed temperatures of the said test sample. The holes allow hot gases into the central region of the floor which enhances convective heat transfer through the system.

Considering the sample results in Figs. 11, 12, 13 and 14, the hottest locations are either where there were holes, or the location is closest to the burner. And consequently, the greatest and most rapid failures on these samples occurred at these locations and cracks propagate from these said locations. All the samples withstood the fire conditions for over 37 min (the shortest period); therefore, all three samples satisfied the insulation criteria, and they could obtain a 30-min rating. It should be noted that the samples were tested with no load on them, thus there can be no conclusive conclusions drawn on whether the samples can be rated for the stability criteria. If tested with no holes the samples should have obtained a 60-min rating.

Test samples 2 and 3 were heating up similarly. They initially heated up rapidly, then proceeded to have limited temperature increase while the dehydration in the

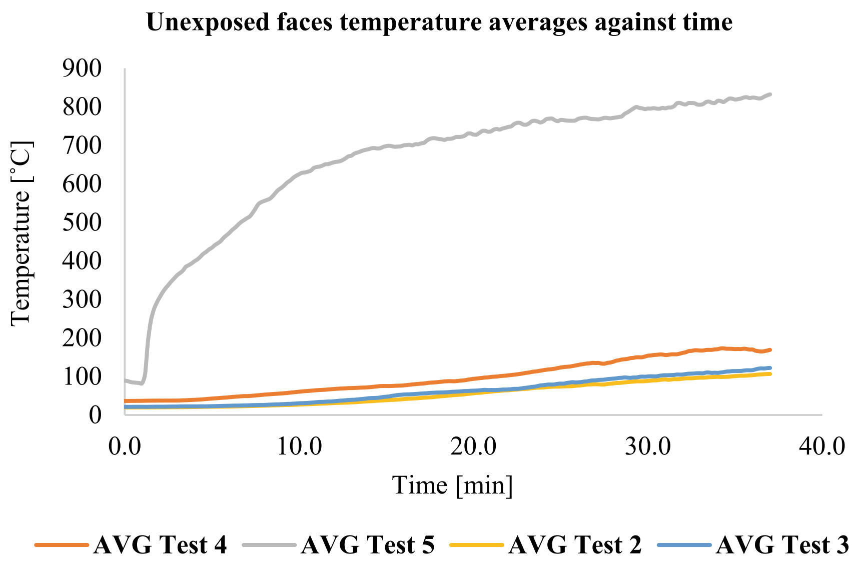


Fig. 10 Average unexposed face temperatures for each test sample. The test results are from the experiments

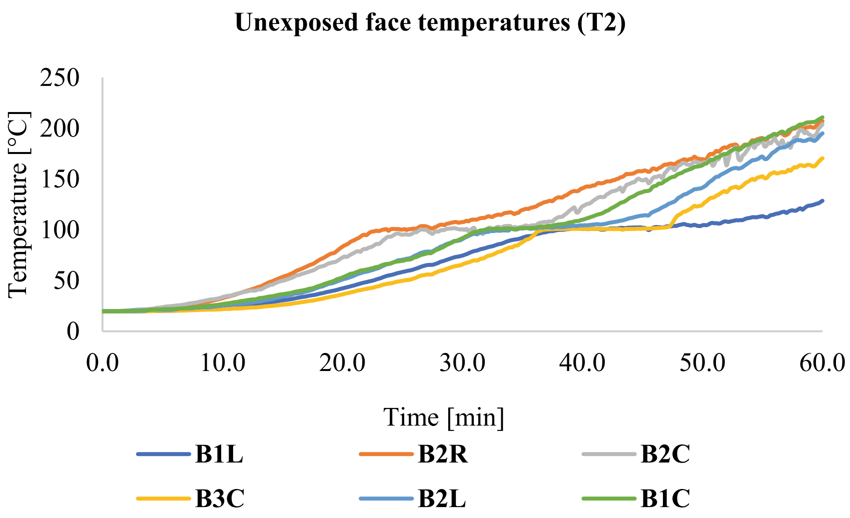


Fig. 11 Unexposed face temperatures at different TC locations for Test sample 2 from the experiments

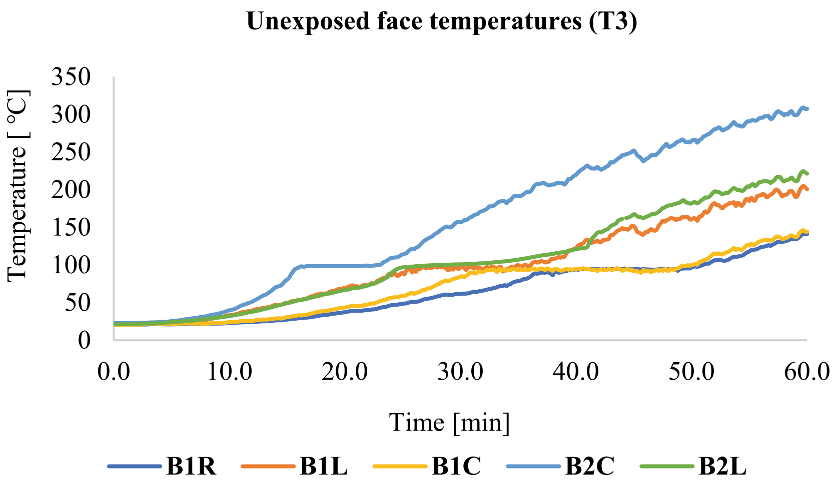


Fig. 12 Unexposed face temperatures at different TC locations for Test sample 3 for the experiments

boards occurred and then finally heated up linearly. Although some locations heated up more rapidly than others, they all followed the same trend. It is worth noting that both the test samples had two holes each, although the holes were not in the same locations. Test 3 also differs from Test 2 in that one of the holes was concealed with a piece of CaSi of the same thickness as the ceiling board (Fig. 15). Test 4 had three holes, one of which was bigger than the other two and covered in the same CaSi

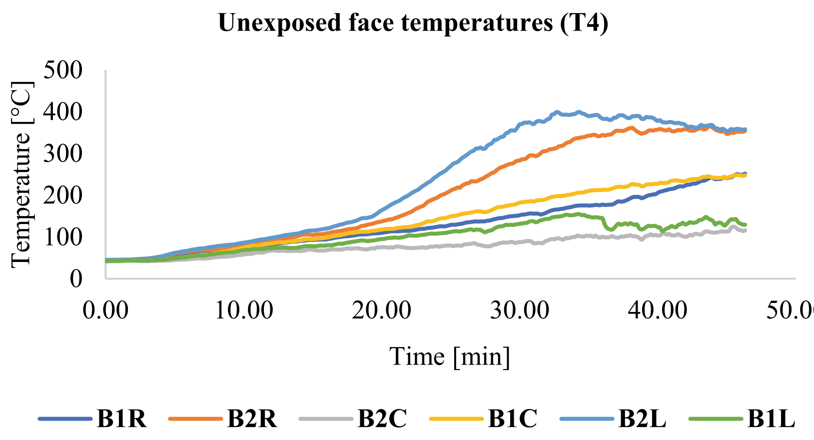


Fig. 13 Unexposed face temperatures at different TC locations for Test sample 4 from experiment

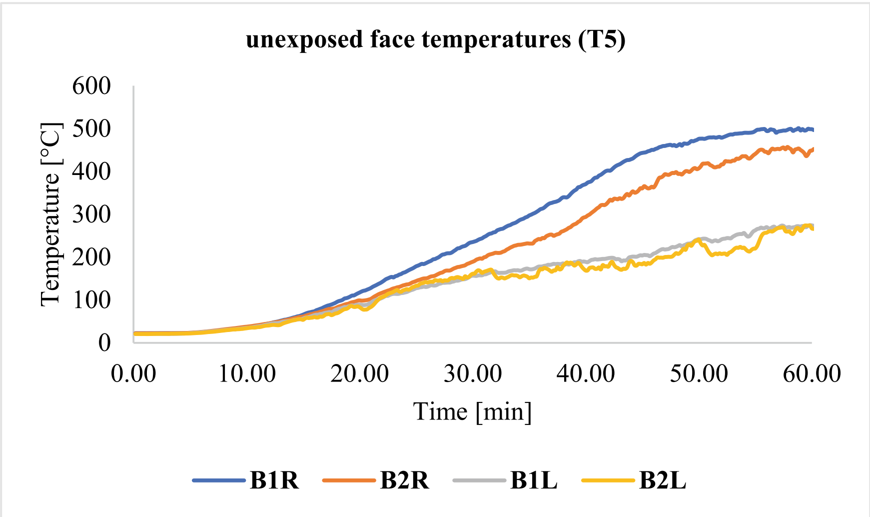


Fig. 14 Unexposed face temperatures at different TC locations for Test sample 5

board as the face on which it laid, as in Test sample 3 (Fig. 15). The heating pattern of this test was different from the first two. The heating was rapid initially, for some locations, but it started to drop and for others, it kept increasing linearly. For all the samples, the unexposed face gains a lot of heat at locations that are directly above the holes and are nearest to the burner, which results in failure more quickly. One hole each on test samples 3 and 4 was covered and the locations above these covered holes heated relatively slowly, highlighting the efficacy of any form of convective and radiative barrier.

Fig. 15 Test sample 3 with one hole covered

3 Modelling

Finite element analyses were developed for the test samples that were physically tested in this work. The models were developed in ABAQUS CAE 2020. The parameters that were used for these models were taken from the work of both Marx [5] and Classen [6] because this work is following up on the work that the two authors did already.

The parts were created as 3D solid homogeneous extruded parts, with the steel sheet as a 3D shell with a 1 mm thickness. The materials were assigned temperature-dependent thermal properties. Table 3 below lists the properties as used in the models, obtained from the work of Classen [6]. The created parts were assigned sections and assembled as dependent instances. The model steps were created for a total time of 2260 s which equates to approximately 37 min. An initial increment size of 0.1 was assigned on the step with a maximum of 10 for a total of 1000 increments. A maximum allowable temperature change of 10 was imposed. A mesh was created on parts as they were dependent and couldn't be meshed on assembly. The DC3D8 (linear hexahedral) and DS4 (linear quadrilateral) elements were created on the mesh with an element size of 0.02 m, making for a single element along the thickness of the boards. The thermocouples were represented by the individual sets that were created on partitioned parts. These thermocouple sets were created in the same positions they were located during the experiments, as in Fig. 16.

The interactions of the models were very important in obtaining comparable results between the experiments and the FEA. Ghojel [10] asserts that neglecting the presence of thermal contact conductance at the steel-concrete interface can lead to significant differences between computed and measured temperatures. The same contact conductance as the one presented by [11] was attributed to the steel-CaSi interface mainly because the system has no concrete, but the gap conductance still needs to be accounted for because, in reality, the gap is responsible for a temperature drop at the interface [12]. In this paper, CaSi was modelled as a concrete moulding,

Table 3 Resultant emissivity's for defined cavities. [6]

Material	Emissivity
CSB	0.8
FCB	0.9
VP 50 (Triangle Cavity)	0.42 at 20 °C 0.8 at 420 °C 0.8 at 800 °C
CBS(e)—VP Decking(r) (Large Cavity)	0.38 at 20 °C 0.67 at 420 °C 0.67 at 800 °C
VP Decking (e)—FCB(r) (small Cavity)	0.4 at 20 °C 0.73 at 420 °C 0.73 at 800 °C

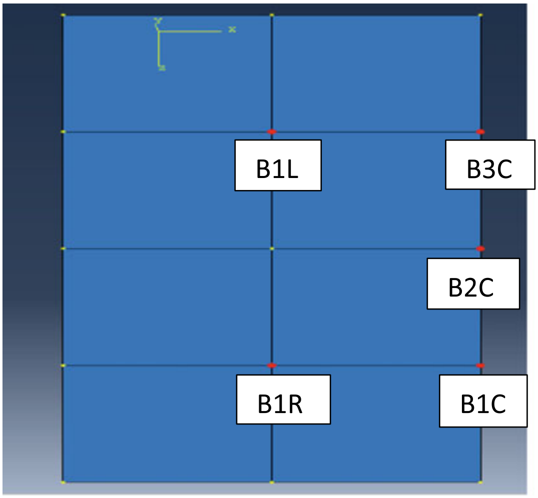


Fig. 16 The unexposed face of the half model with the thermocouple positions as set up in the FEA model. FEA model following Test sample 2. The TC labels are as defined in Sect. 2

that would traditionally be manufactured to withstand the effects of a fire. Radiation and convection are the modes responsible for the major heat transfer that takes place within voids. The voids or cavities (Fig. 17) within the ceiling structure have a notable effect on the rate of heat transfer Radiation had to be modelled within these cavities with the relevant emissivity values assigned to the right cavity, i.e., small cavities and big cavities. The geometries yielded better results when the emissivity values were entered as temperature-dependent parameters for the different-sized cavities (Table 3). The thermal properties are as stated in the Eurocode 1993-1-2 [13], while the material properties of the insulation materials were derived from the work of Classen [6] as in Table 4.

Figures 17 and 18 both show how the heat is transferred from the inside the furnace to the unexposed faces for all the test samples (with the colour red indicating the

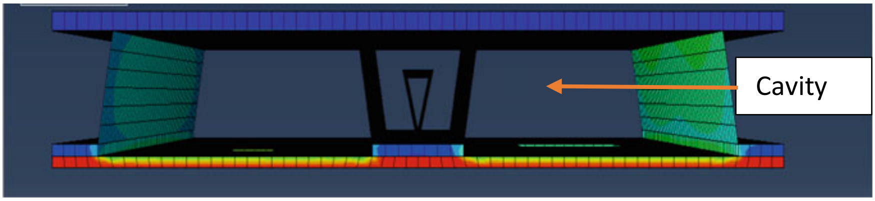


Fig. 17 Contour image of test 4 sample from ABAQUS

Table 4 Material properties of insulation materials in FE models [6]

Material name	Density (kg/m^3)	Conductivity (W/mK)	Specific heat (J/kg °C)	Emissivity
Calcium Silicate Board	943 at 0°C 943 at 100°C 818 at 120°C 818 at 800°C	0.236 at 0°C 0.236 at 20°C 0.330 at 89°C 0.323 at 179°C 0.307 at 272°C 0.162 at 367°C 0.339 at 470 °C 0.339 at 800 °C	1727 at 10 °C 1727 at 90 °C 24,000 at 100 °C 2600 at 110 °C 906 at 400 °C 906 at 800 °C	0.3
Fibre Cement Board	1250	0.25	2777 at 0 °C 2777 at 90 °C 37,000 at 100 °C 4500 at 110 °C 2500 at 400 °C 2500 at 800 °C	0.9

maximum temperature and the colour blue indicating the minimum temperatures). The nodal temperatures are shown on average.

The values of 10 W/m^{2}K and 25 W/m^{2}K were used for the outer and inner surfaces, respectively, for the convective coefficient. These are the values as suggested in the work of Claasen [6] and Marx [5]. Thermal conductance that is defined in the

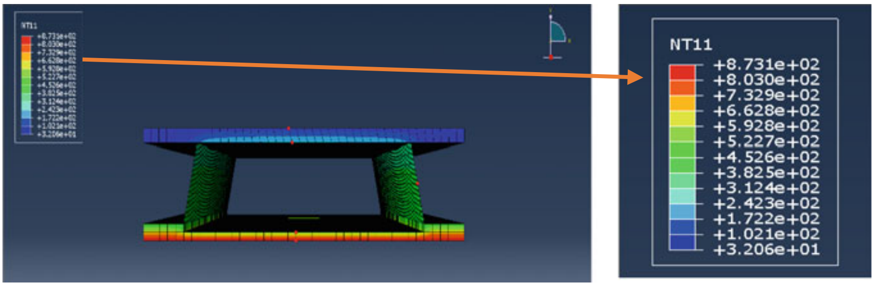


Fig. 18 Contour image of test sample 2 showing the heat distribution from the fore pit to the unexposed face

Table 5 The contact conductance of the steel-concrete interface [11]

Conductance [W/m^{2}K]	Clearance [m]	Temperature [°C]
160.122	0	20 °C
123.272	1e−06	100 °C
108.48	2e−06	200 °C
103.671	3e−06	300 °C
101.449	4e−06	400 °C
100.211	5e−06	500 °C
99.437	6e−06	600 °C
98.9151	7e−06	700 °C
98.5429	8e−06	800 °C
98.2662	9e−06	900 °C
98.0537	1e−05	1000 °C
97.8862	1.1e−05	1100 °C

interactions is important to ensure that there is a contact represented in the modelling. The values used for the thermal conductance were derived from the work of [11] who defined the conductance between steel and concrete as suggested by [10] shown in Table 5.

4 Comparison of Results

Results were obtained from the FEA simulations and compared to experimental data below. The most important result in this paper was the temperatures on the FCB unexposed face, therefore, a thorough comparison was simulated between the two sets of results. For the two models, namely, the one with two holes (where only one half was simulated) and the one with three holes, FEA seems to either over- or underestimate the temperatures (Fig. 19 and 20). The reasons for these phenomena may differ and may exist only for the samples as peculiar as those examined in this paper. As alluded to in Sect. 2, the samples tested in this work all had holes, at different locations, and this means that the samples experienced or were exposed to external influences at different rates. There may have been an unexpected wind during one of the experiments, something that could never be accounted for in an FEA simulation. The above also explains the lower gradient lines that represent the FEA thermocouples whereas the experimental lines had steeper gradients.

Both the FEA and the experimental graphs have similar trends. The temperatures increased in a comparable manner for each of the tests. In Fig. 19, for the experimental results, there is a region within which the temperatures are constant due to the dehydration of the boards. Within this region of constant temperature, there may have been a large amount of heat transferred into and distributed through the flute (or the cavity) areas before any significant amount of heat reached the outer surface of the

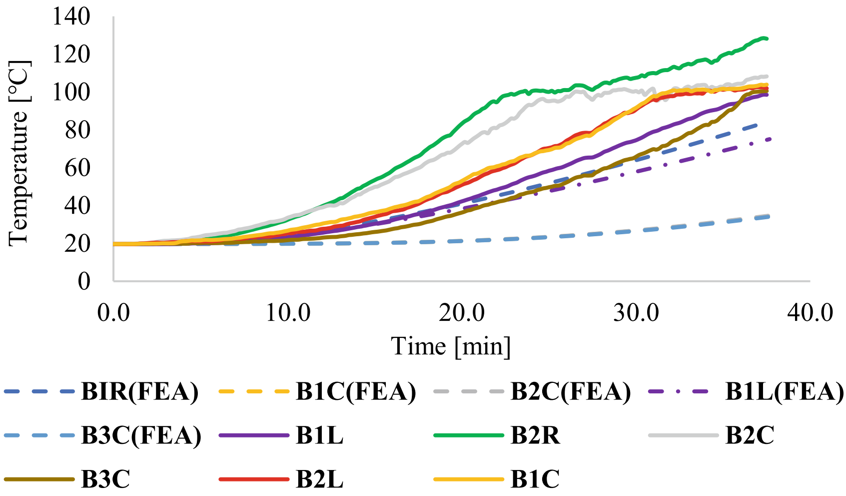


Fig. 19 A comparison of the unexposed side temperatures between the FEA and the experimental results for Test sample 2

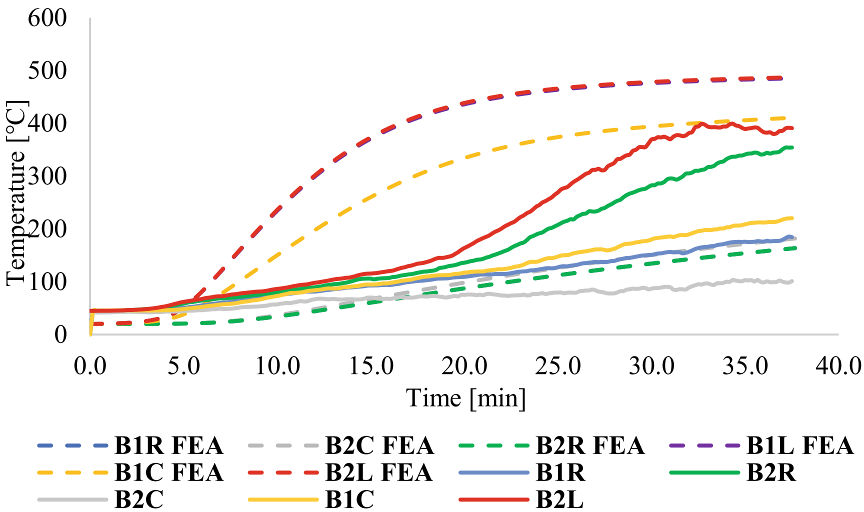


Fig. 20 A comparison of the unexposed side temperatures between the FEA and the experimental results for Test sample 4

FCB. As mentioned in Sect. 2 above, the samples were prefabricated to a bigger size than what the furnace has room for and they had to be downsized, a process during which some of the samples, namely, samples 3 (Fig. 15) and 4 were compromised with pre-testing damage that had some influence on the obtained results.

Table 6 Compared values of the unexposed temperatures between the FEA and the experimental results, for 30-min rating

Test samples	FEA unexposed (FCB) temperatures (˚C)	Experimental FCB unexposed temperatures (˚C)
2 holes (open)	24.9	44.9
3 holes	137.6	105.9

Table 6 is showing the average temperatures on the unexposed surfaces (FCB) of the two samples of the three that were tested. In the above table, what is clear is that both the samples passed for a 30-min rating for insulation and integration. Structural stability is not considered because it is not in the scope of the current paper.

5 Conclusion

This paper has focused on whether FEA can simulate the experimental results, based on the given parameters of the thermal property values for a composite flooring system exposed to fire. There are differences between the two sets of results for all the tested samples, and these differences can be attributed to the fact that the FEA is simulated under perfect conditions which do not exist in the real environment. What is evident from the FEA results is:

- It is crucial to account for the contact conductance in the model.
- It is important to input the thermal properties of the materials, especially the known ones, as temperature-dependant values.
- The cavities within the models play a crucial role in the overall heat transfer through the system, and failure to include cavity radiation in the model could mean the difference between results that are a true reflection of the real environment and results that do not reflect this reality at all.

The holes on the exposed face of the system will lead to different behaviour or response of the systems to fire. The different sized holes and different hole locations mean different fire distribution through different system samples. Further study is required to capture and model the ingress of hot gases through penetrations in ceiling systems.

The more holes there are in a ceiling system, the more rapid the sample fails. It was also evident that the more holes there are in close proximity to each other and/or to the heat source, the more rapid the failure.

All the samples were satisfactory for a 30-min rating against integrity and insulation. Even with the FEA results, although there are considerable differences (in percentage) between the FEA and the experimental results.

On average, the temperatures on the unexposed surfaces (FCB) have differences that range between 29% (test sample 4) and 44% (test sample 2), and although the differences are in comparison slightly bigger for the single locations, the insulation and integrity criteria are still satisfied.

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Built Environment Monitoring, Control, Analysis and Design

Residential Envelope Energy Efficient Design Exploration Preparing for Generative Design

Rita Elias and Raja R. A. Issa

Abstract The design of detached houses involves multiple choices to meet many criteria, such as energy performance, and zoning regulations. Many design factors, including the form of the house, often come into play making the design process more complicated and time-consuming. The number of designs and simulations performed is usually limited due to time and cost constraints. This study aims at proposing a Generative Design (GD) framework to automate the design process of detached houses, and simultaneously optimize many design aspects. Numerous design parameters mainly relating to the house geometry and its energy efficiency were included in the GD study. The GD framework was developed in Dynamo, an Autodesk Revit internal generative design tool that uses the Non-Dominated Sorting Genetic Algorithm (NSGA-II). The floorplan boundary lines having variable dimensions were first created in Dynamo to serve as a reference for walls, floors, roof, and other geometric components. Several Dynamo nodes such as "Walls.ByCurveAndLevel", "Floor.ByOutlineTypeAndLevel, "Roof.ByOutlineTypeAndLevel", and "FamilyInstance.ByFace" were utilized to generate houses with variable walls, floors, roof, windows, and doors, respectively. Afterward, the Dynamo graph was ready to be exported to create and run the GD study and generate different feasible design solutions. Preliminary results included a fully automated design of a single-family house envelope. The designer can run the GD study to generate, compare, and explore different design options, examining the geometry and analysis results to select a final design solution. The findings of this study will maximize the productivity of designers/developers and will tremendously reduce the financial strain and time consumed designing energy-efficient single-family houses using traditional techniques.

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1 Introduction

The design of single-family houses entails multiple decisions to satisfy many requirements, such as energy performance, and zoning regulations. Several design factors such as the house architecture often come into play making the design process more complicated and time-consuming. Traditional energy modeling and simulation techniques require a detailed three-dimensional model, or a set of features describing the building, restricting the designer from changing some building's aspects later to try to improve its energy efficiency. In this case, the designer would have to manually adjust the three-dimensional model or the features' set every time a change is desired. The designer ends up evaluating up to four alternatives given the lengthy time energy analysis and simulations require.

Automating the design process through the application of genetic algorithms can expedite the design process and can optimize many aspects of the design at the same time. Genetic algorithms also help designers gain more insight into design options by analyzing the relationships between inputs and outputs while enhancing the solutions' performance. Designers can then make more informed decisions in a timely manner by leveraging the lessons learned from each generative design study. Repetitive work can be automated through Generative Design (GD).

To develop a computational design, the designer defines a set of instructions, rules, and relationships that accurately determine the steps required to attain a proposed design along with its resulting data and geometry. These steps should be computable or understandable by a computer, so that it can perform and execute the needed calculations. A computational design requires the designer to develop the process that creates the design and not the design itself. The computer iterates through options and data to come up with the design. This allows the designer to concentrate on the creativity of the design saving money, time, and work.

GD is a particular application of the computational design approach, with certain differences. In GD, the designer defines goals to attain a design, instead of writing a detailed programming code for the exact steps as in the case of computational design approaches. Moreover, in GD, the computer automatically executes many design iterations helping the designer to explore the design space and generate multiple design alternatives, instead of just one (compared to the computational design approach). Furthermore, in GD, many design goals, even competing ones, can be satisfied in multiple design solutions generated which are compared, ranked, and evaluated. Generative Design is a framework that combines both human innovation and digital computation to generate better outcomes than possible ones provided by traditional methods. It involves setting quantifiable goals and creating geometric systems based on specific rules and constraints. Generative design changes the way Architecture, Engineering, Construction, and Operations (AECO) companies conceptualize, design, and build. It expands the human's ability by applying genetic algorithms to identify design goals, explore options, and automate the design concept. The designer still needs to identify the design parameters but can generate several design solutions at the same time.

This study aimed at developing a Generative Design framework that automates the design process of single-family houses and serves as the basis for other design optimization purposes. Several design parameters mainly relating to the house geometry and its energy performance were involved in the GD study. The sections of this paper are arranged as follows. First, the most relevant literature about Generative Design and its applications is presented. Secondly, the development of the Generative Design framework is discussed in the methodology section. In the Results and Discussion section, the automated design's implications and the constructability of the design solution were discussed while highlighting some recommendations to consider while developing a generative design framework. Lastly, conclusions and future research work are presented.

2 Literature Review

2.1 Fundamentals of Genetic Algorithms

First proposed by Holland in 1975 [9], Genetic Algorithms (GAs) automate the optimal solution searching process starting off with random samples and then directing the search process using evaluation functions and stochastic operators. GAs were inspired by Charles Darwin's theory of natural selection and turned into computational algorithms that explore the "chromosomes" space and preserve the best ones. In the biological world, a chromosome is a DNA molecule that consists of the binary coding bits "alleles". A chromosome is a binary string that encodes the parameters of interest corresponding to a specific individual. The general workflow of GAs begins with randomly generating an initial population of individuals, which is considered the parent population of the first generation. Afterward, individuals are evaluated based on a fitness criterion that identifies the end of the GA once a solution meets the set requirements.

The GA uses the evolutionary approach and genetic operators such as selection, crossover, and mutation to generate new populations. Two individuals of the first generation are selected as the parents, so their chromosomes crossover (prophase I of meiosis) to generate the new children population. Then, the structure of the gene or chromosome for the children population changes by mutation generating a new random DNA that can be better than previous DNAs. Individuals of the children population are assessed again and ranked all together with the individuals of the parent population based on the fitness criterion. This ranking process is known as "elitism" and preserves the formerly found good individuals or solutions. The best performing solutions constitute the individuals for the next generation, as the probability of a specific solution being chosen for selection and reproduction is proportional to its fitness. This cycle repeats for the number of generations specified by the user [3].

The genetic model developed by Holland (1975) was altered by many other researchers. Although all GAs are based on the same concept, they essentially differ in the method employed to rank and select the solutions. Elitist GAs are more effective in preserving good solutions compared to non-Elitist GAs such as Niched Pareto GA (NPGA) developed by Horn et al. in 1994, multi-objective genetic algorithm (MOGA) developed by Fonseca and Fleming (1993), and Vector Evaluated Genetic Algorithm (VEGA) developed by Schaffer in 1985 [8, 13]. Such non-Elitist GAs hardly succeed in generating a diverse solution set and slowly converge to the Pareto frontier solution.

Many Elitist GAs exist including Strength Pareto Evolutionary Algorithm (SPEA) developed by Zitzler and Thiele (1999), Pareto Archived Evolution Strategy (PAES) developed by Knowles and Corne (1999), and Non-dominated Sorting GA (NSGA) developed by Srinivas and Deb (1994) [10]. NSGA-II is the most common GA given its advantages over other genetic algorithms such as the diversification of the obtained solutions [7]. Also, NSGA-II is the algorithm used by Generative Design in Revit [14].

NSGA-II was introduced in 2000 to include elitism deploying non-dominated sorting and computing the crowded distances to find the Pareto optimal solutions [6]. Pareto optimal solutions or Pareto efficient solutions are feasible solutions where no further improvements can be made. The workflow of NSGA-II is similar to other GAs in the populations' generation. Individuals of both the offspring and the parent populations are evaluated based on their performance on defined target indicators and sorted based on non-domination rank. Solutions in Non-Dominated Front 1, also called Pareto optimal solutions, are ranked as number 1, and have the highest fitness, therefore, they are preferred over other solutions (Fig. 1). This Front 1 set consists of "non-dominated" solutions as these solutions cannot dominate each other taking into consideration the target indicators. Yet, these solutions dominate other solutions located on Fronts 2, 3, and so forth. Each Front consists of a non-dominant set of solutions that do not dominate each other but dominate other solutions located on Fronts with a lower ranking.

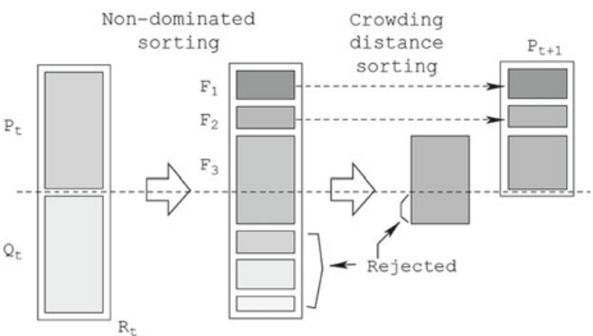

Fig. 1 NSGA-II workflow. (Adapted from [7])

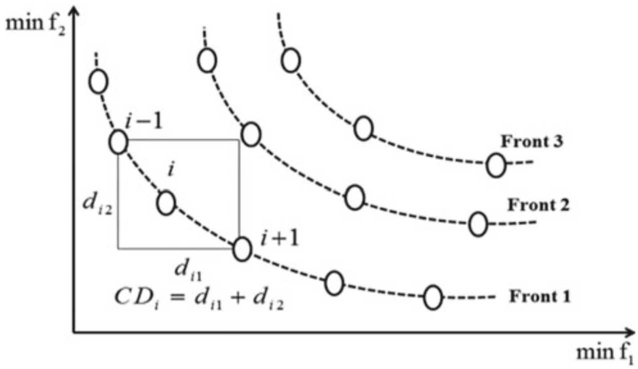

Fig. 2 Crowding distance. (Adapted from Kumar and Yadav [11])

In addition to fitness evaluation, solutions are assessed based on the crowding distance. The crowding distance of a specific solution estimates the density of neighbor solutions. It is therefore the average distance to the two solutions surrounding it (Fig. 2). NSGA-II diversifies the solution space by avoiding convergence to local minima and selecting solutions with a large crowding distance. In other words, when two solutions have the same non-domination rank (i.e., located on the same front), the one located in a less crowded region is preferred over the other. The individuals or solutions located on the boundaries of a front have an infinite crowding distance, and therefore are selected.

Parents are then selected based on both the non-dominated rank and crowding distance, which in turn reproduce and generate the offspring population by crossover and mutation. The non-dominated sorting is performed again on both the parent and offspring populations and only the best N individuals are selected based on the population size or the number of solutions desired [7].

2.2 Generative Design and Automation Procedures for Energy Analysis

The framework of any GD study involves three main steps: Generation, Evaluation, and Evolution. In the first step, many design solutions are generated based on defined design parameters using algorithms specified by the designer. Then, these design solutions are evaluated using quantifiable goals. The evaluation step can be broken down into two processes: Analysis and Ranking. The analysis involves measuring and analyzing the designs generated based on specific goals and functions specified by the designer. Then, these options are ranked and ordered accordingly. The resulted rankings and outcomes indicate the direction towards which the design develops and evolves through computation. Afterward, the designer compares and explores the generated design options, examining the geometry and analysis results. After selecting a design option, the designer integrates it into the project. Therefore, GD provides engineers and designers with better insight to make quicker and more educated decisions.

GD studies can be applied for different purposes. They can help designers in the management and design of buildings and cities while simultaneously optimizing several functions. They can also assist in controlling design trade-offs considering real data, and in arranging conversations about project goals and design features among the different stakeholders involved in the project. Moreover, they allow the designers to better assess the project conditions given the offered transparency of design assumptions [19].

In this section, the applications of GAs and automation procedures related to energy-efficient buildings' design are comprehensively reviewed. [16] investigated the use of Dynamo in Revit and Project Refinery for multi-objective optimization of energy-efficient buildings. Although genetic algorithms can be very useful in the design of energy-efficient buildings, [16] found that the designer needs to be knowledgeable and fluent in Python coding to solve errors related to incompatible software versions, otherwise the workflow would not run entirely. [12] developed a Building Information Modeling (BIM)-based performance optimization framework that specifically aimed at improving the energy performance of a residential building and maximizing the daylight while exploring different design options. Their framework automatically created from the Autodesk Revit model the input file containing the data required for cloud-based energy simulations. A parametric BIM model was then created using Dynamo to make some variable changes that resulted in updated corresponding energy models. Then, the simulation results were fed into the optimization process using Optimo which uses the Non-dominated Sorting Genetic Algorithm II (NSGA-II) to change the BIM model and find the solution domain. At this stage, the energy models were regenerated and sent again to the performance simulation engine Green Building Studio (GBS) as the interaction between Revit and GBS was enabled using Revit-API and GBS-API. However, Optimo's interoperability with Green Building Studio has been discontinued [16]. Also, their framework had limitations as it was not able to perform the parametric changes automatically resulting in a time-consuming optimization process that lasted more than 55 h.

[1] developed a Generative Design by scripting a MATLAB code to improve zone level HVAC systems and enhance their energy efficiency. They considered many base parameters for a given floor plan such as type, size, and location of return grills and diffusers, supply, return, and exhaust ductwork, size and location of equipment, and other parameters, to generate multiple thermal zoning schemes. Design solutions were evaluated based on a multi-objective method employing building performance simulation (BPS) and a life-cycle cost (LCC) analysis. The required information for thermal zoning which involved determining the room type, room load requirements, room adjacency, and room orientation, were manually extracted from the building information model (BIM). The MATLAB code also successfully incorporated peak cooling and heating loads, and the corresponding VAV size for each zone into the GD approach. [2] established a generative system based on a genetic algorithm and the DOE-2.1E building simulation software, to create multiple building facade solutions while reducing the annual energy consumption. GENE_ARCH, a Generative Design software based on evolution, helped architects to improve the energy-efficient and sustainability of architectural solutions [4]. The energies spent for heating, cooling,

ventilation, and lighting, in addition to the embodied energy for construction materials and greenhouse gas emissions were evaluated. To validate their study, they used the Faculty of Architecture of the University of Porto given its clear and complex elevation composition rules emphasizing the flexibility of the GD as it incorporates constraints that affect some architectural design goals [2, 4].

[20] developed a parametric generative algorithm that automatically generated design schemes of typical Chinese urban dwellings and evaluated their energy performance using Ladybug and Honeybee, which are environmental analysis plugins for Grasshopper for Rhino, along with Python. Their framework started with the spatial form features extraction of dwelling database that consisted of 300 Chinese design schemes such as the location and shape of doors and windows, and the windows' orientation. Then, different design schemes having various orientations, rooms' functions and arrangements, room sizes, and circulation information were automatically generated. Other parameters related to the building envelope such as walls and windows' heat transfer coefficients were fixed throughout the generative design. Afterward, the generated schemes were evaluated based on the total energy consumption.

[17] used a genetic algorithm in Grasshopper to perform a parametric-based optimization for a five-story residential building optimizing daylighting (Spatial daylighting illumination SDA300/50%) and energy performance (Energy Use Intensity EUI). Multiple design options were generated with various building parameters such as construction material, shading device configurations, and glass material representing the parametric model. Afterward, the design options were assessed based on building simulation executed by Ladybug and Honeybee plugins. The optimization process was performed using the Octopus plugin. Pareto optimal solutions were found among around 300 solutions produced in six generations. [18] developed a simulation-optimization tool based on a genetic algorithm coupled with DOE-2, a building energy simulation engine to optimize residential building shape and envelope in terms of building's energy use. They focused on investigating the effect of different building shapes on energy use and chose the Building America Research Benchmark model as a case study. They found that rectangular and trapezoidal-shaped buildings outperformed other building shapes in terms of life-cycle cost. Furthermore, envelope features were considered in the optimization process including foundation types, wall and roof constructions, insulation materials, and window types and areas. [5] proved that integrating cooling systems into the multi-objective optimization of form and envelope in the early design stages is very beneficial in terms of minimizing the cooling energy consumption and having a good daylighting performance.

Therefore, most of the GD frameworks developed by other researchers were limited as they were unable to automatically perform the parametric changes resulting in an extensive and time-consuming energy optimization procedure. Moreover, important building features needed for optimization were in most cases manually extracted from the building information model (BIM). Additionally, most of the developed optimization procedures, if not all of them, were based on genetic algorithms and coupled with building energy simulation engines limiting the design optimization procedure due to time and cost constraints. Hence, no research intended to explore multiple design options for single-family houses using generative design were accessible.

This study filled these research gaps by developing a Generative Design framework within a visual programming environment Dynamo coupled with a genetic-algorithm-based optimization to help professionals in AECO companies in the design of detached houses. Dynamo automatically extracted building features and parameters needed for energy analysis purposes. The GD study will boost the designers' productivity, and tremendously reduce the time needed to do the same work applying traditional methods.

3 Methodology

The GD framework that generates different house design alternatives and evaluates them according to set fitness criteria was developed within a visual programming environment Dynamo and Generative Design which is an Autodesk Revit add-on that allows designers to explore, evaluate and enhance their designs. Dynamo is equally accessible to both non-programmers and programmers. It allows users to visually script behavior and define the logic by connecting nodes through wires to process information from the inputs all the way to the outputs which can be either numerical values or geometries. Dynamo creates robust Building Information Models (BIM) using a whole collection of nodes particularly designed for Revit and others from third-party AECO libraries. As for Generative design in Revit, its main advantage is that it handles all the back-end work of design options' generation, iteration, and optimization. Moreover, Generative Design for Revit facilitates generative design workflows using already created scripts, directly from the Revit interface, especially for not Dynamo-savvy users.

As previously mentioned, the main three steps involved in GD are: Generate, Evaluate, and Optimize. Therefore, a parametric model was first generated to explore the entire solution space using Dynamo. The parametric system was conceptualized using a set of rules and constraints to prepare for the last step which is optimization. Therefore, the Dynamo graph was produced to allow for many iterations to happen adjusting the values of specific parameters and creating numerous design options.

The purpose of the generative design framework in this study was to build houses with specific geometries focusing on the envelope of the house rather than the interior design. The envelope consisted of (1) the slab on grade (the floor), (2) walls, (3) windows and entry door, and (4) the roof.

3.1 Floor

To generate detached houses with variable dimensions, their boundary lines were first created using the Dynamo nodes "Rectangle.ByWidthLength" and "NumberSlider" to create a rectangular floorplan with variable Width and Length (Fig. 3). Two number sliders with values ranging between 40 and 53 feet were used, each connected to the input ports "width" and "length" of the "Rectangle.ByWidthLength" node with a step of 6 inches (step being the interval between two sequential values). These ranges were retrieved from data available online about the typical square footage of a detached house in the United States [15]. The width and length parameters were specified to be among the inputs needed for the GD study. A poly curve was then created out of the rectangle using the “PolyCurve.Curves” node serving as the outline for subsequent building components such as the floor and walls. It was also essential to reverse the curve’s direction using the “Curve.Reverse” node to properly orient the floors and walls.

Following the polycurve’s outline, the slab-on-grade was generated using the “Floor.ByOutlineTypeAndLevel” node. The floor level was set to Level 1, as there were only two defined levels within the Revit project, with Level 2 being the roof. As for the type selection, a list of different floor types was created using “Element.Type”, “Floor Type”, and “All Elements of Type” nodes. Afterward, a family type was called using the “List.GetItemAtIndex” node and a number slider reflecting the indices of the floor types available in the list. This number slider for the floor types was set to be one of the variable inputs of the generative design framework (Fig. 3). The number slider had a minimum value of 0 and a maximum value that equals the number of elements (n) in the list minus one, as shown in Eq. (1):

$$maximum\ value\ for\ number\ slider = n - 1 \tag{1}$$

The number slider’s step was 1. Each of the possible floor types corresponded to a number on the number slider, allowing for the possibility of different floor types for the GD study.

The floor area was one of the outputs of the GD study given its effect on the energy performance of the house. It was determined based on the generated floor, using a “String” node referring to “Area” that fed into an “Element.GetParameterValueByName” node.

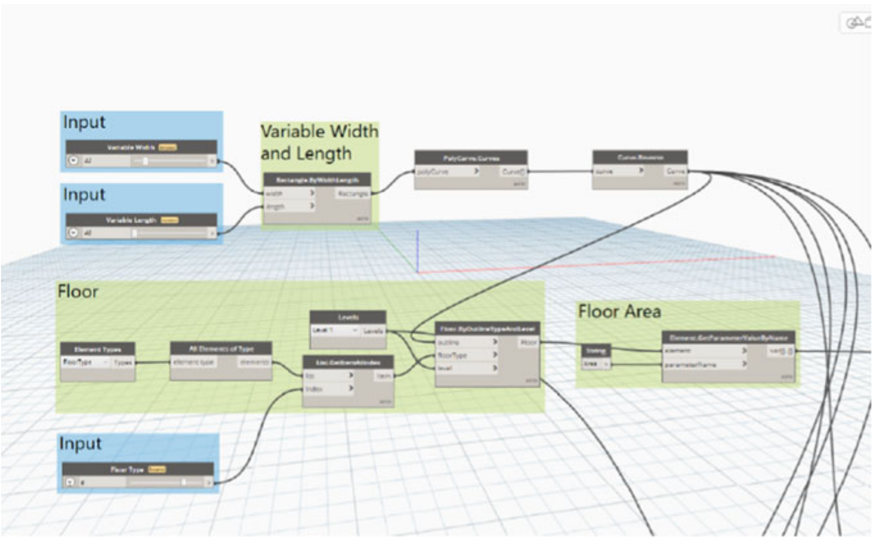

Fig. 3 Floor Generation

3.2 Walls

Walls were built using the Dynamo node "Walls.ByCurveAndLevel" with the start level set to the ground level, and the end level set to the roof level. The curve for this node was the variable house footprint generated in the previous step using the Dynamo node "Rectangle.ByWidthLength". The curve of the rectangular footprint was reversed previously to avoid any flipped direction of the wall interior and exterior finishes. An offset equating to half of the walls' thickness, was also applied to the curve to align the walls with the house floor. Without this alignment, the edge of the floors aligned with the interior edge of the walls, rather than the exterior edge. As for the wall type, a list of family types having different thermal properties was created by compiling all possible exterior wall types (Fig. 4). A number slider node was used to make the selection of wall types variable, where each step on the number slider represents the index of the family type in the list created. Therefore, the number slider for wall types was specified to be a variable input for the generative design framework.

The total area of walls was set as an output of the GD study and was generated using multiple "Element.GetParameterValueByName" nodes along with a "String" node referring to "Area" feeding into them. "Code Block" nodes along with a "List.GetItemAtIndex" node were used, to sum up the walls' areas and get the walls' total area through a "Watch" node (Fig. 5).

3.3 Windows and Entry Door

This study sought to generate two windows on each of the four sides of the house. To do so, the first step involved creating a list of all potential window types. A

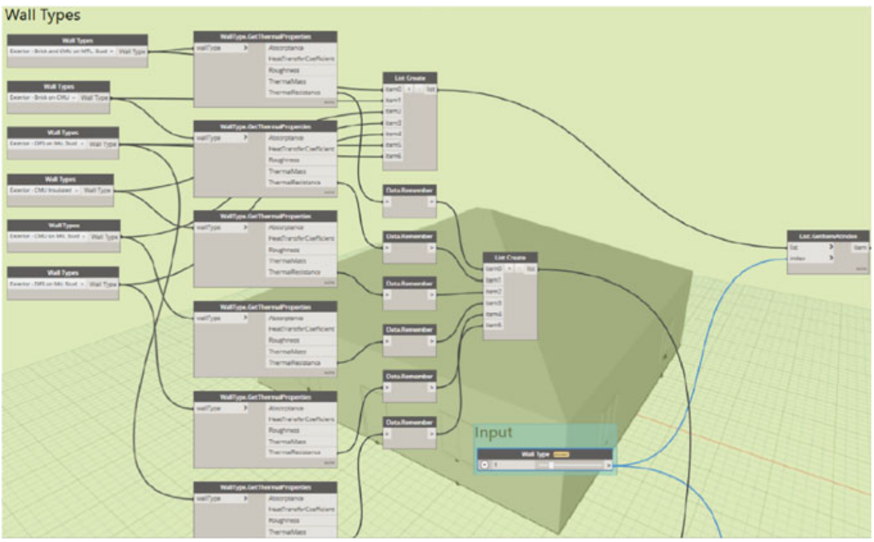

Fig. 4 Walls' Generation

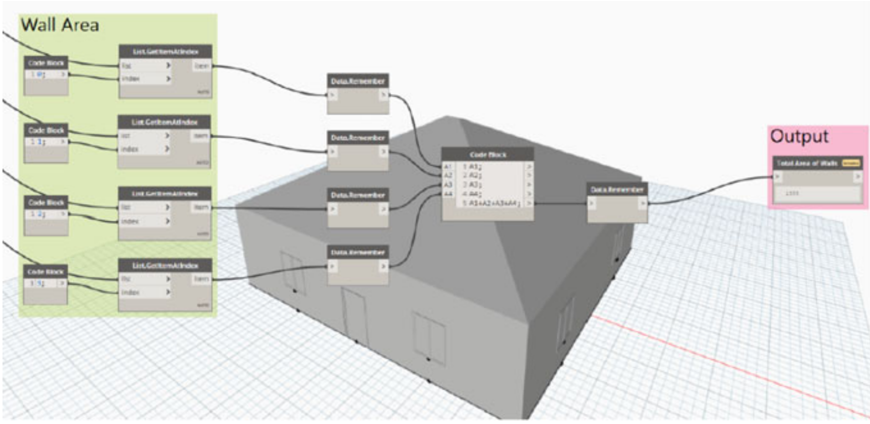

Fig. 5 Walls' Area Retrieved from Dynamo

"List.GetItemAtIndex" node was used along with a number slider to introduce variability for the window family type while running the GD study. The corresponding number slider was specified as a variable input. To install the windows, "points" were placed at the quarter and three-quarters spots along each of the four walls using "Curve.PointAtParameter," "Point," and "Number" nodes. A code block was used to offset the points generated along the curve by a sill height of 3 feet in the z-direction. Following the points' locations, the windows were installed using "Wall.InsertDoorOrWindow" nodes along with Level 1.

Regarding the entry door, this study did not seek to make its type a variable. However, the door could be placed at the center of any of the four exterior walls of the house using a "Curve.PointAtParameter" node, with the parameter set to 0.5 along with a number slider and a "List.GetItemAtIndex" nodes. The selected family type for the door was "Single-Flush" and the level was set to 1 (Fig. 6).

Fig. 6 Entry Door Generation

The Glass to Floor Area was set to be an output of the GD study and was calculated in a Code Block to find the ratio between Glass and Floor Area. All windows were selected through a "Categories" node that fed into an "All Elements of Category" node to calculate their corresponding area using an "Element.GetParameterValueByName" node and a "String" node set to "Area".

3.4 Roof

The roof was generated in a similar fashion to that of the floors, though it was slightly more complicated due to the added variability of the roof's slope. The roof type needed to be automatically selected by the GD study. To allow for this automatic selection, a list of roof types was created, and a number slider was used to refer to the index of every roof type available. Accordingly, the number slider referring to the roof type was one of the inputs of the GD study (Fig. 7). Possible roof slopes were defined and put into a list using a "Code Block" and a "List.Create" nodes. The number slider connected to the list of possible slopes was also set as an input of the GD study to make the roof slope variable. The level of the roof was set to level 2. The roof was generated following the variable rectangular house floorplan and using a "FootPrintRoof.ByEdgesAndSlopes" node. The roof area (also set as an output of the GD study) was found using a "String" node (set to "Area") that fed into an "Element.GetParameterValueByName" node. The roof's thermal resistance was retrieved from the roof type using a "RoofType.GetThermalProperties" node and was decided to be one of the GD study outputs.

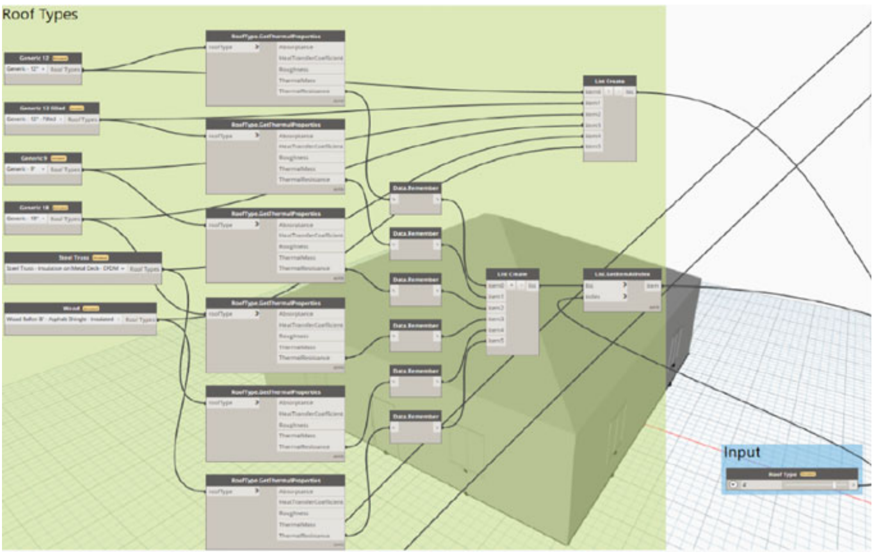

Fig. 7 Roof Types

Therefore, a Dynamo script was developed to extract the building parameters mainly needed for the energy performance evaluation step. The parametric model consisted of many environmental independent variables including Conditioned Floor Area, Glass to Floor Area, Roof Area, Total Area of Walls, and thermal properties of Windows, Walls, and Roof. Input and output nodes in the Dynamo graph were defined to prepare for Generative Design. Input nodes included all the "Number Sliders" that listed the possible floor types, window types, etc., and were highlighted in blue in Figs. 3, 4, 5 and 7. Outputs, mainly relating to the house energy efficiency, included the final calculation or result for each of the node groups, such as the floor area or roof area and were highlighted in pink within the images of the Dynamo graph in Figs. 3, 4, 5 and 7. The Dynamo script developed in this study can be adjusted accordingly to include the numerical outputs needed to meet specific design goals. The Dynamo graph can then be exported to Generative Design to generate multiple design solutions using an optimization engine, such as NSGA-II, that indicates the direction towards which the design develops and evolves through computation based on specific goals. The design options can then be evaluated based on the outputs specified by the designer.

4 Results and Discussion

This section will not only discuss the implications of the automated design and the constructability of the design solution but will also provide the new generative design users with some recommendations to consider while developing the Dynamo graph for generative design.

Preliminary results included a fully automated design of a detached envelope as well as a Dynamo graph that can be exported into Generative Design to analyze the various choices that go into the design of this house envelope. This study sought to completely automate the design process of a single-family house envelope through the use of Dynamo without any initial setup within Autodesk Revit or any other software. Unlike previous studies found in the literature review, the Dynamo nodes within this study establish all the house design features without relying upon pre-designed walls, floors, or other guidelines. This process decreases the dependency of the study on Revit itself and exemplifies the concept that Dynamo can design a 3D model without any preexisting elements. The house envelope generated by the Dynamo file (also shown in Fig. 8 and 9) was considered constructible because each of the building components aligned and coordinated well with each other, e.g., the walls aligned with the floors regardless of the floorplan's dimensions. Additionally, the materials, dimensions, and other qualities of the house envelope were carefully chosen for the house design to be considered constructible. For example, only solid (non-glazed) walls were used for the exterior walls of the home. Moreover, the range of possible dimensions/slopes of the house components was based on real data found online regarding the typical size of a single-family house in the United States. Also, windows and doors appropriately cut through the walls creating the needed wall openings, indicating the constructability of the house envelope. This research was able to automate the design of a single-family house envelope in preparation for use in

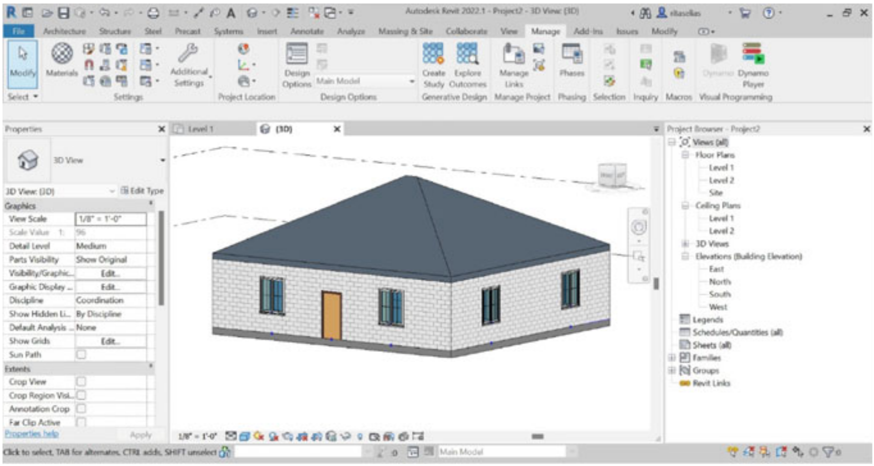

Fig. 8 Potential House Envelope from Generative Design (3D View)

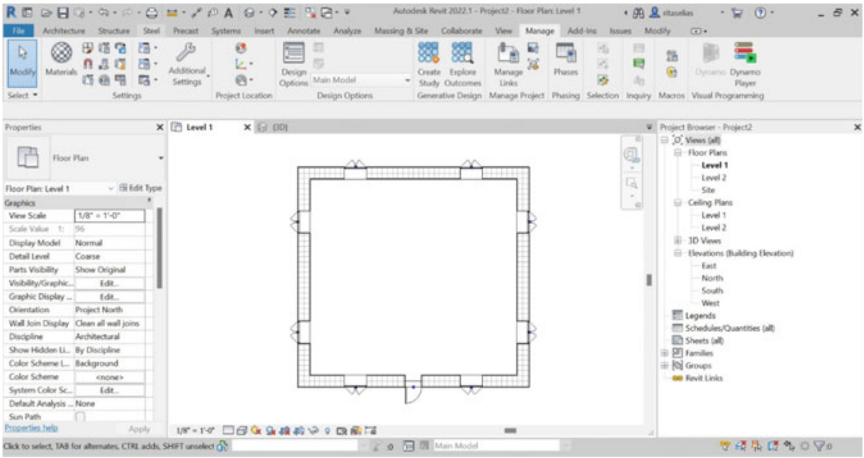

Fig. 9 Potential House Envelope from Generative Design (Floorplan)

Generative Design, as it did not export the Dynamo file into Generative Design. Yet, the developed Dynamo graph can be adjusted to meet specific design goals allowing for many iterations to happen and creating numerous design options. Generative Design could consider dozens, if not hundreds, of design solutions while optimizing important factors relating to the design and performance of the house.

The designer should consider many factors while developing a Dynamo script for Generative Design, otherwise, it would be impossible to export and run the GD study due to a few issues with the Dynamo nodes and their connections. Different types of errors can arise when trying to export a Dynamo graph into generative design, including a lack of inputs/outputs, duplication of nodes, missing nodes, dependency of the Dynamo script on a Revit file, etc. Errors can most of the time be easily fixed by adding "Data.Remember" nodes to cache data within the Dynamo file. These nodes essentially store the data in a more manageable way for the software to retrieve later throughout the process. For instance, a "Data.Remember" node was added after the "WallType.GetThermalProperties" node in order to cache the data before being fed into an output. This method also eliminates the Revit dependency issue. Moreover, a Dynamo script that is dependent on a Revit file, i.e. some Dynamo nodes directly take information from the Revit file, cannot be exported into generative design. To avoid this issue, the user should not place any Revit-dependent nodes between the Input and Output nodes of the study. Such issues should be thought of from the beginning of the work, otherwise, the user may lose all of the progress made on any design process and may have to rethink all the logic behind it. For example, instead of using an "Element.Type" node to get a list of possible wall types from Revit, the user better lists each possible wall type individually to then compile all the options into a list.

5 Conclusions and Future Research

This research developed a Generative Design (GD) framework using Dynamo (an Autodesk Revit plugin) to automate the design process of detached houses and prepare for Generative Design to simultaneously optimize multiple design aspects. Many input nodes were included to allow for variation and iteration of the base design. The results included an automated design of a single-story detached house envelope as well as a Dynamo graph that can be exported into Generative Design to generate and examine different feasible design solutions while optimizing the house performance for different conditions and situations. The designer can run the GD study to generate, compare, and explore different design options, examining the geometry and analysis results to select a final design solution. The findings of this study will maximize the productivity of designers/developers and will tremendously reduce the financial strain and time consumed designing an energy-efficient envelope for detached houses as compared to traditional techniques. However, this study has limitations. The study was limited to generating the house envelope design, rather than going through the whole generative design process that also involves an evolution step. Furthermore, the Generative Design framework was limited to generating house designs of specific geometries following the typical design of detached houses in the United States and only focusing on the exterior envelope of the house disregarding the interior elements. Also, although several design factors influence residential buildings' energy performance, the developed generative design framework comprised very few input variables not accounting for many parameters and factors that greatly affect the energy use of buildings. Future research must involve all the steps needed for a complete generative design process to consider a potential list of high-ranking design solutions that fit within the designated design parameters. Future studies should continue exploring and adjusting the existing Dynamo graph to also design the interior of the house using some additional Dynamo nodes and adapt the design for variable shapes, heights, and materials while also satisfying the energy efficiency requirements. Further studies should include more outputs and parameters to better optimize the design solutions and their energy performance.

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Drivers of Machine Learning Applications in the Construction Industry of Developing Economies

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Abstract Stakeholders in the construction industry have over the years made frantic efforts in seeking solutions to the problems facing the industry. The advent of technological innovations such as machine learning applications seek to abate some of these challenges by modernizing construction processes and activities, and ultimately improving on construction projects delivery. This study seeks to examine the propelling factors for the adoption of machine learning applications in the construction industry. Data gathered was subjected to appropriate data analysis techniques. Findings from the study revealed that the most significant drivers for the adoption of machine learning applications are the fast changing, field based and project nature of the construction industry, and the need for accurate results. Also, it was revealed that there is no difference among the different professionals' view of the drivers of machine learning applications in the construction industry. The study made recommendations that would aid the integration of machine learning applications in construction activities for better and more efficient processes in construction project delivery.

Keywords Construction Industry · Developing Economies · Drivers · Machine Learning · Project Delivery

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1 Introduction

In recent years, machine learning (ML) algorithms have influenced every part of our lives, this includes engineering, health and wellness, law and order, commerce, entertainment, finance, human capital management, communication, transportation, and philanthropy. Just like other algorithms, the data on which they are trained and the models they produce are getting more powerful and more ingrained in society [1]. One of the most significant developments in structural engineering applications of Neural Network (NN) in the 1990's was the neural dynamics model of [2]; this was applied for fully automated optimum design of a 144-floor super high rise building structure with over 20,000 members, the tallest structure ever optimized up to that time [3]. Over the years, the applications of ML and computer vision techniques are considered to have steadily grown in the Architecture, Engineering, Construction, and Facilities Management (AEC/FM) industry. It is quite evident that the industry is still plagued with a lot of daunting challenges [4, 5]. The inherent challenges of the construction industry such as cost overruns and schedule delays have become a norm. The industry still experiences multi-billion-dollar infrastructure project team members still being more comfortable with email and spreadsheets rather than more structured project management systems [6]. Mega projects with multi-billion-dollar capital investments with tight schedules are on the rise and companies are looking to technology to increase the efficiency of their building and information management processes [7, 8].

The application of image processing and computer vision can foster different areas of construction management including jobsite layout design, automated progress monitoring of projects, automated 3D modeling and as-built documentation of jobsites, quality control of construction material, and structural health monitoring and damage assessment [9, 10]. Also, Abanda *et al.*, [11] opined that with technologies such as cloud-based project management systems and building information management software, organizations today have much more data to analyze and learn from. Furthermore, ML applications have the potential to increase the efficiency of the construction process, as the industry is one of the most fragmented in the world. The potential of ML modeling to be adopted for assigning productivity rates, construction project databases, constructability analysis and other structural engineering methods, makes it a powerful tool for decision making and changing the image of a construction industry [12]. With the glaring benefits of adopting ML applications in construction processes, there is the need for assessing the propelling factors for its adoption. Based on the aforementioned, this study empirically examines the drivers for integrating ML applications in construction process delivery and management.

2 Literature

Several packages implementing ML algorithms are available such as Netlab, Spider and BNT for Matlab; Nodelib, Torch for C++; and CREST for python. Others are Ayasdi, NeuroSolutions and open-source tools Weka, KNIME are also available with GUI [13]. According to Sonnenburg *et al.* [14], the availability of tools and support is expected to increase the acceptance of ML in the industry. Some of the attributes related to this factor are: if the available tools are open source or proprietary, how much support is available and how much they cost. Others include if the given tool is compatible with existing measurement systems and in-house competences with respect to its usage [15]. Consulting services can also help specific companies to get started with new approaches that they do not have enough experience with, thus helping acceptance of the new techniques and tools in the industry.

While availability of such tools is likely to increase the adoption of ML in construction industry, other attributes such as the drive for better project delivery is also important in determining the level and speed with which ML is adopted in the construction industry [16]. Gadomi and Haider [17] noted that one possible way of enhancing adoption through tool and support availability is by making available problem specific customized solutions for highly relevant industrial problems. Other activities that can potentially accelerate the adoption process is integration of ML based algorithms in existing software packages widely used within the industry such as Microsoft Neural Network algorithm available for SQL Server [15].

An innovation is considered to have relative advantage if it is technically superior in terms of cost and functionality than the technology it supersedes. Fichman and Kemerer [18] affirmed that ML technologies are open-source, scalable, cheaper to store and process complex and large volume of data. ML concept takes a position from storing data in raw format. The reduced data emanates from heterogeneous sources, thereby all analytical, ML and reporting tools run against Hadoop Distributed File System (HDFS) [19]. ML principles and technologies provide greater flexibility to consolidate data from various sources into one singe place. Consolidated data into a single platform provides improved data mining and business intelligence capabilities [20]. However, Richards and King [21] stated that data privacy is one of the concerns with ML and that it has issues in terms of privacy, confidentiality, and identity. Scalability is one of the core competencies features for data warehousing success. One of the key benefits to ML data clusters is scale-out storage system. ML technologies provide scalability in terms of storage, data processing, and scalable mining algorithms [22]. Professional vendor support is very important because most of the ML tools and technologies are open source. Organizations might want to make sure vendor support is available to help them get their data platforms running even when new versions of tools and technologies arrive [23].

3 Methodology

The study makes a bid to assess the drivers of adopting ML applications and technologies in the construction industry. A quantitative approach was utilized with questionnaires as the instrument for data collection, using Lagos state, Nigeria as the study area. The respondents of the study are professionals in the built environment namely: Architects, Quantity Surveyors, Builders, Engineers, and Project Managers. The sampled professionals for the study have at least five years working experience in the construction industry. Snowball sampling technique was deployed for the study due to the difficulty encountered in identifying professionals with at least five years working experience. The instrument for data collection was distributed electronically to a total of ninety-five respondents, while eighty-seven responses were retrieved, and all were appropriate for analysis. The questionnaire comprised of two sections; the former was on the background information of respondents while latter asked respondents to rate the drivers of adopting of ML applications based on their importance on a 5-point Likert scale. The methods of data analysis for the study includes Mean Item Score, and Kruskal-Wallis H-test. The choice of Kruskal Wallis H-test was premised on the fact that since different professionals formed the population of the study, there was a need to ascertain if there is any statistical difference in the opinions of the respondents based on their professional designation. The test produced the chi-square *p*-value of the identified drivers. Any resulting *p*-value greater than 0.05 indicates that there is no significant difference in the opinions of the different professionals. While, when the p-value is less than 0.05, it indicates that there is a statistical difference in the in the opinions of the different professionals. Also, Cronbach's α was deployed in ascertaining the validity of the research instrument and gave a value of 0.815, which proves its appropriateness as suggested by Tan [24].

4 Findings

4.1 Background Information of Respondents

The background information of the respondents indicates that 24.1 and 23% of the respondents are Quantity Surveyors and Architects respectively. Other respondents are Project Managers with 21.8%, while 18.4 and 12.7% of the respondents are Engineers and Builders respectively. Based on academic qualifications, 32.2% of the respondents have B.Sc/B.Tech; 26.4% have a Master's degree, 24.1% have Higher National Diploma, 10.3% have Doctorate degree while 6.9% have National Diploma. Also, based on years of experience, 31.0% of the respondents have 11–15 years, 25.3% have 6–10 years, 11.5% have 16–20 years of experience, 12.6% have more than 20 years, while 19.5% have a minimum of 5 years of experience.

Table 1 Drivers of Machine Learning Applications

Drivers	Mean	R	$K - W$	
			X^2	Sig.
Fast changing, field based and project nature of the industry	4.45	1	1.92	0.598
Need for accurate results	4.43	2	0.16	0.984
Evolving use of IT in the construction industry	4.32	3	3.071	0.381
Rapid advances in software programming technologies	4.23	4	0.672	0.88
Availability of open-source tools	4.13	5	2.733	0.435
Need for improvement in consultancy service	4.12	6	2.272	0.518
Compatibility with existing systems	4.11	7	3.81	0.283
Need for real time information and data retrieval	4.11	7	2.154	0.541
Need for efficient analytical prediction	4.09	9	0.428	0.934
Technological innovation	4.09	9	0.462	0.927

NB: R = Rank; X^2 = Chi-square

4.2 Drivers of the Adoption of Machine Learning Applications

Table 1 shows the mean responses elicited from of respondents based on the importance of driving factors for adopting ML applications and technologies in the construction industry. The table shows the most important drivers are fast changing, field based and project nature of the industry with a mean value of 4.45 ranked first; the need for accurate results with mean value of 4.43 ranked second; the use of IT in the construction industry with mean value of 4.32 ranked third; and the fourth ranked driver is rapid advances in software programming technologies with a mean value of 4.23. A cursory look at the table shows that all the identified drivers for ML adoption in the construction industry all have a mean value well above 4.00, thus indicating that the identified drivers in the study proved to be significant. Also, Kruskal-Wallis H test was deployed in ascertaining the difference in the opinions of the respondents of the study based on professional designation. Findings from the study indicate that the *p*-value of the identified drivers are all above 0.05. This establishes that there is a relationship in the professionals' opinion on the drivers of machine learning. Furthermore, indicating that there is no significant difference in the opinions of the professionals with respect to the drivers of machine learning applications.

5 Discussion of Findings

The study aimed at unravelling the drivers for the adoption of ML applications and technologies in the construction industry. Revealed from the study as the most important drivers are the fast changing, field based and project nature of the industry, and the need for accurate results. This connotes that the dynamic and ever-changing nature of construction processes and activities is a major push for the utilization of ML applications in construction processes. This view is corroborated by Nicholas and Steyn [8] and Rashidi *et al.*, [10] who observed that the construction industry is characterized by complexities, conservative features and prone to high risk, hence the need for sophisticated technological infusion in its processes. In general, the demand to meet up with the fast evolving and dynamic nature of the construction industry is a potent driver for the espousal of digital technologies such as ML. Also, the need for precise and accurate result is equally a major propelling measure for the adoption of ML in the construction industry. This is supported by Sepasgoza and Davis [16] who noted that the need for effective delivery in construction processes is a major factor in the decision to adopt innovative technologies. Furthermore, in the context of the daunting challenges plaguing the construction industry, Kamara *et al.*, [25] opined that the industry is the in line for a step change because of the glaring problems faced. Furthermore, the findings of this study shows that construction professionals have a unified view on the drivers of adopting machine learning principles for the construction industry. This might not be unconnected with the fact that all professionals engaged in the delivery of construction projects may be faced similar underlining challenges, hence, their unified stance on the perceived drivers for the espousal of ML applications in the construction industry.

6 Conclusion and Recommendations

An examination of the propelling factors for the adoption of machine learning principles and technologies was carried out by the study. Revealed from the study as the most important drivers are the fast-changing nature, field based and project nature of the construction industry, and the need for accurate results. Also, the study observed that there is no significant difference in construction professionals' perception on the drivers of ML applications and technologies in the construction industry. With the establishment that the construction industry is still attributed with challenges and taking into cognizance the fast-evolving world of technological innovations, it is best that the industry adapts and get acquainted with innovative ideas for solving problems. To this end, it is recommended that stakeholders and policy makers in the construction industry should as a matter of utmost importance embark on integrating ideas such as ML applications and technologies in construction processes and activities. Furthermore, regular sensitization can be carried out by professional bodies in the construction industry in collaboration with the vendors of these ML applications.

This study was carried out in Lagos state, Nigeria with construction professionals being the target respondents. Future studies can be carried out in other parts of the country to give a broader perspective on the subject. Also, the inclusion of IT professionals and vendors as target respondents would also give a different and more robust dimension on the propelling factors for ML principles and technologies in the construction industry.

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An Ontology-Based Framework for Building Energy Simulation in the Operation Phase

Zhaoji Wu, Jack C. P. Cheng, and Zhe Wang

Abstract Buildings account for a large proportion of energy consumption, and improving building energy efficiency during the operation phase has attracted increasing research attention to achieve the carbon neutrality goal. Building energy simulation is a powerful tool to predict and manage building energy performance during the operation phase. Decision making can be informed by timely and reliable simulation results. However, building energy simulation requires various data and information including building geometries, thermal properties of constructions, Heating, Ventilation, and Air-conditioning (HVAC) systems, etc. Collecting these data and information from different sources (e.g., Building Information Modeling (BIM), Building Management Systems (BMS)) can be a tedious and time-consuming job, which limits a timely prediction and decision-making. This study proposes an ontology-based framework which can integrate data for building energy simulation from different data sources. Firstly, we collect and integrate four types of data (i.e., weather, building, internal heat gain, and HVAC system) from different sources. Ontology models are designed by integrating existing ontology models Brick Schema and Building Topology Ontology (BOT). An inference rule for thermal zoning is proposed. Secondly, a group of rooms in a campus building are selected as a case study to demonstrate the implementation of the models and the inference rule. The proposed models reduce the efforts needed to collect and integrate data for building energy simulation during the operation phase. Using the proposed model, data needed for building energy simulation can be obtained promptly and accurately, which strongly supports building energy management towards energy efficiency.

Keywords Building energy management · Ontology · Data integration · Energy efficiency

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1 Introduction

The building operation accounts for 30% of worldwide energy use and 28% of energy-related carbon emissions according to the data in 2019 [1]. More attention is paid to energy efficiency of buildings during the operation phase, especially under the urgent trend of carbon neutrality. Building energy prediction is one of the key parts in building energy management. With accurate prediction, building managers can foresee the quantitative energy use in later operation phases and adopt optimal control strategies towards energy efficiency.

1.1 Building Energy Prediction

According to ASHRAE Handbook [2], there are two main approaches for building energy prediction, i.e., forward (classical) approach and data-driven (inverse) approach. The forward (classical) approach (a.k.a. Physical modeling approach) belongs to white-box models and relies on thermodynamics rules. To achieve accurate calculation, the approach requires detailed input parameters and highly complex thermodynamic models [3]. Such input parameters include location, weather data, building geometry, construction typologies, internal loads, HVAC systems, operating strategies, and schedules [4].

The data-driven approach belongs to black-box models and predicts energy consumption based on historical data with statistic models or machine learning methods. Compared with the physical modeling approach, the data-driven approach can achieve prediction without knowing physical details of building characteristics and expertise in thermodynamics [5]. Although less expertise is needed, ample data are still required for model training in the data-driven approach. According to Sun et al. [6], in the process of feature engineering in the data-driven approach, seven feature types are needed, including meteorological information, indoor environmental information, occupancy related data, time index, building characteristic data, socioeconomic information, and historical data.

No matter in the forward approach or the data-driven approach, a great number of input data are essential. The lack of precise input data will result in low accuracy of prediction [7]. The required data belong to different types and come from various information sources. For example, building geometries may be provided by Building Information Modeling (BIM) while operation strategies and schedules of Heating, Ventilation, and Air-conditioning (HVAC) may be provided by Building Management Systems (BMS). Collecting different information and data from various sources manually can be a tedious and time-consuming job, which hardly achieved timely prediction and decision-making during the operation phase. Consequently, efficient data model for data integration from different information sources are urgently needed for building energy prediction in the operation phase.

1.2 Semantic Web Technologies for Building Energy Management

Semantic web technologies and linked data technologies focus on combinations of information and data, and can be a solution to the integration of multiple information sources for improving the availability and efficiency of information [8]. Since the early attempts to introduce semantic web technologies to Architecture, Engineering and Construction (AEC) by Pan et al. [9] and Elghamrawy and Boukamp [10], more applications of semantic web technologies have been studied in AEC industry. Three goals can be achieved by semantic web technologies in AEC industry, i.e., interoperability, linking across domains, and logic inference and proof [8].

The design of semantic-web-based models is application-driven. Building performance analysis during operation phases, which require information from multiple domains, is one of the motivations. Jiang et al. [11] combined BIM and ontology for automatic green building evaluation. Hu et al. [12] proposed a hybrid link-data architecture for building performance optimization. The study stated that it is usually more efficient to leave data such as performance measurements in their native format while new mechanism that automatically prepares data streams for processing by rule-based performance definitions should be proposed. More studies can be referred to Lorry et al. [13] and Hu et al.'s [14] work. In these studies, ontology models were constructed to transform data from heterogeneous sources into semantically enriched information. The evaluation work was conducted by leveraging reasoning based on the proposed models.

Building energy management is one important aspect of building performance analysis during the operation phase. Steps of building energy management include evaluation, decision-making and action. Evaluation metrics (i.e., key performance indicators (KPIs)) are quantitative indices for building energy performance inspected by building managers. Zhang et al. [15] proposed an ontology-based approach for automatically calculating the KPI to support building energy evaluation. Hu et al. [16] proposed a framework integrating Web Ontology Language ontologies, Resource Description Framework instances, and a set of predefined rules to infer implicit knowledge, to satisfy data requirements of performance metrics for performance assessments. The framework integrated multi-domain including weather, buildings, sensors, calendars, etc. which can provide a holistic evaluation of building energy performance. Optimization is one key tool for decision-making. Schachinger and Kastner [17] proposed an automatic generation method for optimization problems of building energy management based on machine-readable ontology models. After evaluation, the aim of building energy management is to make corresponding actions towards energy efficiency according to proper decisions. Han et al. [18] stated that structural framework for organizing information and knowledge representation in knowledge-based decision models were lack in previous studies. Hence, Han et al. [18] proposed an ontology model for building energy management which can make reasoning rules from the knowledge bases of accumulated building energy saving measures. Degha et al. [19] proposed an ontology-based context-awareness system which can identify the particular device or behavior causing the energy waste and alleviate the waste by providing adequate energy saving decisions. Some studies were aimed at overall building energy management. Lork et al. [20] proposed an ontology-based framework for buildings energy management including three interconnected modules, i.e., building management system, benchmarking, and evaluation & control modules.

In the existing studies [15, 16], performance metrics were used for evaluation of building energy performance, and the evaluation work was conducted by leveraging reasoning based on the proposed models according to some formulae. The evaluation is conducted by historic data. Building energy simulation is another powerful quantitative tool for building energy evaluation. However, few studies were conducted in terms of semantic webs for building energy simulation. Pauwels et al. [21] proposed a method to transfer SimModel into ontology models. The SimModel is an XML-based data model connecting BIM and energy simulation engines. It enables geometric and HVAC integration for energy simulation engines, but other important elements for energy simulation, e.g., materials, space types, thermal zones and space loads, are not considered [4, 22]. Consequently, the limitation hinders the overall performance of the ontology model proposed by Pauwels et al. [21] in terms of building energy simulation.

1.3 Objectives

To achieve energy efficiency, evaluation of energy performance is essential in building the operation phase. Building energy simulation is a powerful tool for energy evaluation. Data interoperability and cross domain are issues when conducting building energy simulation during the operation phase. Semantic web technologies provide solutions to these issues. However, there is a lack of studies on ontology models for building energy simulation. Our study proposes an ontology-based framework which can integrate data for building energy simulation from different sources. The study takes forward approach (physical modeling approach) as example, to construct ontology-based models for building energy simulation. Four domains of data are studied, including weather, building, internal heat gain, and HVAC system. A group of rooms in a campus building are selected as the case to demonstrate the implementation of the model. Through the proposed models, data needed for building energy simulation can be obtained promptly and accurately, which strongly supports building energy management towards energy efficiency.

2 Proposed Framework

The design principle of the ontology model is to separate static data and dynamic data. The static data are stored in the ontology model while the dynamic data are store in the databases. The ontology model can provide storage address information which maps to the databases. There are four necessary information domains for energy simulation including weather, building, internal heat gain and HVAC system. Accordingly, four ontology models for each of them and cross-domain interference rules are designed for building energy simulation. The proposed ontology components have a prefix *bes*.

2.1 Ontology Model of Weather

There are some existing ontology models of weather for building energy performance assessment [16] and smart building [19]. However, in these ontology models, each environmental parameter, e.g., temperature, relative humidity, is set as an individual class. For building energy simulation, weather data are imported into energy simulation engine as one holistic weather file, e.g., epw file for EnergyPlus. Weather data are dynamic and should be stored in databases according to the design principle. It is not necessary to set an individual class for each environmental parameter. The key static information in the ontology model is the address where the weather data are stored.

According to the type of weather data, three classes are set, i.e., TMYWeather, HistoricWeather and ForecastWeather. TMYWeather refers to weather data of a Typical Meteorological Year (TMY) and can be used for annual studies of energy design or retrofit. HistoricWeather refers to historic weather data (e.g., Actual Meteorological Year (AMY)) and can be used for energy model calibration. ForecastWeather refers to the forecasted weather data and can be used for energy consumption prediction during operation phases. Each class is equipped with a data property fileStoreAt which stores the file addresses for TMY files or database names for historic weather data and forecast weather data (Fig. 1).

2.2 Ontology Model of Building

Geometries and thermal properties of construction materials are two key types of building data for building energy simulation. Existing ontology models which describe building information include ifcOWL, Building Topology Ontology (BOT), etc. For building energy simulation, ifcOWL contains detailed and sometimes redundant building information, whereas BOT focuses on topological relationships among building elements. Besides, BOT has a clear alignment with Brick Schema, an

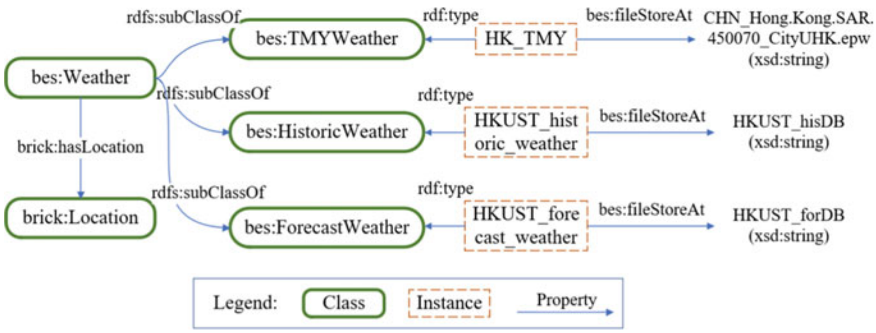


Fig. 1 Ontology model of weather

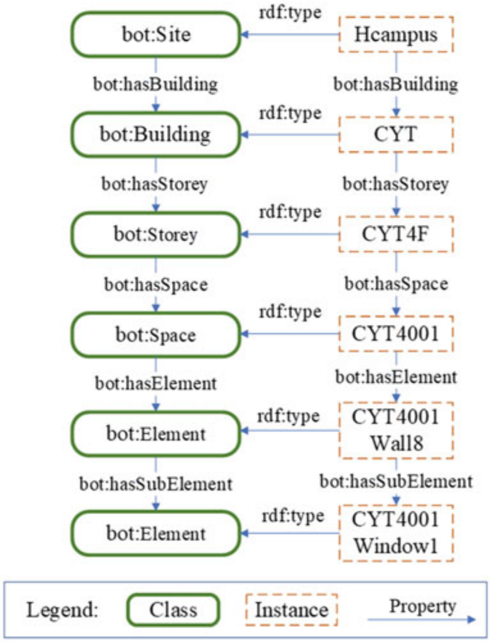
emerging ontology model for building energy systems. Consequently, in this study, BOT is adapted to describe building information. Nevertheless, BOT does not contain thermal properties of construction materials. To address these shortcomings, we proposed some extensions to the existing BOT model.

The BOT extension needs to store the necessary data which are required by energy simulation engines. The bot:Space (Fig. 3) describes a space unit which should contain the data of north direction, origin coordinate, ceiling height, volume and type. These data are set as data properties of the class bot:Space. The bot:Element (Fig. 4) describes a construction entity, e.g., wall, floor and roof and should contain necessary information set as data properties including surface type, outside boundary condition and vertex coordinates. Each element should have a type of construction which is consisted of several layers of materials. Each material is set by necessary thermal properties e.g., thermal conductivity and specific heat. The bot:SubElement (Fig. 5) describes one element hosting another (e.g., a wall hosts a window). Similar to the bot:Element, the bot:SubElement also contains necessary information including surface type, outside boundary condition and vertex coordinates. The construction of bot:SubElement is simplified without materials but contains necessary thermal data e.g., U-factor and Solar Heat Gain Coefficient (SHGC). The window construction is corresponding to WindowMaterialSimpleGlazingSystem in EnergyPlus which sets window as a holistic construction without details of constituting materials (Fig. 5).

2.3 *Ontology Model of Internal Heat Gain*

Equipment and occupancy are two major sources of internal heat gain. Equipment and occupancy are located at certain spaces and hence the class brick:Equipment and brick:Occupancy are linked to bot:Space with object property brick:hasLocation. Internal heat gain can be quantified using two types of data, i.e., power and schedule. Taking occupancy as an example, power is related to occupants' activities and is a function of space types. Schedule is a timetable to indicate when equipment is

Fig. 2 Ontology model of spatial units based on BOT



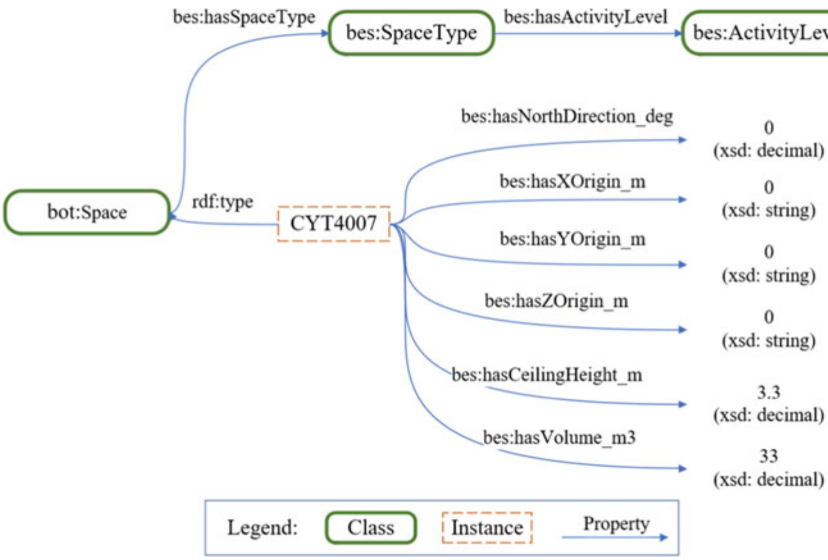


Fig. 3 Extension of bot:Space for building energy simulation

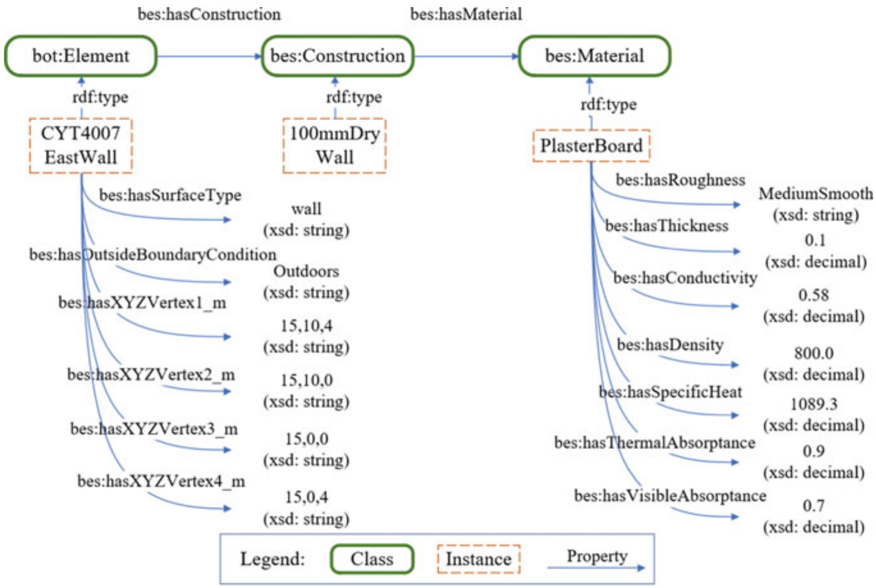


Fig. 4 Extension of bot:Element for building energy simulation

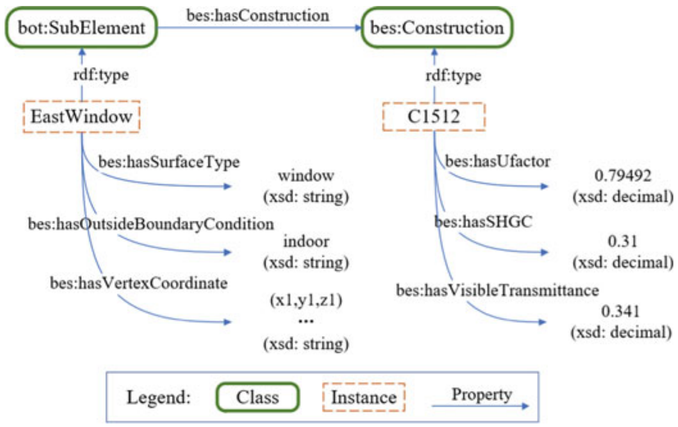


Fig. 5 Extension of bot:SubElement for building energy simulation

running or when spaces are occupied. The timetables are stored in databases and the address information is stored in the ontology model which is similar to weather files in the ontology model of weather (Figs. 6 and 7).

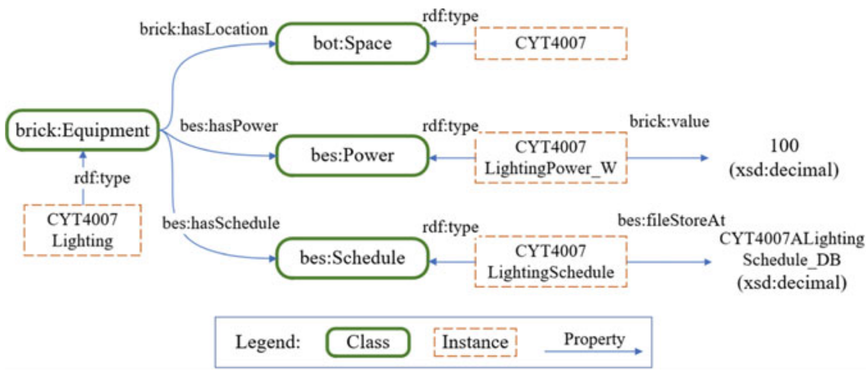


Fig. 6 Ontology model of equipment

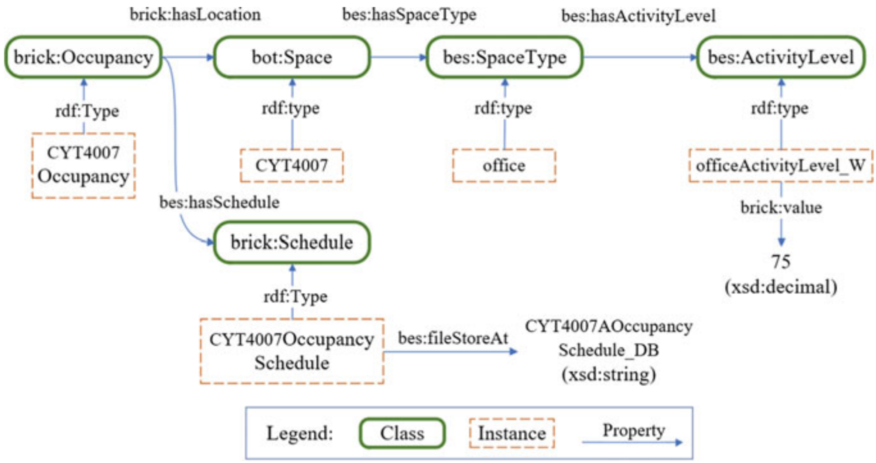


Fig. 7 Ontology model of Occupancy

2.4 Ontology Model of HVAC System

Brick Schema is an open-source standardized ontology model for physical, logical and virtual assets in buildings and the relationships between them. Brick Schema can describe HVAC systems comprehensively, and hence this study reuses Brick Schema as the ontology model of HVAC systems with some extensions when needed.

For HVAC systems, this study focuses on AHU-VAV (Air Handling Unit—Variable Air Volume) system. Figure 8 shows the components and their relationship in an AHU-VAV system. For building energy simulation, cooling or heating setpoint are important inputs. The classes brick:CoolingTemperatureSetpoint and brick:HeatingTemperatureSetpoint are used to store the setpoints. Meanwhile, schedules, another important inputs, are stored in database, with its address stored in the

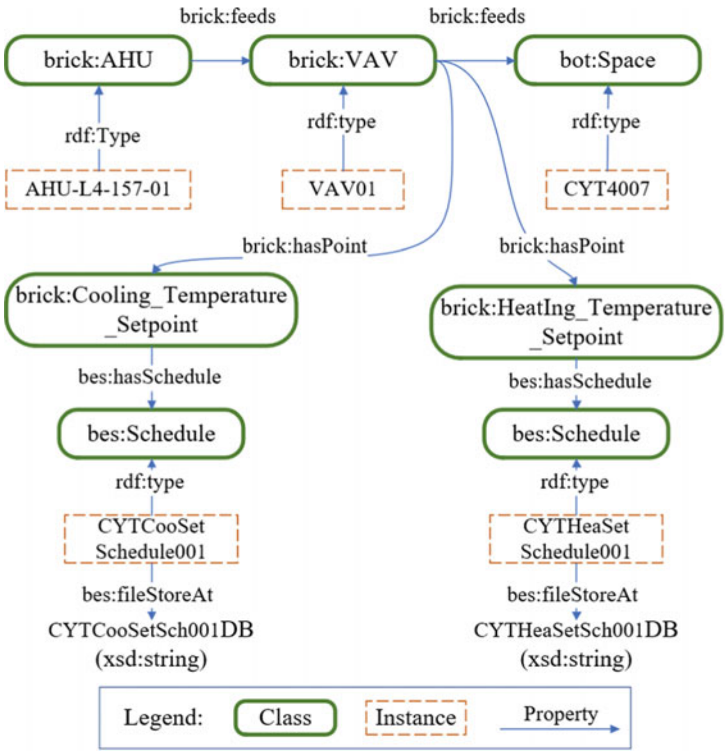


Fig. 8 Ontology model of HVAC system

ontology model. This representation is similar to schedule files in the ontology model of equipment and occupancy.

2.5 *Inference Rule of Thermal Zoning*

Existing building energy simulation engines usually assume that indoor air of each zone is well-mixed. Such zone is called thermal zone and various zoning strategies have significant impact on simulation results. Consequently, thermal zoning is a critical step of building energy simulation. However, thermal zoning is not discussed in existing studies of building energy simulation with ontology models. According to the review by Shin et al. [23], spatial units can be grouped into one zone or split into multiple zones depending on the factors including solar gain, orientation, occupancy, schedule, space function, etc. In the proposed ontology models, these factors are usually set as asserted properties from multiple domains. Thermal zone

Table 1 The inference rules for thermal zoning

Reasoning for thermal zoning	
1	bot:Space(?spacea)
2	^bot:Space(?spaceb)
3	^bot:adjacentZone(?spacea, ?spaceb)
4	^bes:hasSpaceType(?spacea, ?spacetypea)
5	^bes:hasSpaceType(?spaceb, ?spacetypeb)
6	^sameAs(?spacetypea, ?spacetypeb)
7	^brick:VAV(?vava)
8	^brick:feeds(?vava, ?spacea)
9	^brick:Cooling_Temperature_Setpoint(?setpointa)
10	^brick:isPointOf(?setpointa, ?vava)
11	^bes:Schedule(?schedulea)
12	^bes:hasSchedule(?setpointa, ?schedulea)
13	^brick:VAV(?vavb)
14	^brick:feeds(?vavb, ?spaceb)
15	^brick:Cooling_Temperature_Setpoint(?setpointb)
16	^brick:isPointOf(?setpointb, ?vavb)
17	^bes:Schedule(?scheduleb)
18	^bes:hasSchedule(?setpointb, ?scheduleb)
19	^sameAs(?schedulea, ?scheduleb)
20	-> bes:sameThermalZone(?spacea, ?spaceb)

information belongs to implicit knowledge which can be inferred from asserted cross-domain knowledge by generic inference engines. In this study, Semantic Web Rule Language (SWRL) [24] is applied to enable reasoning for thermal zoning.

In this study, two spatial units can be grouped into one thermal zone if (1) they are adjacent to each other, (2) they have the same space function, and (3) they share the same cooling or heating setpoint and schedule. Table 1 shows the inference rule for thermal zoning. Lines 1–3 ensure that the two units satisfy the criterion (1), lines 4–6 ensure that they satisfy the criterion (2), and lines 7–19 ensure that they satisfy the criterion (3).

3 Illustrative Example

To validate the proposed ontology models and inference rule, a group of rooms in an academic building in The Hong Kong University of Science and Technology (HKUST) are studied as the illustrative example. Figure 9 shows the layout of the rooms.

Fig. 9 Layout of the illustrative example

To conduct building energy simulation, four types of information domains, i.e., weather, building, internal heat gain, and HVAC system, are involved. For the weather, three types of weather data are included. The TMY data are retrieved from the epw file. The historical weather data come from the local weather station in the HKUST campus, and the forecast weather data come from the civic observatory. For the building, the BIM models which contains the information of the geometries and thermal properties of the constructions are served as the information sources for the ontology models. For the internal heat gain, the occupancy information is retrieved from the Pulse Project which monitors the number of the facility users in the HKUST campus. The equipment information is retrieved from the BMS of the campus. The BMS also serves as the information sources for the HVAC system ontology model (Fig. 10).

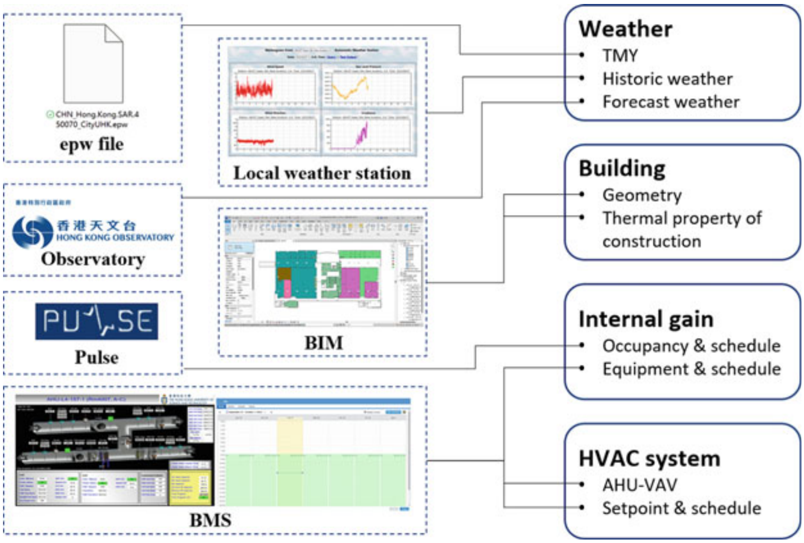


Fig. 10 Information sources of the ontology models

The ontology models are developed, and the inference rule are implemented in the software Protégé. Figure 11 shows parts of the classes, individuals, data properties, and object properties of the ontology models in Protégé. The static information is stored in the ontology models while the dynamic data, e.g., historic or forecast weather data, and schedules of equipment, occupancies setpoints, are stored in databases. Via data property bes:fileStoreAt, users can retrieve the necessary data by the locations of the databases (Fig. 12).

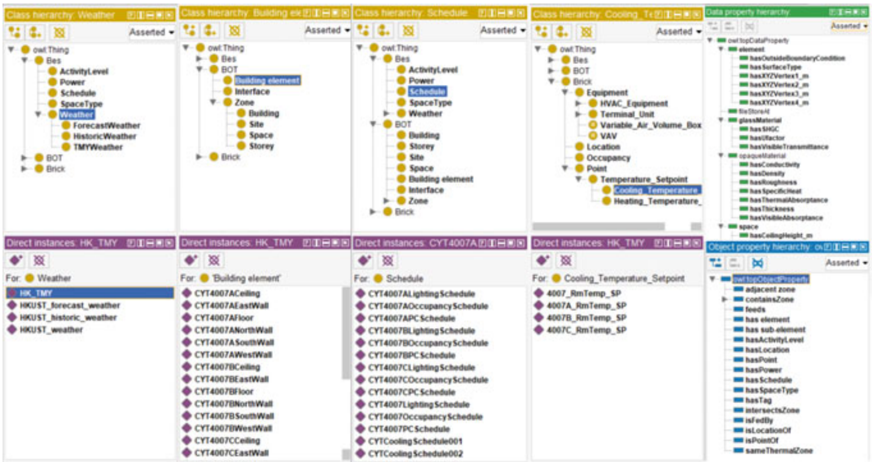


Fig. 11 Examples of the ontology models in Protégé

Fig. 12 Example of dynamic data linked by file address

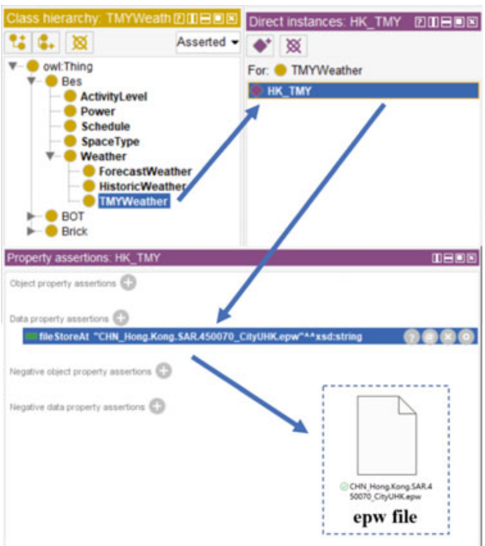


Table 2 Basic information of the rooms

Room	Space type	Setpoint schedule
4007	Office	CYTCoolingSchedule001
4007A	Office	CYTCoolingSchedule002
4007B	Office	CYTCoolingSchedule001
4007C	Office	CYTCoolingSchedule002

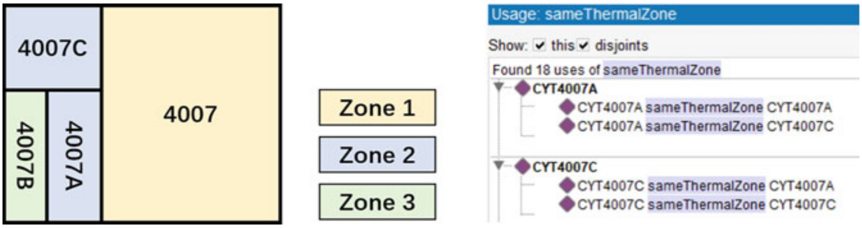


Fig. 13 Results of thermal zoning

After the establishment of the ontology models, reasoning can be conducted to generate thermal zones automatically. The basic information of the four rooms is shown in Table 2. The four rooms serve as offices. CYT4007 shares the same cooling setpoint schedule with CYT4007C while CYT4007A shares the same schedule with CYT4007B. The zoning results are shown in Fig. 13. The rooms which can be grouped into one zone are deduced to have the property sameThermalZone. Because CYT4007A and CYT4007B have the same space type and setpoint schedule, they are grouped into one thermal zone. Although CYT4007A and CYT4007B have the same space type and setpoint schedule, they are not adjacent to each other, and hence they are not grouped into one thermal zone. The reasoning results are the same to the ground truth, which validate the inference rule proposed in this study.

4 Conclusion

Building energy simulation is a powerful tool to predict and manage building energy performance in the operation stage. However, developing building energy models relies on various data from multiple sources. To collect the data and develop the model is time and expertise demanding. In this study, we proposed an ontology-based framework to reduce the data management and integration efforts for building energy simulation during the operation stage. We developed ontology models that cover four data domains, including weather, building, internal heat gain and HVAC system. Our ontology model is built upon the existing ontology models BOT and Brick Schema, so that our proposed models can satisfy the reusability in the Findable, Accessible, Interoperable, and Reusable (FAIR) principle. An inference rule is proposed to generate thermal zones automatically based on the ontology models. A group of rooms in an academic building in the HKUST campus are selected as the illustrative example. The ontology models of weather, building, internal heat gain and HVAC system for the rooms are established from multiple information sources. Automatic thermal zoning is conducted, which delivered a zoning result that is the same to the ground truth. Using our proposed models, data needed for building energy simulation can be obtained promptly and accurately, which strongly supports building energy management towards energy efficiency.

To achieve timely prediction and decision-making of building energy performance during the operation stage, fully automatic building energy simulation is ideal. This study is a preliminary study on the ontology-based framework, which only focuses on the data integration and preparation. The next step is to automatically generate building energy simulation models (e.g., the idf file for EnergyPlus) using the information retrieved from the proposed ontology models. By mapping the ontology models to building energy simulation models, fast and automatic building energy simulation can be achieved, which is the ultimate goal of this study.

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A Multi-stage Approach to Understand GIS Model Enrichment Used for Decision-Making Support When Developing Energy Retrofit Strategies on a Neighborhood Level

Christian-Dominik Thiele, Puyan A. Zadeh, Najme Hashempour, Sheryl Staub-French, and Uwe Rüppel

Abstract In the AEC sector, energy performance targets of buildings continuously increase for contributing to reduce carbon dioxide. This is usually done on building level, but the focus continuously shifts to larger scales such as neighborhoods, e.g. for identifying buildings with the most retrofitting potential. For this, low detailed GIS models can serve as a basis for energy simulations and are broadly available. However, neighborhood energy simulations hold many challenges, such as the lack of accurate and sufficient data to perform reliable simulations. Information such as window positions or thermal parameters of the building elements can thereby help to increase the quality of the energy simulation results. Therefore, in this paper, challenges of data collection are presented and discussed. To enable users to find a trade-off between accuracy and reliability of a neighborhood simulation and the effort to provide this data, the authors developed the concept of the Neighborhood Model States (NMS). Furthermore, occurring challenges in enriching the GIS model for each NMS are discussed on the example of buildings from the UBC campus.

Keywords Energy Simulation · Neighborhood Level · Neighborhood Model States · Level of Detail (LOD) · Level of Granularity · Geometric information · Non-geometric information · BIM · GIS · Retrofitting

1 Introduction

Climate change is certainly one of the most pressing problems in this day and age. As current reports show, there is a huge potential to save energy in the AEC sec-

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tor [1]. This can be reached e.g. through developing suitable retrofit strategies by replacing fossil fuel-based heating systems with electric heat pumps and improving building insulation. As a result, many governmental agencies and control bodies in different countries have developed strategies and encourage energy retrofits through implementing certain laws and offering financial incentives to building owners. To reach Global Climate targets as set in the Paris Agreement [2, 3], it is important to focus on larger scales and conduct energy analysis at neighborhood levels instead of individual buildings. For this aim, it is necessary to develop and use tools that can estimate the energy consumption of neighborhoods [4]. As the authors in [5, 6] highlight, the estimation of energy consumption at the neighborhood level enables the opportunity to combat climate change by creating livable and energy efficient neighborhoods, as well as to support energy efficiency, sustainability, and management of cities. More particularly, automated energy simulations on a neighborhood level can be used for evaluating the impacts of potential retrofitting measures, or for identifying specific critical buildings with a priority to be energy retrofitted [5, 7]. According to [7], changing the retrofit analysis perspective from individual buildings to neighborhoods has a great potential for bigger savings and lower investments. In this way, the decision makers can quickly identify the most critical buildings that need retrofitting and can then perform more precise and intensive analysis on those specific buildings. This can be especially beneficial to large owners of buildings with close proximity to each other, such as university and hospital campuses, etc. However, most currently available energy simulation tools are designed to analyze only individual buildings, which require a large amount of data with high level of precision. This is why it is a fundamental research challenge to change the perspective from individual buildings to neighborhood levels [4].

To perform energy simulations on any level, several parameters must be known. These include, on the one hand, geometric information such as the height and footprint of the buildings. On the other hand, non-geometric information like the thermal parameters of the exterior wall layers and the type of the installed HVAC system. However, on a large scale, such as neighborhoods, there are significant challenges that surface when it comes to availability of the data, data inconsistencies, and data privacy issues [8]. Although these challenges can also apply to individual buildings, they become even more challenging on a larger scale. While data for individual buildings can be collected on site from Building Information Models (BIMs), building drawings, and other project documents, this level of data collection is no longer feasible for larger scales, such as neighborhoods, due to the availability and consistency of the required data. This is why, when analyzing a collection of buildings, such as in a neighborhood, practitioners are often limited to only relying on the data from Geographic Information Systems (GIS) with low levels of detail. Since GIS data that is used for performing neighborhood energy simulations is often inhomogeneous regarding the provided amount of information as well as their reliability [9], practitioners need to find ways to enrich the GIS data to be able to conduct useful and reliable simulations that can be used for developing retrofit strategies. However, enriching GIS data is complicated, cumbersome and expensive [10].

Therefore, the main research objective is to address this gap between the required data for energy simulations and the available data. This is done by investigating and understanding the challenges and resulting efforts when gathering additional geometric and non-geometric information (Sect. 4).

For understanding the GIS model enrichment, an innovative Neighborhood Model State (NMS) concept is developed. This concept consists of four model states with their respective geometric and non-geometric information components that can be added to the original GIS data. The information content for each NMS increases progressively, and each state is respectively analyzed for the challenges in data acquisition and their potential impacts on the quality of the energy simulation outcomes. To demonstrate the concept of NMS, two representative use case buildings, the Engineering Student Center (ESC) and the Centre for Interactive Research on Sustainability (CIRS) at the University of British Columbia (UBC) Vancouver Campus in Canada are used in this work. A GIS model for the entire UBC Vancouver campus is available, where the selected buildings could be extracted for further analysis.

In the following Section, an overview about the role of the data in neighborhood energy simulations, as well as energy simulations on large scales in general, is given. Then, in Sect. 3, the research methodology is presented. In Sect. 4 the concept of the NMS are introduced and examples for challenges in data acquisition for different neighborhood model states are presented and discussed. Finally, in Sect. 5 the results of the research are concluded.

2 Background

As described, for existing buildings, usually only limited digital data is available, and what is available, is mostly unstructured. Therefore, extensive and time-consuming on-site explorations and measurements can be the consequence to acquire needed information like wall layers, materials, geometric dimensions etc. On a small scale, the collection of these geometric and non-geometric information is manageable, but for multiple buildings e.g. on a neighborhood level this procedure is too time-consuming and in consequence not applicable. To give an insight about how energy advisors and engineers gather their data for energy simulations on neighborhood levels, a detailed literature review was conducted.

2.1 The Role of Data for Energy Simulations

As is well known, BIM's on the scale of individual buildings can serve as the basis for different stakeholders during the planning and operational phase. It thereby can be a collection of different specialist models and can include necessary information for energy simulations. Energy related specialist models are commonly referred to as BEM (Building Energy Modeling). By increasing the scope to a neighborhood level, a comparable method exists, namely UBEM (Urban Energy Modeling) or USEM

Table 1 Needed data to perform energy simulations (based on [9])

	Minimum information	Additional information
Geometric	Footprint Envelope composition (layers)	Glazing (WWR) Basement Roof type and shape Interaction with adjacent buildings (shading)
Non-geometric	Weather data Heating system	Year of construction Thermal zones/stories HVAC information Number of Occupants Occupant behavior

(Urban-Scale Energy Modeling), for which researchers see a strong potential [8, 11] but also are challenging due to the complexity of urban energy systems [12]. Energy simulation on large scales can basically be classified into two approaches: top-down and bottom-up. The top-down approach is usually data-driven and can be based on statistical energy use and historical data, among others [8]. On the other hand, there is the bottom-up approach, which is physics-based and engineering models and simulations are used. Therefore, usually more individual data is necessary which can have significant uncertainties in building energy estimates at an urban scale, as the authors in [8] are stating. Additionally, when buildings are modeled individually, it can require a higher computational power regarding the provided information [13].

In this context, the bottom-up physics-based approach is chosen, since it is very suitable for in-depth urban scale analyses [8]. This results in a need for extensive data that has to be gathered as it builds the foundation for the simulation. Therefore, an overview about the needed data is given in Table 1. These parameters are in the literature often categorized as geometric and non-geometric information, which is taken up in this publication. Furthermore, the authors distinguish the data in between minimum mandatory data that is needed to get at least a result from the simulation, and additional data that can lead to more reliable results if provided.

To grade the complexity and amount of included geometric and non-geometric information of the respective data, the concept of Level of Detail (LOD) is common and well known on the building level from the BIM methodology. For GIS, this concept has been adopted, although different GIS have different definitions.

One of the most well-known GIS is CityGML on which the concept of LOD will be elaborated. CityGML provides geometrical data of neighborhoods or even municipalities by using an XML-based format and is defined in the OGC CityGML Encoding Standard [14]. This geospatial data is largely available, e.g. for most European countries [15]. CityGML is currently being revised, the upcoming version of CityGML will be version 3. In the previous version, a LOD was describing the whole building (e.g. LOD4 means very detailed facade including furniture) but is now getting harmonized in version 3 with the definition of BIM. There, the LOD does not obligatorily mean the whole building, but can describe specific components individually. For example, it is now possible to have a very low LOD of the outer shell combined with a highly detailed inner interior model. So, all the building parts can have their own LOD, as known from BIM [16]. Additionally, the LOD of CityGML models varies significantly depending on regions [17]. Furthermore, Biljecki et al. [18] showed, that the CityGML 2.0 LOD concept as currently defined in [14] is inconclusive, since each LOD can be interpreted in multiple ways [18]. However, in the upcoming CityGML version 3 the usability and inconsistencies are improved [19].

When it comes to geometric representations, most of the existing tools are using GIS models (namely CityGML). Even though low detailed CityGML models offer only a specific amount of information as well as a limited accuracy regarding geometric representations, this data source is commonly used as a basis for energy simulations on neighborhood levels. Next to CityGML, more possibilities to exchange geospatial data are GeoJSON and Shapefile. Unfortunately, these data types do not provide schemas to further define building properties [20]. It is also worth mentioning KML (Keyhole Markup Language) as an alternative file format and data source for retrieving geometric and geospatial data. KML is used, for example, by Google to display geographic data in Google Earth and is based on the XML standard [21]. While the acquisition of geometrical data on neighborhood levels is well documented, existing reviews with profound discussions on non-geometric acquisition for UBEMs are lacking [10].

The quality of the simulation can be continuously improved by adding more known details as expected and by increasing its LOD. The influence of the different input parameters have been dissected through several sensitivity analyses [4, 9, 17, 18, 22]. As an example, the authors in [4] showed the influence of different parameters on the quality of energy simulations by performing a sensitivity analysis through varying individual geometrical and physical factors. Therefore, they used six case study buildings of different building types. They found out that for the geometry, the deviation of between LOD1 and LOD2 models is smaller or equal to 10%, the comparison between LOD2 and LOD3 is again smaller than 12%. Furthermore, they varied parameters such as the windows-to-wall ratio, U-values of the walls among others. They concluded that depending on the data availability and assumptions being made, errors up to 80% could occur. For the user behavior parameters, errors up to 40% have been encountered. These numbers underline the necessity of having reliable underlying data for energy simulations.

The authors from another study that is concerned with a sensitivity analysis is [9]. Here, the authors used a comprehensive neighborhood data set of approx. 8,600 buildings from a city in Germany. They limited their analysis to the comparison of LOD1 and LOD2 representations, even though they looked at a considerably large dataset. The authors looked into the effect of varying parameters like the error of using LOD2 instead of LOD1 models, the role of basements, attics, window-to-wall ratio, air change behavior, internal gains, among others. Eventually, they come to a similar conclusion as the authors from [4]. They noted that the available LOD affects other parameters with sizable roles regarding the result of the energy simulation. Due to a lack of LOD3 data, they couldn't assume their influence on the energy simulation result. Finally, they provided a ranking about must-have parameters (besides a LOD1 city model), which are absolutely essential for doing neighborhood simulations, such as the building year of construction, the building function, refurbishment information, and residence type. Further information has a less impactful consequence when missing than these (error over 30%).

However, since this assessment in both case studies have been done by the simulation platform SimStadt, which is inferring information from data sets and benchmarking data libraries [9], it may not be transferable to other simulation tools.

2.2 Energy Simulations on Neighborhood Level

The Building Energy Simulation Tools web directory (BEST-D) lists over 170 different tools to perform energy simulations. More than 50 can be used for a whole-building energy simulation [23]. However, most building energy evaluation tools are for the analyses of individual buildings and require a high amount of data [4]. There are some tools that originated mostly from research projects, to overcome this problem. Popular ones, SimStadt, CitySim, UrbanSim and CityBES will be presented in the following.

The urban simulation tool SimStadt and SimStadt 2.0 respectively was developed in research projects finished in 2015 and 2020. The platform analyzes districts or even regions regarding their heating requirements, photovoltaic studies, and renewable energy supply scenarios [24]. For that, it uses a bottom-up physic-based approach. Its focus was less on getting as accurate models as possible, but to provide a reliable simulation tool using existing data points for basic decision-making. It is validated through three case studies [25].

CitySim is another tool that tries to support urban energy planners to reduce energy consumption and emission of greenhouse gasses. It thereby provides the possibility to enrich geometrical buildings with thermophysical properties. The calculation is based on statistical values for occupants' presence and behavior and offers typical HVAC systems. As a simulation engine, CitySim Solver was developed and comes with its own proprietary XML file format. The engine was validated in field studies [26].

City Buildings, Energy, and Sustainability (CityBES) is a web-based data and computing platform sponsored by Lawrence Berkeley National Lab. It uses CityGML as an open standard and is based on EnergyPlus as a simulation engine. The tool allows adding additional data like weather data, information about the building stock through CityGML and GeoJSON and further standards and codes. It supports scenarios like energy benchmarking and energy retrofit analysis [27].

As the literature review shows, many research projects are focusing on the development of tools that can support city planners when it comes to energy related questions. However, it remains an open problem that for bottom-up approaches a significant amount of data is required. The research presented in this paper seeks to address this gap by identifying openly available data and enriching base models used for analysis, such as CityGML files.

3 Methodology

The main objective of this research is to investigate the relevance of the granularity in geometric and non-geometric building information for energy simulations on the neighborhood level, and to highlight the challenges in performing such simulations. For this aim, the research team conducted a thorough review of the related literature to understand the necessity of different impact factors when performing energy simulations for neighborhoods (Sect. 2).

For understanding the information required to perform energy simulations, several energy simulation tools were reviewed, and the respective data gathering effort were identified. Based on this, a better understanding of a needed trade-off between the effort to gather the data and the accuracy of the energy simulation was gained. The results of this analysis are presented in Sect. 4.1.

For the development of the neighborhood model state (NMS) concept, a CityGML model of the UBC campus was used as an example. In addition, models of the City of Vancouver were examined. These models were then decomposed into individual buildings and evaluated for their suitability for energy simulations and their LOD. BIMs of selected campus buildings were also used and compared to the CityGML models for accuracy. This ultimately allowed the identification of challenges and difficulties in neighborhood-level data collection. Based on the literature review and the conducted research, difficulties in data acquisition were crystallized and the concept of the neighborhood model states was developed which is presented in Sect. 4.2.

The developed NMS concept was then applied to two representative example buildings of the UBC campus. The specific challenges resulting from those examples are discussed and presented in Sect. 4.3.

4 Neighborhood Model States (NMS)

4.1 Data Acquisition and Enrichment for Energy Simulation on Neighborhood Level

As the authors in [7] state, energy simulations for neighborhoods can support decision makers to better prioritize effective retrofitting measures. Furthermore, the authors in [17] highlight that decision-makers need access to reliable quantification of the energy demand of all (or most of) buildings within a neighborhood to be able to have a correct assessment of the feasibility of district energy systems.

When it comes to the shifting from single buildings to a higher scale, such as a neighborhood, there is a trade-off between the accuracy of the simulation outcomes and the ease of data acquisition and simplicity of compiling energy simulations. Although reaching the highest level of accuracy is desirable, the main purpose of such analyses is often identifying the low performing buildings in a neighborhood

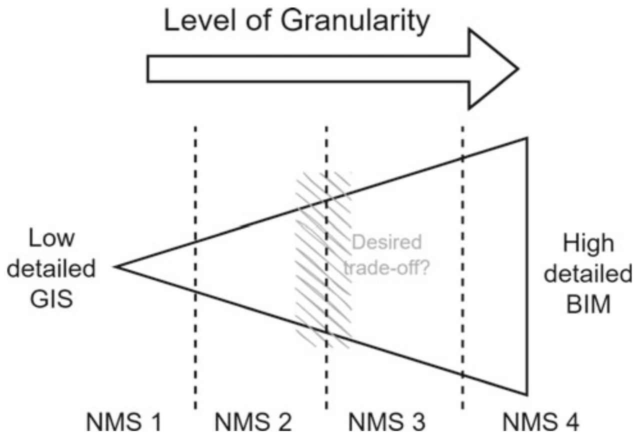

Fig. 1 Discrepancy between NMSs regarding the granularity of geometric and non-geometric information

and choosing suitable investment strategies to address their performance deficiencies. In other words, a highly detailed energy simulation wouldn't be necessarily required for this stage and such detailed analysis can be made once the specific low performing buildings are selected for the retrofitting process. At that time, comprehensive data collection from those specific buildings and a detailed energy analysis can be conducted.

Therefore, while the granularity of building data can vastly vary from NMS1 (rough GIS models) to NMS4 (detailed BIMs), when performing energy simulations for neighborhoods, the desired level of granularity in the data can settle somewhere between a rough geospatial representation and a highly detailed individual 3D visualization as shown in Fig. 1.

Since the highly granular models such as BIMs are currently not expected to be available for most neighborhoods, the question emerges as to what extent low LOD GIS models need to be enriched to achieve sufficient energy simulation outcomes for neighborhoods. On this basis, low performing buildings and their performance discrepancy to the other neighborhood buildings can be identified while considering the accessibility to the needed information.

To answer this question, it is necessary to investigate whether changes, i.e. increasing the accuracy in geometric data would lead to noticeable better results. The same investigation must be conducted for the non-geometric data as well. These investigations are not mutually exclusive, but the amount of efforts for theextra data acquisition and enrichment for each data point must be considered and evaluated to better understand the trade-off between the reliability of the simulation outcomes and the ease of data acquisition. For this aim, the new classification of the neighborhood model states can be used to provide a better understanding of such trade-offs.

4.2 Neighborhood Model States for Energy Simulations

It is often the case that high granularity building data, including BIMs, are not available for the entire buildings of a neighborhood. On the other hand, there are numerous databases available that provide GIS models for many cities and their neighborhoods [17], which can be used for different neighborhood-based analyses. However, as for the energy simulations, the available GIS models are mostly limited to simple geometric representations, and lack in non-geometric data, which potentially can lead to imprecise energy simulation results for neighborhoods [9]. This is especially critical when using energy simulators designed for working with detailed building models for the neighborhood analysis purposes. Therefore, GIS models need to be adjusted and enriched by adding more detailed information to be more suitable for energy simulation purposes.

As discussed in Sect. 2, there are different interpretations of LOD when dealing with GIS models and BIMs. Furthermore, the LOD for GIS models can vary significantly depending on regions, and also each GIS LOD can be interpreted in multiple ways [18]. To avoid misinterpretations and inconsistencies, this research proposes a new classification for the different neighborhood model states based on the required geometric and non-geometric data for each state, in accordance with the difficulty of acquiring this data.

This new classification demonstrates a gradual increase in the granularity of the geometric and non-geometric data, which ultimately can be used for high resolution energy modelings. In defining these model states, we paid extra attention to the readiness and accessibility of each data point. In this classification, the NMS1 represents the lowest granularity of the data with the highest accessibility potential, while the NMS4 represents the highest granularity of the data and is comparable to the building data available in high detailed BIMs. The higher the level of NMS is, the more challenging the data acquisition gets so that NMS4 data can often be obtained only by having detailed building plans or conducting extensive in-situ explorations using LiDAR and other technologies. The details of the new proposed classification for neighborhood model states are shown in Table 2, where there is a distinction made between geometric and non-geometric data for each neighborhood model state.

Table 2 Classification of the neighborhood model states (NMS) for energy simulations on neighborhood level.

NMS1	NMS2	NMS3	NMS4
Geometric	Geometric	Geometric	Geometric
1) Rough geometry ($\leqslant LOD1$[a])	1) Rough geometry ($\leqslant LOD1$)	1) Rough geometry ($\leqslant LOD1$)[c]	1) ~~Rough geometry ($\leqslant LOD1$)~~
2) GIS position and orientation	2) GIS position and orientation	2) GIS position and orientation	2) GIS position and orientation
3) Rough zone determination	3) Rough zone determination	3) ~~Rough zone determination~~	3) ~~Rough zone determination~~
	4) Partially fenes-tration ratio[b]	4) ~~Partially fenestration ratio~~[b]	4) ~~Partially fenestration ratio~~[b]
	5) Roof shape	5) Roof shape	5) ~~Roof shape~~
		6) Full fenes tration ratio[a]	6) ~~Full fenestration ratio~~[a]
			7) Basement
			8) Exact window locations
			9) Inner layout & exact zones
			10) More accurate geometry ($\geqslant LOD3$)
Non-geometric	Non-geometric	Non-geometric	Non-geometric
a) Weather data	a) Weather data	a) Weather data	a) Weather data
	b) Building usage type	b) Building usage type	b) Building usage type
	c) Year of construction	c) Year of construction	c) Year of construction
	d) Occupancy numbers	d) Occupancy numbers	d) Occupancy numbers
		e) Heating system	e) Heating system
		f) Wall layers	f) Wall layers
			g) Occupancy behavior
			h) Historical operational data (bills)
			i) Exact data of HVAC system

[a] In accordance with the CityGML 3.0 definition.
b2 WWR: Window-to-Wall Ratio.
c The dimensions of the geometry should be validated.
Crossed: obsolete, replaced by a more accurate feature.

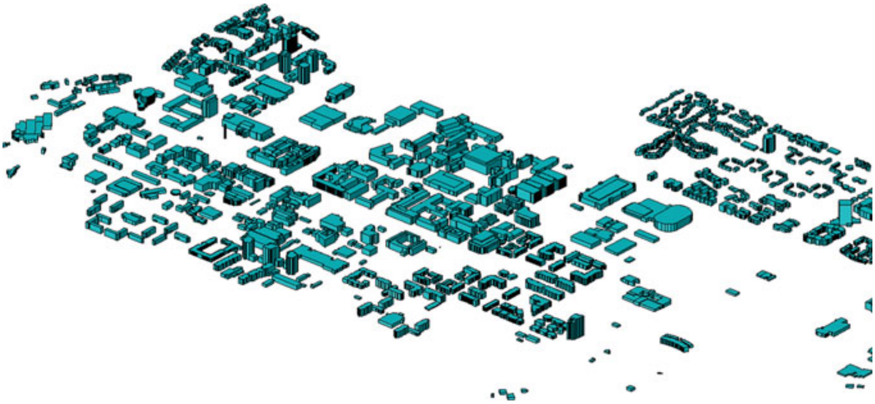

Fig. 2 CityGML Model (LOD1, provided by UBC) of UBC Campus, Vancouver

4.3 Challenges of Data Acquisition on the Example of UBC Buildings

To discuss the data acquisition and its challenges for each NMS, an exemplary neighborhood as a use case is selected. The chosen neighborhood is the campus of the University of British Columbia (UBC) in Vancouver, Canada. For this neighborhood, a low detailed CityGML GIS model is available (Fig. 2). Considering UBC as the exemplary neighborhood also has the convenience of having access to operational data when it comes to the validation of the simulations.

As example buildings for the UBC neighborhood, the Engineering Student Center (ESC) as well as the Centre for Interactive Research on Sustainability (CIRS) were selected. The architecture of the ESC is simple and squares well regarding the complexity. It was opened in 2015 as a break and study room for undergrad engineering students. The CIRS building however represents a complex geometry with a versatile facade, which was created as a case study building for an energy efficient building. The CIRS building was opened in 2011.

The selected buildings will be used as examples in the following subsection, where the process of collecting geometric and non-geometric data and their respective challenges for the data acquisition for each NMS will be discussed.

Neighborhood Model State 1 (NMS1). The geometry data for NMS1 is very basic and can be obtained from various sources, e.g. from municipalities, databases or operators of large facilities (such as universities, hospitals etc.). This can be GIS models such as CityGML models. These data are usually widely-used and easy to obtain, but they are mostly not more detailed than LOD1 (floor area and average height of the building). Therefore, the quality of the geometry may vary. As for the UBC sample buildings, the geometry of the CIRS building is very accurate. In contrast, the geometry of the ESC building in the GIS model is too small by a factor of 2 in each dimension, resulting in a significantly underestimated volume. The fact, that the building is surrounded by large buildings could be a contributor to this outcome. If the number of stories is determined by the average height of the building, these geometric inaccuracies can have an impact. Assuming an average story height of 3.00 m, the ESC building would have only one story, since it's CityGML model height is 4.35 m. This is not the case, since the ESC building actually consists of 2 stories.

The originally GIS models usually do not come with many non-geometric information and therefore an adjustment should be conducted. If the simulation should be run based on the available information of NMS1, many additional assumptions need to made, such as the layers of the walls, the building type, setpoint temperatures and the heating system.

Neighborhood Model State 2 (NMS2). The NMS2 is based on NMS1, which is basically the rough CityGML geometry. In NMS1, important features like the Window-To-Wall-Ratio (WWR) and information about the roof shape are usually missing. These should be added in NMS2. The fenestration of a building is a major feature for energy simulations, since it can have a significant influence on the U-Value of the building envelope. This is especially because windows usually have a higher heat transmission than the surrounding wall.

Some non-geometric parameters such as building usage type, year of construction, and information about the number of occupants, are further features that can contribute to a more reliable simulation. These parameters are often easy to access and therefore should be considered as model enrichment measures to reach NMS2. While the building type may be found in some NMS1 models, the year of construction and the number of occupants are usually not available. The building type can give hints for the schedule and density of the building occupants. The year of construction can be important, since the building envelope of a building could be estimated based on typical related archetypes. The number of occupants in accordance with the building schedule can have a significant impact on the simulation.

Neighborhood Model State 3 (NMS3). If a rough WWR is known, influences like the orientation of the windows can be additionally considered for an even more accurate simulation. The orientation of the windows can thereby have a significant impact on the heat transmission through the building envelope [28]. However, obtaining the orientation of the windows is even more challenging than the guessing of a rough WWR. Therefore, advanced algorithms might be necessary. Regarding the possible errors in the geometric representation, a check of the underlying model should be performed to ensure the basic geometry is correct.

At this stage, further non-geometric parameters like the heating system and the wall layers should be considered more precisely. Thereby, it needs to be differentiated between basically three common heating systems: district heating, fossil fuel based heating (gas, oil), and electric heat pumps. However, complex neighborhoods like UBC are also likely to have complex heating systems. In the example of the ESC building, the heating systems consist of a heat pump which is supported by district heating. The heating system of the CIRS building is even more complex. Here multiple electrical heat pumps working together, and the system is even overarching multiple buildings that exchange heat. Identifying the exact layer composition of walls is a comparable challenge. Even for individual buildings, energy advisors need to guess the layers in case it is not even known to the homeowner. Due to the risk of releasing harmful particles like asbestos, energy advisors are urged to not drill or open the walls in any way for investigating the wall layers, which makes it nearly impossible to reliably determine the construction of the walls on a large scale.

Neighborhood Model State 4 (NMS4). The last NMS is the most detailed one. It includes all the features that are necessary for a reliable energy simulation. That level of detail required for this NMS is comparable to the design BIM version of a building with an LOD of 300 and above. However, the data acquisition for this NMS is the most challenging one regarding the availability of the data and on a district level usually not feasible. Here, different additional data parameters can be considered, such as the information about a basement, accurate zone information, the inner layout, the exact heating system and the exact wall layers. This information is usually available in BIMs, however even here can be considerable differences between design, construction and as-build models. Also, non-geometric information like historical operational data and the accurate used heating system should be added to reach this enrichment. This information can be obtained from owners, but is usually not accessible on larger scales. Probably the most challenging part of the NMS4 is the acquisition of the occupancy behavior (such as ventilation habits or the actual desired temperature).

5 Discussion

As the conducted literature review showed, energy simulations on a neighborhood level can contribute to reducing the emission of greenhouse gasses and are a promising instrument to reach the self-imposed objectives in the fight against climate change. However, the literature also mentions when performing energy simulations on a large scale, it comes with problems that impact the reliability of the simulation. Therefore, the authors proposed a multi-stage approach to understand GIS model enrichment on a neighborhood level, the Neighborhood Model States (NMS) concept. This consists of four levels with increasing amounts of information, based on an initial (and usually low detailed) GIS model. The NMS levels are thereby oriented on the feasibility of gathering the additional information to enrich the basic GIS model.

In the course of developing the NMS concept, many problems arose that underlined the challenges of enriching low level GIS models with reliable and accessible data. To demonstrate the concept, two representative buildings of the UBC campus were chosen, the ESC and the CIRS building. Even though both buildings came from the same CityGML model, one showed a significant underestimated volume. This can lead to not reliable energy simulations. However, these models usually serve as basis for neighborhood energy simulations and are used unverified, which is due to a lack of verification possibilities. This shows, that there is a strong need of algorithms which uses additional databases to further enhance GIS models.

Since data availability is one of the most challenging problems when it comes to simulation on large scales, the authors also want to encourage further deployment of comprehensive and accessible databases. For neighborhoods, cities can serve as an example, where much more relevant data is being made available through open data platforms.

To be able to do all these kinds of data enrichment, much manual work is required, and therefore it is not feasible to do it for multiple buildings on a large scale by hand. Based on this work, the authors are currently working on an automatization approach for enriching the individual buildings in a neighborhood. For this, they are working on AI algorithms to automatically extract window ratios and positions from openly available satellite images as well as on an automated dimension validation method. This will increase the reliability of the simulations significantly. Also, the authors aim to operationalize the NMS concept by scaling it to the extent of the UBC campus. Furthermore, the authors are interested in the investigation of the challenges in the data exchange between GIS models, UBEMs and energy simulation software.

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Feasibility of an Automated Inspection Process Adoption for Quality Housing Delivery in South Africa

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Abstract Housing inspection is an essential task to ensure quality delivery during construction operations, in accordance with relevant building manuals and standards. It is critical to ensure that customers are satisfied with housing delivery by monitoring construction activities per stage inspections. The evidence gathered from housing construction inspectors as well as from previous studies suggests that the effectiveness and efficiency of inspection processes currently in the South African construction industry are unsatisfactory. This paper reports on South African research that explores the feasibility of adopting an automated inspection approach to incorporate digital technologies such as 3D laser scanners, drone technologies, and Building Information Modeling (BIM) into the housing construction inspection process to facilitate more effective and efficient data collection, processing, and reporting for improvement of the inspection process. The paper also discusses the interview results of housing construction inspectors about the possibility of adopting an automated inspection approach. The results show that the automated approach with the new digital technologies has the potential to improve housing construction inspection for the delivery of quality housing. The research efforts will also enhance the current knowledge of the housing construction inspection process.

Keywords Automated inspection · Feasibility · Housing construction · Quality delivery · South Africa

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1 Introduction

The poor housing delivery in South Africa like other developing countries is faced with issues which can be considered quantitively and qualitatively in the construction sector. Quantitatively, the country is still experiencing a huge housing backlog [1–4]. This is despite the government's achievement of handing over 4.3 million houses between 1994 and 2015, which benefited more than 20 million people [5]. According to [6] national housing backlog was about 2.1 million in 2010 and 2.3 million in 2018 which indicate that the problem is an increasing one. Even with the Government and private sector coming together with monetary investment in trying to accelerate the quality housing delivery, the issues have not been alleviated [1].

Similarly, the South African construction industry shows a promising adoption of new technologies for quality inspection monitoring such as the use of Drones to inspect buildings under construction [7], but there are still issues with quality delivery of housing seen in customer dissatisfactions [8, 9]. As a result, the current housing backlog is worsened [4] and the previously disadvantaged people remain without shelter which makes it difficult for South African government to effectively participate towards the year 2030 agenda of ensuring that everyone will shelter in quality houses.

Having acknowledged the above government awareness and interventions to mitigate housing delivery challenges. It was also found from the literature that automation could be the solution in delivery of quality housing to contribute at solving the current problems [10–14]. Over the past years, empirical studies on automated inspection process received significant popularity in the construction industry such as bridge inspection, existing building inspection, ongoing building construction inspection [14]. Instead of paper and pen inspection from the traditional method of inspecting, this automated inspection process method offers to the inspector the ability to efficiently and effectively inspect and delivery quality of housing construction to the customers if implemented [15].

Despite awareness of the potential impact to inspection process if automation is implemented, little empirical studies have been carried out on the feasibility of implementing automated inspection process on the actual housing construction phases. In one of the few studies of automation for quality monitoring, automated inspection approaches are still operating in isolation with lack of interoperability between software programs where comprehensive information could be exchanged among inspectorates [16, 17]. Another study by [18] suggest that BIM-enabled inspection technology can assist inspectors to be able to define all the inspection tasks before actual site inspection and reduce inspector's workload by making inspection process straightforward although it still need to be tested on the actual construction project. Moreover, [19] suggest that there is a need to link these suggested automated inspection approaches in a common data environment (CDE) where there is potential benefit of achieving transparency and openness of the inspection process as well as to make it easier for inspectorates to gain access to all comprehensive data about the houses being inspected. Ultimately, this will improve the efficiency and effectiveness of inspection process for quality housing delivery.

Little is however known on how feasible the above approaches can be implemented on the actual construction project with the ultimate benefit for quality inspection entities to improve inspection process, and the subject is suited for qualitative approach. Therefore, exploratory study was carried out from inspection entities in South Africa, Gauteng Province to explore the feasibility of implementing automated inspection process for quality housing delivery to the satisfaction of customers. Also, study contacted by [4] attest to the fact that South Africa cannot be left behind with the fourth industrial revolution (4IR) on quality housing delivery.

1.1 This Study

The aim of this study was to explore the feasibility of adopting an automated inspection approach to incorporate digital technologies such as 3D laser scanners, drone technologies, and Building Information Modeling (BIM) into the housing construction inspection process to facilitate more effective and efficient data collection, processing, and reporting for improvement of the inspection process. The research question for this study was as follows: What automated inspection digital technologies can inspection entities in South Africa adopt to improve efficiency and effectiveness of data collection?

2 Method

2.1 Study Design

This study was carried out using phenomenological qualitative design approach supported by [20]. It was used to explore experiences and views as well as perceptions of housing inspectors on the feasibility of automating inspection process for improvement of quality housing delivery. A qualitative research approach explores and tries to understand social or human experiences about the phenomenon being studied [21]. It is the method suitable for the exploration of a research study where little is done on the research topic [22]. In this qualitative study, the semi-structured interviews were used to collect inspectorates' experiences and perceptions about the feasibility of automating inspection process in the South African housing construction sector.

2.2 Sampling and Recruitment

The sampling method chosen for this study was purposive sampling looking at the specific nature of the research at hand and the limited number of potential interviewees as this research was carried out during the COVID-19 pandemic with many restrictions such as social isolation which slowed down the participants' recruitment [23]. Thus, purposive sampling was used to ensure that housing inspectors who participated were experienced and knowledgeable to provide rich information for this research study.

The recruitment of housing inspectors and inspectorate managers who participated in this study were written a formal email which explained the aim and objective of this study. Also, a consent form was emailed to interviewees during recruitment which was signed and emailed back to me. Through snowballing, sampled participants further assisted by identifying other possible candidates who could fit the study criteria [24, 25].

2.3 Data Collection

Data can either be primarily or secondarily collected. In this study, primary data was collected with remote interviews which took place between 15 to 65 min. Face to face interviews in qualitative studies is considered a golden standard because of potential it has in producing participants honest views on the sensitive topics [26]. However, due to many restrictions on mobility and the need for social distancing during the COVID-19 pandemic, individual interviews were used as a tool for this study, and interviews were conducted digitally with Microsoft teams and telephonically depending on the choice of the participant [27, 28]. Unstructured, but guided by open-ended research questions were used. According to [27] "data collection through this remote online platform can be feasible, safe, and very convenient".

2.4 Data Analysis

This study interviews ranged from 15 to 65 min. The transcriptions were verbatim and analysed using thematic analysis as advised by [29] in their research study. The data analysis in this study was inductive allowing themes to be identified from data rather than a more deductive approach used for quantitative data analysis [25]. Most qualitative data is analysed with the help of software such as NVivo, MAXQDA, ATLAS.ti to explain, understand or interpret meaningful and symbolic content of qualitative data without risking trustworthiness but enhancing it [30]. For the study at hand, ATLAS.ti 9 was used to aid with coding data from the transcription's documents. Compared to other software, it was found to being more rigorous and bring more trustworthiness to qualitative study [30, 31]. Moreover, [30] support the use of ATLAS. ti 9 looking at its practical benefit of enhancing the credibility of the study by making the research processes replicable and more transparent.

2.5 Ethical Approval

All study interviewees were fully informed about the purpose of this study, the processes used to collect qualitative data. Informed written consent was a requirement for interviewees before participations. This is because ethical considerations also form an important role in research design. In line with designing research to be more rigorous, it should also be designed ethically where confidentiality and anonymity are assured to interviewees [32]. It was therefore imperative to protect the interests of interviewees in this study. For that reason, interviewees were first informed that the data would be used for research purposes before provided written/verbal consent. The research aims, data disclosure procedures as well as the steps taken to protect their personal information were also mentioned to them. The approval to carry out interviews from different housing inspection entities was granted by the University of Johannesburg Research Ethics Committee (approval number: UJ_FEBE_FEPC_00061) considering four principles of ethical concerns as suggested by [33].

3 Results and Discussion

3.1 Overview of Interviewees

There were 12 interviewees, both males and females of various ethnic and social backgrounds with housing inspection work experience in Gauteng Province South Africa all meeting the criteria of the study as explained in the invitation letter. The interviewees years of experience as inspectors ranged from 3 to 5 years for juniors and above 5 years as senior inspectors. The basic demographic characteristics of the participating individuals are summarised in Table 1 below. Pseudonyms were used to maintain anonymity as indicated the consent form**.** The inspectorate managers were contacted to help locate interviewees. The contacts details of inspectors were provided with their consent for those who were willing to participate in the study.

3.2 Feasibility of Adopting an Automated Inspection Process

Figure 1 below present network with three themes and relevant sub-themes of the study, and the links as expressed by interviewees on each theme. A discussion of the

Table 1 Characteristics of interviewees (n = 12)

ID	Pseudonym	Gender	Position	Years of experience	Qualification	Role	Location	Interview technique, date, and duration
1.	Bokang	Male	Junior inspector	Above 3 years but less than 5 years	Construction Management	Housing inspector	South Africa, Gauteng province	Microsoft teams; 28/10/2020; 60 min
2.	Aurora	Female	Junior inspector	Above 3 years but less than 5 years	Civil Engineering	Housing inspector	South Africa, Gauteng province	Telephone interview; 28/10/2020; 45 min
3.	Kwetsa	Female	Junior inspector	Above 3 years but less than 5 years	Quantity Surveying	Housing inspector	South Africa, Gauteng province	Microsoft teams; 28/10/2020; 60 min
4.	Lekaota	Male	Senior inspector	Above 5 years	Architecture	Housing inspector	South Africa, Gauteng province	Microsoft teams; 29/10/2020; 63 min
5.	Mohau	Male	Senior inspector	Above 5 years	Construction Management	Housing inspector	South Africa, Gauteng province	Telephone interview; 29/10/2020; 60 min
6.	Mashuka	Male	Senior inspector	Above 5 years	Architecture	Housing inspector	South Africa, Gauteng province	Microsoft teams; 31/10/2020; 64 min
7.	Dikwekwe	Male	Senior inspector	Above 5 years	Civil Engineering	Housing inspector	South Africa, Gauteng province	Telephone interview; 03/11/2020; 55 min
8.	Neo	Male	Senior inspector	Above 5 years	Civil Engineering	Housing inspector	South Africa, Gauteng province	Telephone interview; 03/11/2020; 15 min

(continued)

Table 1 (continued)

ID	Pseudonym	Gender	Position	Years of experience	Qualification	Role	Location	Interview technique, date, and duration
9.	Bohlokwa	Female	Senior inspector	Above 5 years	Quantity Surveying	Housing inspector	South Africa, Gauteng province	Microsoft teams; 10/11/2020; 55 min
10.	Kahiso	Female	Senior inspector	Above 5 years	Civil Engineering	Housing inspector	South Africa, Gauteng province	Microsoft teams; 16/11/2020; 60 min
11.	Poloko	Female	Senior inspector	Above 5 years	Quantity Surveying	Housing inspector	South Africa, Gauteng province	Telephone interview; 16/11/2020; 45 min
12.	Nthati	Female	Senior inspector	Above 5 years	Construction Management	Housing inspector	South Africa, Gauteng province	Telephone interview 18/11/2020; 55 min

findings in each theme follows. The quotes presented in the discussion of the findings of the research study have been taken verbatim from the interview transcriptions and have not been altered in any way. The importance is on representing interviewees views, experiences and perceptions honestly.

Inspection Process

Despite challenges with the inspection process, interviewees expressed passion for their work and felt they could do better with an improved inspection process. They felt that the inspection process is not supportive to inspect all houses without compromising the quality of housing delivery. They seemed to be saying: "*We know that we do our work, but the inspection process in place fails us*". This indicated that they wanted things to change in the way inspections are conducted. Three sub-themes were identified within this theme.

Need for the Automatically Linked Inspection Task All interviewee talked about the importance of linking the inspection tasks automatically. They opined that inspection organisations inefficiency and ineffectiveness in delivery of quality housing will persist if this need is overlooked. All the interviewees recommended the need for automatically linked inspection task to avoid time waste as expressed by interviewee 3 and 4 stating that:

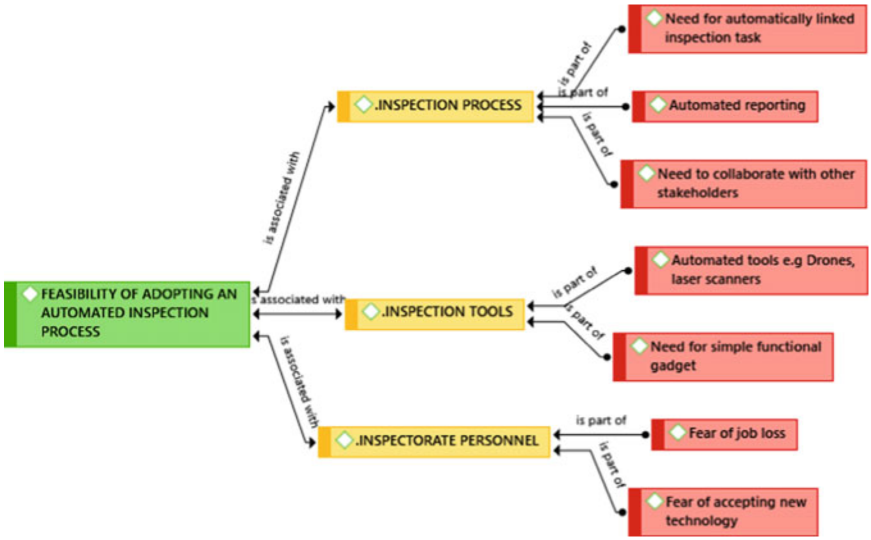

Fig. 1 Feasibility for adopting automated inspection process

We have requested that when they do enrolment, they must also link the plans submitted by home builders into the gadget and align them with a specific site number ***(interviewee 3).***

In that way when I conduct my inspection on-site and they have used that link, I can do the report and the report will automatically go to the linked people ***(interviewee 4).***

They also felt the need to automatically link their day-to-day task with other inspection organisations. Most interviewees felt that this linkage between them could improve the intention of quality housing delivery and their flexibility in sharing the tasks. Interviewee 1 and 10 explained why all inspection organisations should link their inspection tasks:

There must be a linkage to the local authority, municipality to my system that I am working with to say these are approved drawings ***(interviewee 1).***

If we could link automatically with warranty provider and Department of Human Settlements (DHS) so that when we come across a builder who is not building with good quality material or the mixture of concrete is not right for example, we will be able to call warranty provider to jump in because we as Municipality we focus on compliance, not quality ***(interviewee 10).***

According to [34, 35], linking of inspection process has the potential of improving the delivery of quality housing. This is supported by the study conducted by [17] who found out that inspection tasks can be managed more efficiently when carried out through the link to the database which is more time-saving compared to the traditional method of inspecting. Inspectors will be able to work hand in hand in managing inspection tasks than the current situation of working in silos.

Automated Reporting Five interviewees support the need for automated reporting of inspection data than manual capture of data. They expressed some hope that an automated inspection process will assist with the efficiency when it comes to reporting of data. Interviewee 10 mentioned that:

> *When it comes to reporting, I don't have to back to the office to capture the report, but I can just send the report from the site or on my way home* ***(interviewee 10).***

Upon closer examination of the interviewee's 10 opinions regarding the need for automated reporting of inspection data, it is evident that traveling back and forth to the office just to go and submit inspection data is frustrating. This view is consistent with most inspectors interviewed, where the frustration in this process is blamed on the traditional method of inspecting. This was also supported in the study by [36] where they mentioned that although the inspection process is largely manual, there is a feasibility for the automation approach to the inspection process of houses.

Need for Collaboration with Other Stakeholders The first two themes in the "Suggestions for improved inspection process" category seemed to suggest the need for collaboration with other inspection institutions in the construction of housing in South Africa. This was expressed by eleven interviewees out of twelve and formed the next theme.

> *As I highlighted earlier, the collaboration of the inspection institutions like warranty provider, Municipality, etc. can produce the system whereby I as warranty provider inspector I can get approved drawings without having to ask anyone (interviewee 1).*

Interviewees felt that working in silos with other inspection organisations adds to ineffectiveness and the possibility of failure to effectively inspect all houses. These were the same findings by [37] where they found that lack of proper integration between inspection organisations such as warranty provider and other government departments could lead to poor quality housing delivery. The interviewees of this felt that the joint inspections could assist in their organisations mandate to quality housing delivery. They further mentioned that having to rely on builders for drawings as was one of the challenges that would be mitigated by the collaboration of inspection organisations.

Inspection Tools

Housing inspectors from the interviews reckoned that adopting an automated inspection process will improve the quality of housing delivery, this is due to automated tools that can be used which will provide them with freedom from tedious physical inspection tasks and able them to focus on other tasks. They suggested that automated inspection tools will be of great help in assisting them to effectively carry out the inspection process to deliver quality housing that is currently compromised due to ineffective inspection tools. They mentioned that improvement in quality delivery of housing was unlikely to happen until the adoption of automated inspection tools. Under this theme, two sub-themes were identified.

Automated Tools E.G Drones, Laser Scanners All interviewees showed their preference for the automated inspection process with tools such as drones, laser scanners saying they could assist them towards quality housing delivery if used like other industries are doing. They further made example with the current global pandemic that the automated tools can improve the processes where one interviewee said "the automation part as we have realised with Covid-19, some certain things were done digitally. I think it's the introduction of the digital world, the Fourth Industrial Revolution (4IR)" (interviewee 8). They seemed to emphasise the need for automated tools to assist during the inspections. To express their wish and need for change from the use of traditional inspection tools as discussed above, interviewees 1, 5, and 6 eloquently said:

> *In terms of the laser tools, it will be great as well. It will say one time if I want to know if the room is 3m length by 3.5 widths. You won't need to walk around the room doing that, it will be effective, it will save time, and also minimise the errors of reading the tape **(interviewee 1).***

> *We must use those laser tools. Because on-site can be frustrating where you have to teach builders how to use fishline, square, spirit level **(interviewee 5).***

> *If you're going to be stuck in traffic for two hours, you're not going to reach the inspection target but, with a drone, you can just direct it and remember, you cannot bribe the drone. If something is wrong, it is wrong, it reports things as is. (***Interviewee 6**).

The interviewees affirmed the need to get automated tools to assist them with daily inspection tasks was important to them. They described the benefits that will come with the use of automated tools that they will be relieved from the frustration of having to spend hours measuring one house or stuck in traffic while there are many more other houses awaiting inspection. They are worried as well with some of their colleagues taking bribes on-site from poor workmanship and they believe that one cannot bribe the drone that if something is wrong, it is wrong, it reports things as they are. They also suggest that an automated inspection process will be more effective than a traditional inspection process in terms of timesaving, cost-saving, and the ultimate quality delivery of housing. In support of this view, [38–40] observed that the use of digital tools such as drones and laser scanners to help inspectors leads to the more effective inspection process.

Need for Simple Functional Gadget Most of the inspectors expressed their experiences with the current gadget they use and reported its dysfunctionality as stated in theme two. They seemed to be asking for the simple functional gadget that can effectively assist as a tool to carry out the inspection task. One of the interviewees mentioned that:

> *The simplicity of the gadget will greatly. If it can have GPS so that when I punch in the street name it gives me the map that says this street of erf number at the particular location, to know if it's in Midrand, or waterfall, etc. It gives me an easy way of finding the site **(interviewee 1).***

Some interviewees made suggestions of the kind of gadget that could be suitable in assisting them to carry out inspection tasks. They explained the need to get a simple gadget that will have all the important features that will contribute to improving efficiency during the inspection process. They insisted that inspectors should have gadgets so simple but with easy access to building plans on it and other decision support tools to conduct inspections to avoid challenges. This is supported by [41] who proposed a simple gadget that is efficient in data collection.

Inspectorate Personnel

The two themes above under feasibility of adopting an automated inspection process seemed to suggest that all interviewees will be happy for automated inspection process saying the inspection process of houses is ineffective. However, in this theme, some of the inspectorates expressed fear of job loss in case their organisation adopts an automated inspection process. They also fear the demands of new technology having to improve on their qualification to fit in. Two sub-themes were identified under this theme.

Fear of Job Lose Some interviewees expressed their fear of job loss because of the consequences that might come with the adoption of an automated inspection process. They felt that inspection is visual and there is no way it can be automated, as interviewees 3, 4, and 5 strongly commended:

> *I do not see any need for an automatic inspection process besides that the inspector must be there* ***(interviewee 3).***

> *I think, unfortunately, it comes with some negative because human settlement won't be involved then, there will be job loss* ***(interviewee 6).***

> *Robots it's a no! if we use robots, it means we won't have jobs. I will say no because the robot is the system that is being fed with the information and some of our brothers and fathers working on-site don't know the language that robot speaks unlike us who will take means to explain* ***(interviewee 5).***

Housing inspectors reckoned that majority of inspectors will lose their jobs by implementing an automated inspection process, this may be due to inspection organisations need to get skilled inspectors to carry out automated inspection tasks. Besides, there were only a few respondents from the interviews that perceived a bad impact by the adoption of the automated inspection process. It is also important to note that the automated inspection process will still require the inspector's involvement [42]. Thus, inspectors should not fear job loss but look at it as the method that will relieve them of their workload.

Fear of New Technology Acceptance Three interviewees were reluctant during the interviews to talk about new technology that could assist them with daily inspection tasks. They had assumptions that new technologies cannot address the social issues that humans are handling daily on construction sites. They were also concerned with difficulties that might come with it and some said:

> *I just think I am born before technology (BBT)* ***(interviewee 3).***

Technology sometimes… isn't it will be formatted so it will be difficult to incorporate what you didn't see in the report. Sometimes I do not trust those technologies because some things need human judgment. You will think things are correct only to find out they are not ***(interviewee 9).***

I don't think a human touch can be replaced by any gadget whatsoever. You will always need that human element for everything. There are social issues that a drone cannot address, there are other environmental issues that a drone can't address. So, you can't necessarily say, now a drone is going to take away all those inspections ***(interviewee 7).***

Some interviewees felt that technology will not work for them as they believe inspection can only be conducted by inspectors physically. They hesitate in accepting new technology and they felt that they are born before technology. They do not want to hear anything to do with technology and they felt that even if technology could be implemented, there will still be a need to address the social issue that technology like a drone will not address. However, [43] carried out a study looking at the shift from the use of paperwork to digital capture of data on-site. The study used the technology acceptance model (TAM) where they found that inspectors were willing to use technology which also showed potential adoption of the automated inspection process for improvement of quality housing delivery.

It was found that inspectors are willing to use an automated inspection process if it could be implemented in their organisations. They believe that the use of automation-assisted inspection tools and technologies such as drones, laser scanners could assist them tremendously as it cannot be bribed or pretend not to see poor workmanship resulting in poor quality housing delivery.

4 Conclusion

This study was to explore the feasibility of automating inspection process in South Africa for quality housing delivery. Implementing the automated inspection process could significantly reduce the inspectorate's workload, as their stage inspection can be shifted towards more automation that will ultimately assist inspection entities to achieve their mandate of assuring quality housing delivery to the satisfaction of customers. Currently, inspection process relies heavily on an induvial inspectorate when visiting different sites for quality inspection. It can be concluded from the analysed data of 12 interviewees' views from different inspection entities in South Africa Gauteng province who voluntarily participated in this study that were dissatisfied with the current traditional inspection process where they highly recommended that moving to more automated inspection process will be of great help for them looking at the issues, they face on daily inspections such as getting stuck on traffic and end up missing the inspections. It is strongly recommended that South African inspection entities adopt automated inspection process to improve efficiency and effectiveness which will ultimately aid delivery of quality housing to the satisfaction of customers. It becomes more critical especially when inspecting many houses, a day or complex structures that are lately designed and detailed inspections are expected to be delivered by individual inspectorates driving site to site. Therefore, a more automated inspection process will assist greatly with more houses inspected simultaneously and quality checked by multiple inspectorates. It is evident from the views and perceptions of interviews guarantees the feasibility of automating inspection process to improve inspection process, but future studies are still needed in other provinces as the current study was limited to Gauteng province. Moreover, another study is needed to investigate the cost required to fully have an automated inspection process that will cater for thousands of daily constructed houses in South Africa.

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Information Modeling and Digital Twin Technology (BIM, BrIM, CIM, GIS)

Building Information Modelling in Healthcare Design and Construction: A Bibliometric Review and Systematic Review

Tan Tan, Grant Mills, Eleni Papadonikolaki, Yue Xu, and Ke Chen

Abstract Healthcare facilities play a key role in responding United Nations goals, such as sustainability, health and welling. The outbreak of the COVID-19 epidemic has driven much attention to expanding healthcare capacity through advanced digital technologies, such as Building Information Modelling (BIM). Nevertheless, a systematic review of research achievements is lacking. This research uses bibliometric and systemic literature review methods to investigate BIM applications in Healthcare Design and Construction (HDC). The bibliometric investigation focuses on country, journal co-citation, and keyword clustering analyses. The systematic review classifies application domains, BIM actions, and other digital technologies accompanying BIM. Finally, 17 major BIM actions are summarized for six major domains, including operability, resilience, collaboration, sustainability and constructability. This study reveals that the outbreak of COVID-19 has greatly stimulated the academic interest in digital technologies for HDC, and there is geographical uniqueness highly relevant to local government policies and national healthcare services. However, related research is still in a relatively preliminary stage.

Keywords Literature review · Healthcare architecture · Digital technology · BIM · Healthcare design and construction

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1 Introduction

According to the World Health Statistics from the WHO [1], more than half of the world's 7.3 billion people cannot access the essential health services they need. Especially in remote and underdeveloped areas, it is hard for people to access healthcare facilities. In response, a United Nations goal aims to improve health-related sustainable development and achieve universal health coverage by 2030. Healthcare facilities will play a critical role [2], although the shortage of healthcare capacity and inefficiency in healthcare building delivery remains a significant challenge [3, 4]. Another serious challenge in terms of sustainability also exists at the same time. The energy consumption and greenhouse gas emissions caused by buildings account for about one-third of emissions. They may double in 2050, while the United Nations estimates that the urban population in 2050 will increase by 2.5 billion. The outbreak of the COVID-19 pandemic has intensified the global consensus on these challenges, as it has exacerbated capacity shortages and a crisis in healthcare facilities. Some countries are trying to expand the healthcare capacity in a short period and smooth the virus's expansion speed through rapid healthcare construction projects. The urgent need for healthcare services has accelerated the development of healthcare facilities worldwide.

However, Healthcare Design and Construction (HDC) has the highest risk of encountering major and unforeseen problems among all project types. A healthcare construction project involves hundreds of stakeholders and suppliers. The initiative of Building Information Modeling (BIM) has become a trend in the literature on HDC to deal with these challenges. BIM can transform traditional information management and integrate data from different disciplines [5]. Namely, horizontal integration among various stakeholders and vertical integration of information at different stages becomes possible with the incentive of BIM [6]. Many studies have shown that BIM has a profound impact on how healthcare projects are designed and delivered. Studies have reported the successful implementation of BIM in healthcare construction in different countries, such as the Netherlands [7], Norway [8], Australia [9], United Kingdom [10], and United States [11]. Many articles describe BIM as incredibly beneficial in designing frontiers of hospital spaces with numerous technical appliances and demanding performance requirements. However, BIM implementation also faces challenges. The reality in HDC is that introducing BIM must be done so alongside a range of complicated design standards and requirements, and so there is a significant need for further review.

This study aims to develop a comprehensive literature review for the application of BIM within the context of HDC to fill the gap. There are no systematic review in this emerging area. The research method combines bibliometric analysis and systematic analysis. Selected literature is illustrated through a country analysis, journal co-citation analysis, and keyword clustering analysis. In addition, application domains will be chategorised along with an analysis of BIM actions in various building stages, and against various techniques for working with BIM. This study will identify the trend towards BIM HDC, and develops propositions and challenges for future BIM applications.

2 Methodology

This study combines bibliometric analysis and systematic review to understand the BIM applications in HDC. Bibliometrics review provides comprehensive and objective statistics of the scholarly output and academic data to accelerate the speed and comprehension in understanding a sample of articles [12]. Systematic review is a labour-intensive method that uses reproducible methods to test hypotheses, summarise existing results, and evaluate the consistency of previous studies to improve the accuracy of the review.

The authors examined several databases including WOS, Scopus, and google scholar, comparing their coverage of disciplines and their suitability for visualisation software. In the end, WOS was selected. The initial search included queries using a combination of healthcare building-related keywords and “BIM”, including (“hospital*” or “healthcare*”) and (“building*” or “construction*” or “architectur*” or “design”) and (“BIM” and “building”) or “building information modeling” or “building information modelling”. Academic journal papers from SCI, SSCI, and AHCI were considered. In order to understand the overall development of the target field, there was no restriction on the time of publication for the search, but only articles in English were considered. In the end, 71 articles were obtained, all of which were exported as tab-delimited bibliographic data.

For the analytical protocol, the mixed review used in this paper was divided into two phases, the first phase being a bibliometric review to integrate the knowledge structure, evolutionary history and trends of the target domain. The visual analysis in the bibliometric review phase has been followed by country analysis to obtain the current status in various countries’ development; journal co-citation analysis to obtain the most influential journals; keyword clustering analysis to explore the main topics. The second phase is a systematic review. The 71 articles were screened according to three principles: (a) the term ‘healthcare building’ was identified as referring specifically to a building type rather than to the architectural focus on healthcare in general. (b) Some of the articles proposed a generalised digital building technique and selected healthcare buildings as case studies. At this point only the single healthcare building case is retained, rather than being generalised to multiple building types. (c) BIM should be used as the primary digital technology tool in the article, rather than just using BIM as a comparison or padding. Twenty four articles were removed, and the remaining 47 articles were kept for further study. Through a summary of the selected literature, the systematic review phase analysed the application of BIM in the HDC domain, its actions throughout the building life cycle and its integration with other technologies. For the data analysis phase, the six stages of data analysis included: (1) reading the abstracts, keywords and conclusions of the papers; (2) generating codes using Excel; (3) generating initial themes and formulating initial sub-themes; (4) merging and collating the sub-themes once all articles had been read; and (5) defining and naming the themes. Five main domains, 13 supercodes and 28 secondary codes were finally identified.

3 Results

3.1 Country Analysis

As shown in Fig. 1, among the selection of literature, the earliest academic publications on BIM in HDC was published by the United States (US) in 2010, although prior to this time there was earlier applications of advanced computing in healthcare design and construction. An explosive growth in research in this area across countries began in 2019. In particular, in 2020, due to the prevalence of COVID-19, researchers reached an unprecedented peak in this area, publishing 16 articles, four times the number published in 2018. The country that contributed significantly to the increase in research during the epidemic was China involved in the publication of five and eight articles in 2021 and 2022 respectively. At the same time, China is also the country involved in the most published literature with 17 articles. It is followed by the US and the United Kingdom (UK) with 10 and 8 articles respectively. In terms of inter-country collaboration, China and the US, have the highest number of publications (five). Taken together, it can be seen that the US is a pioneer in the publication of academic research on BIM in HDC. Secondly, the UK and Australia have also been contributing research in related areas. In addition, China has been the most active participant and contributor after its involvement in 2015. It is worth noting that there may be other countries that already have well-established measures and more practice regarding HDC, yet the results may not be published in journal papers, but shared, for example, in some conferences, books or grey literature. In addition, research focusing on HDC is occurring in many countries, reflecting their geographical uniqueness, and is highly relevant to local government policy and national healthcare delivery .

3.2 Journal Co-citation Analysis

Figure 2 shows that the journal “Automation in Construction” (AIC) has acted a significant role to share the impacts of research in the target area, with 58 co-citations in 71 publications. This is followed by “Advanced Engineering Informatics” and “Journal of Information Technology in Construction”, with 33 and 28 co-citations respectively. Other major journals include “Journal of Building Engineering”, “Journal of Construction Engineering and Management” and “Engineering Construction and Architectural Management”. Regarding the publication counts,

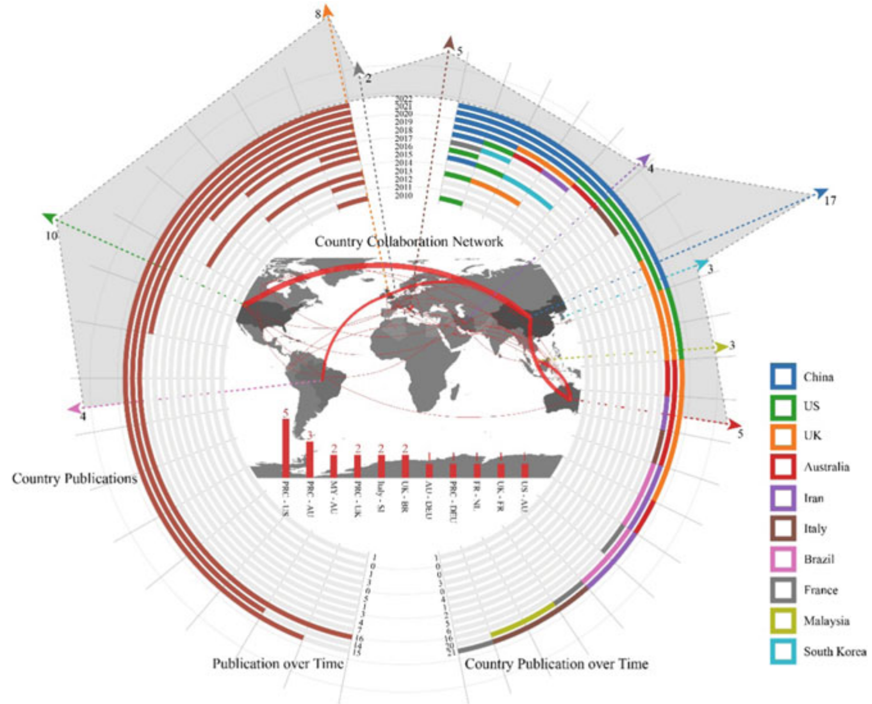

Fig. 1 Country analysis

"AIC" published 14 articles, then Sustainability published 11 articles, which accounts for the most, as other journals are all no more than 3 published articles related to BIM in HDC. It can be seen that the AIC contains a relatively comprehensive range of research on BIM in HDC in all phases of the building lifecycle, with the largest number of articles in the construction, operation and maintenance phases. The main focus of its publications is on the advancement and development of digital technology itself. "Sustainability" focuses on how these digital technologies, such as BIM, can be used to make HDC green or sustainable. Other journals also show their own taste for publication. For example, all three articles published in "Journal of Management in Engineering" focuses on the implications of management, especially a perspective on collaboration, from the adoption of BIM in HDC. Compared with other journals, "Building Research & Information" shows more attention on the design studies, as three published papers all investigate the BIM in design stage.

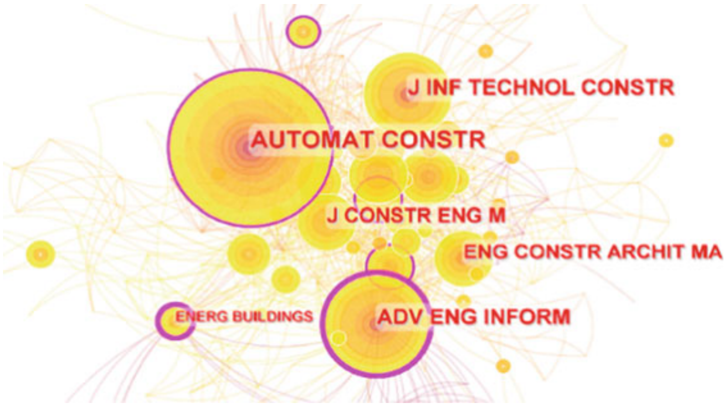

Fig. 2 Analysis of the count of co-citations and betweenness centrality of journals

3.3 Keyword Clustering Analysis

Nine keyword clusters were obtained and eight were retained after eliminating invalid clusters. The average size of the clusters was 19.5 and the average silhouette of the clusters was 0.8735. When the silhouette is greater than 0.7, it indicates a high homogeneity of the clusters and the results are convincing [15]. This study analysis six main clusters with silhouette above 0.7, namely value methodology, collaborative design, requirement management, design errors, optimal building design, and Chinese hospital (see Fig. 3). Specifically, cluster 0 is "Value Methodology". Value methodology, sometimes referred to as value engineering [16] is often defined as a method and process of analysing an entire system to remove unnecessary costs and improve performance and potential [17]. BIM, as a tool capable of integrating various forms of building information, often provides the basic information for analysing value [18]. Cluster 1 is "Collaborative Design". Keywords in the cluster include "construction", "information" and "maintenance". The emergence of BIM is itself related to the much greater complexity and fragmentation of architecture projects nowadays, which require a great deal of information exchange and sharing [19]. The discussion of BIM therefore often includes the idea of collaborative working across boundaries and disciplines [20]. The ability to provide collaborative design is also one of the main advantages of BIM, as it enables the exchange of increased information flows between stakeholders in architecture projects [21], alleviate unnecessary duplication of work and errors [22] and ultimately achieve high quality design outcomes and cost effectiveness [23]. As one of the most functionally complex building forms with the most diverse needs, it is promising to apply BIM-based collaborative design in HDC. Cluster 2 is "Requirements Management" referred to as a method of integrating multiple requirements, such as clients, users and government regulations, within a building project to improve project performance. BIM tools are used to assist in the dissemination and processing of information, simplifying the process and increasing efficiency to support the construction industry in demand management. Cluster 4 is “Design errors”. The keywords in this cluster are “management” and “impact”. Errors in the building design process are inevitable in the course of a construction project, but they can lead to delays, rework or cost overruns if not fixed in time. Traditionally, the detection of errors in the implementation of construction projects has often relied on manual troubleshooting, which is inefficient and inaccurate [24]. However, BIM can help save time and costs by warning of potential problems to automatically detect design errors, helping humans to better complete building design projects [24]. As a result, automated BIM-based design error detection is on the rise. Many of the key words in cluster 7 “Optimal Building Design” have ‘early’ as a prefix, such as early design, early decision and early assessment. The overall design and assessment of a project at an early stage is of great importance in achieving the best possible architectural design. BIM may have the potential to significantly assist designers in making decisions in the early stages of design to achieve optimal design. The cluster 8 “Chinese hospital”, which highlights the use of BIM in Chinese hospitals and especially the unprecedented rate of building completion of Huoshenshan and Leishenshan hospitals in Wuhan, China for combating the outbreak of COVID-19. These studies emphasizes the acceleration of digital technologies and off-site construction for speeding advanced hospital construction for health emergencies.

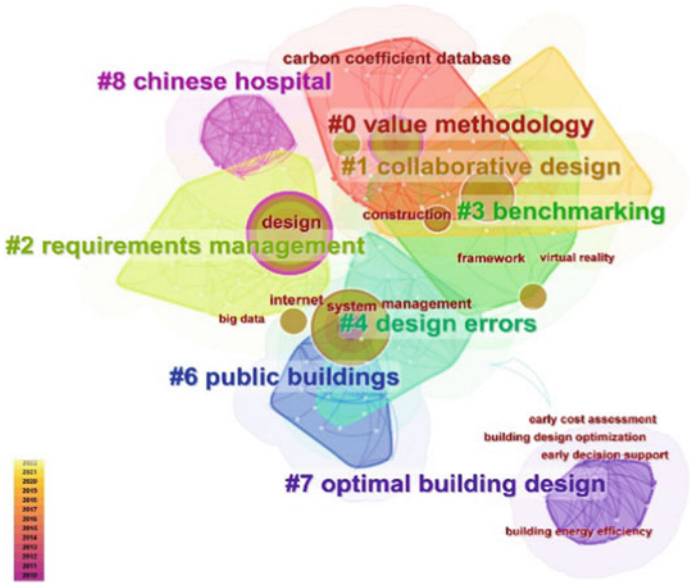

Fig. 3 Keyword clustering analysis

3.4 Classification of Application Domains

As shown in Table 1, the five main application domains of BIM for healthcare were identified: operability, resilience, collaboration, sustainability, and constructability. Twelve of the reviewed papers were related to operability, accounting for 25.5%, with a focus mainly on the post-completion phase of hospital operations, including facility management, user-friendliness optimisation, and benchmarking. Eleven of the papers reviewed were related to resilience, accounting for 23.4%, focusing on the adaptability of healthcare buildings to external disasters such as epidemics, fires, earthquakes and other disturbances, including health emergency and conventional disaster response. The most significant proportion of health emergencies is based on the practical experience of responding to COVID-19 to explore the BIM application in healthcare buildings. There are eleven papers related to collaboration (23.4%). Collaboration in the design phase was mainly related to the use of Virtual Reality (VR) technology to create virtual working environments. In addition, nine articles (19.1%) are related to sustainability, focusing mainly on energy consumption in buildings. And two articles were related to constructability, accounting for 4.3%.

3.5 BIM Actions for HDC

This paper classifies the full lifecycle stages of a building according to the role of BIM in 47 articles, divided into four stages: planning, design, construction and post completion (see Table 2). Design and post completion, especially detailed design and operation, are two major phases adopting BIM actions. With the explosion of COVID-19, many studies have begun to focus on the integration of modular hospital with BIM, and BIM-enabled design for manufacture and assembly in HDC. BIM actions embody the capabilities that drive rapid healthcare construction in these research. In addition, the study shows that current research mainly focuses on the BIM as a digital tool to support the databases or modelling functions. However, there is few studies about BIM as an innovative digital process for HDC. In the context of HDC, it does not perform the adoption of BIM features that are different from other building types. Therefore, in this part, the study of BIM-driven healthcare facilities have more generalization capabilities than uniqueness. As can be seen, the existing literature tends to take a reductionist view for BIM research. That is, if the HDC is viewed as a process of building a complex system (i.e. a hospital), these studies attempt to single out parts of the overall system, i.e. a particular sub-system, as a specific scenario for the study of BIM technology. This approach although has specific benefits, for example by reducing the complexity of the overall technology application scenario. The negative situation is that this way of attention and research is also hindering the application of BIM, i.e. these fragments or small snapshots of implementation prohibiting a full understanding of a whole system/whole-project process approach to BIM implementation.

Table 1 Classification of application domains

Domain	Code/super codes	Second Code
Operability (12)	Facility management (8)	Facility management improvement
		Facility maintenance
	User-friendliness optimisation (2)	Patient natural view analysis
		Indoor navigation sign optimisation
	Benchmarking (2)	KPI benchmarking system development
Resilience (11)	Health emergency (7)	Emergency hospital design and construction
		Emergency hospital design
		Emergency hospital construction
		Facilities interconnection hospital
	Conventional disaster response (4)	Resilience performance analysis
		Fire rescue simulation
		Emergency evacuation
		Emergency decision support
Collaboration (11)	Design collaboration (7)	Virtual design work environment
		Integrated design systems
		Co-design tool development
		Client requirement management
		Construction collaboration network
	Construction collaboration (1)	Construction collaboration
	Design-construction collaboration (2)	Design-construction collaboration
Sustainability (9)	Energy consumption (6)	Energy consumption analysis
		Green Building Early Design
	Building component recycling (2)	Building component recycling
	Resource allocation optimisation (1)	Resource allocation optimisation
Constructability (2)		Rule checking
		Error Management
Other (2)2		

3.6 Other Digital Technologies Working with BIM

Other digital technologies were investigated alongside BIM to facilitate HDC. As shown in Fig. 4, emerging digital technologies including VR, Radio-Frequency Identification (RFID), Cyber-physical systems (CPS) and Internet of Things (IOT), 5G,

Table 2 BIM actions for HDC

Stages		BIM actions for HDC				
Planning (3)		Modelling client requirements using BIM tools	As a data source of both geometric and semantic information			
Design	Concept Design (3)	Modelling of the model objects using BIM software	As a data source for predictive analysis of performance			
	Detailed Design (12)	Automated clash checking to send BIM warnings	Technical support for green performance assessment of buildings	As a data source for design optimisation		
Construction (7)		As a data source to support construction coordination	Provision of construction site spatial data	Digital simulation of construction details		
Post-completion	Operation (17)	As a data source for facility management	Modelling occupant semantic data models	As a data source for resilience optimisation and assessment	As a data source and modelling for digital twin	As a data source to analyse energy consumption
	Maintenance (3)	As a data source searching or filtering various facility maintenance data				
	Renovation (1)	Modelling existing structures				

Geographic Information System (GIS), Artificial Intelligence (AI), Mixed Reality (MR), Unmanned Aerial Vehicle (UAV) site track, robotic assembly and cloud computing. Among them, VR appears five times, accounting for one-third of the total and often promoting it use to visualise and enhance stakeholder spatial awareness and simplify the amount of BIM data [25]. Specifically in the identified literature, the role of VR is mainly in providing a new approach on design, visualisation and immersive experience. For example, Lin, Chen [26] developed a semi-immersive VR and BIM-based design for healthcare design, and Roupe, Johansson [27] developed an immersive VR-based virtual co-design environment. In terms of the different building stages, digital technologies are concentrated in the detailed design, construction and operation stage. The most frequent occurrence was in the operation stage (7 times) and with a high variety (6 sub-types). On average, 0.41 other digital technologies appear per article and 60% of other digital technologies types appear in the operations stage. Building operations are often combined with digital information and digital technologies to achieve more efficient management, with specific benefits in terms of personnel use, response speed, work efficiency and management models [28]. For example, Zhou argue that IOT and cloud computing combined with BIM have changed the data management model of intelligent hospitals [29]; Peng, Zhang [30] used AI engines to improve the speed of response to operational status anomalies in smart hospitals, and MR to improve the work efficiency of staff in checking for operational status anomalies. In terms of application domains, apart from "Collaboration - Design collaboration - Virtual design work environment" using VR, other digital technologies that appear more frequently are "Sustainability - Building component recycling - Building component recycling" (3 times). The digital technologies used in this domain are RFID, CPS and IOT, GIS, all of which are used to monitor abandoned or temporarily non-functional building components and create digital virtual models for them .

4 Discussion and Conclusion

Emerging BIM techniques for HDC include functionalities embodied in BIM and new BIM-enabled techniques. Pikas, Koskela [31] summarised 12 BIM functionalities in healthcare construction through multiple case analysis, including visualisation of form, model changes tracking, predictive analysis of performance, automated generation of drawings and documents, modelling temporary structures (scaffolding) and existing structures, automated clash checking, online communication of product and process information, online meeting sessions, reuse of model information, site planning, 4D and 5D scheduling, information for survey and scanning systems, project statues tracking, and as-built model. Many studies have shown the BIM's profound impact on how healthcare projects are designed and delivered. Many articles describe BIM as incredibly beneficial in designing frontiers of hospital spaces with numerous technical appliances and demanding performance requirements. BIM's wide range

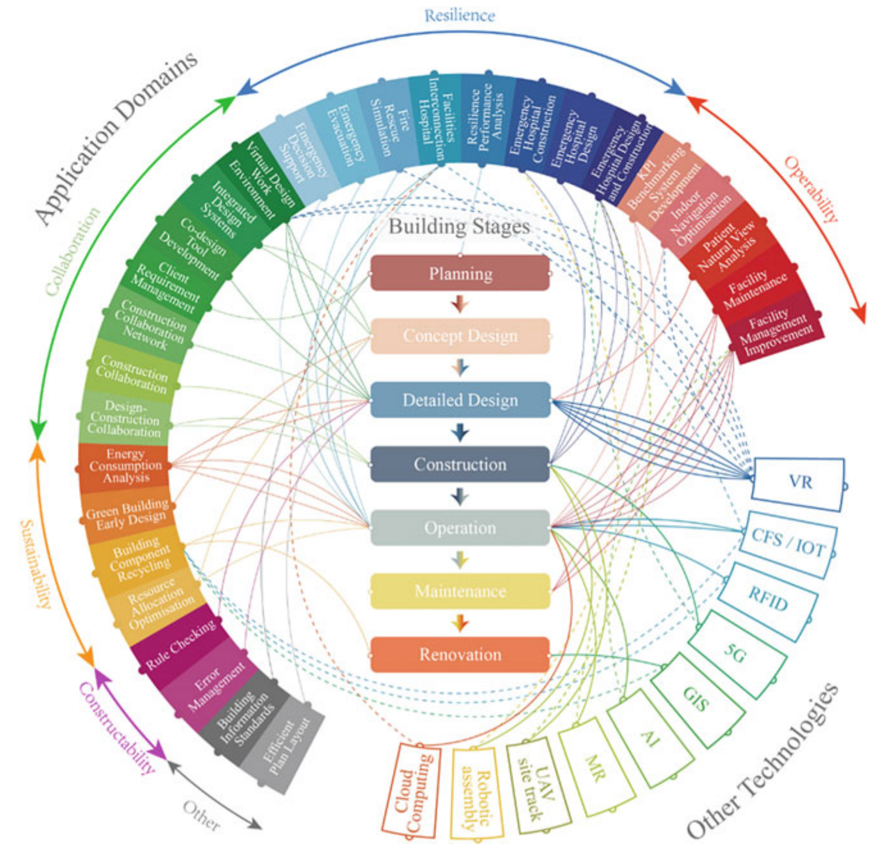

Fig. 4 Other digital technologies working with BIM

of usability and versatility allows it to be combined with a variety of advanced information technologies to better realise project expectations and drive the digitalisation of buildings [32]. However, implementing BIM also faces challenges. The necessity and evidence to introduce BIM to cope with complicated design requirements, such as hygiene, safety, and equipment, need further review and discussion.

This review shows that the outbreak of the COVID-19 epidemic has greatly contributed to an explosion of research related to HDC, especially digitization, in terms of the number of publications. Research focusing on HDC is occurring in many countries, reflecting its geographical uniqueness that is highly relevant to local government policies and national healthcare services. Despite the national differences, commonalities remain in the way digital technologies are used and in their capabilities. Mainstream journals in the field of AEC assume the main role of disseminating relevant literature and are gradually gaining popularity to the attention of an increasing number of journals.

A proportion of the studies do not examine healthcare buildings as a specialised field, but only use them in case selection as empirical scenarios to test their theories and techniques. Some studies, on the other hand, have specifically chosen healthcare buildings for specific BIM studies. Both cases reflect the uniqueness and representativeness of HDC. In detail, healthcare buildings can represent complex engineering, complex projects and complex building functions. As such, healthcare buildings are often used as a case study when examining these complexities. This complexity comes from two aspects: on the one hand, it is the diversity of functions, which represent a wide range of knowledge, design expertise and the hundreds of suppliers and stakeholders involved. The second aspect is that the functions have a huge impact, i.e. the daily use of building functions that affect health, well-being and safety.

The study shows that 17 major BIM actions are applied for six major domains, including operability, resilience, collaboration, sustainability and constructability. These BIM actions represent common BIM functions that match the functions summarized in the case study by Pikas, Koskela [31]. However, it can be seen by the phase division that many building lifecycles are not fully studied regarding BIM. For example, in the planning, conceptual design and renovation phases, the application of BIM functions is still relatively homogeneous, and many BIM functions do not exist in the literature. Therefore, future research can do more research on these building phases that lack attention. Among the many accompanying technologies, VR is the digital technology most highly associated with, with all focus on the design phase. As seen from the results, there are a wide range of real-life scenarios for applying digital technology in HDC. Future research could try to combine more technologies, such as IOT, robotics, UVA and etc., with BIM to address the capacity challenges of healthcare delivery.

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Digital Twin Technology as a Paradigm for Smart Management in the Built Environment

Olushola Akinshipe, Clinton Aigbavboa, and Chimay Anumba

Abstract The 21st-century industry world is constantly seeking diverse ways to shrink costs and time while boosting productivity and efficiency. Utilising digital twin technology is a veritable means of achieving that in the building sector. This will help better predict the future, enhancing decision-making and, in turn, reducing operational cost and downtime while simultaneously enhancing building efficiency and productivity. This study, therefore, investigates ways that digital twin technology can be used to make facility management systems proactive in nature. The study is designed to follow a methodical review of literature. It draws relevant data and information from extant studies conducted on digital twin technology within the built environment field as well as the entire field of science, technology, and engineering. A framework for management was conceptualised through this research and named 'Digital Twin Based Smart Management Plan'. A strategic process for the Smart Management Plan was developed and classified into initiation, modelling, utilisation and reuse phases. The Digital Twin-Based Smart Management Plan framework ensures complete interaction among the process, people, place, and device.

Keywords Digital twin · Cyber-Physical Systems · Facility management · Building Automation Systems · Building management

1 Background to the Study

In the recent past, studies have suggested that the building industry is static regarding technological innovations. However, lately, contemporary technologies are beginning to emerge within the industry, which is a welcome development and a forward push

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on the right track towards enhancing productivity and sustainable development [1]. A major factor for the motivated adoption of digital twin technology is its multi-faceted industry relevance. This relevance encompasses the engineering, production, and operation of industry-level systems which can only be achieved through a complex interrelationship of different fourth industrial revolution technologies that have graced the twenty-first century [2]. Numerous fields are beginning to intellectualise the application of digital twin technology to specific areas. Generally, it is used to pre-empt complications and optimise system efficiency [3]. With its pioneer success in the aeronautic industry, digital twin became a key paradigm in the era of industry computation and the fourth industrial revolution [4]. The building industry should not be left out of this technological advancement. There is a need for the building industry to take advantage of the digital twin technology and use it to optimise the numerous aspects of a facility's life cycle from conception to deconstruction.

Over time, various ICT-aided systems have been utilised for FM practices; however, most have been deemed less efficient owing to the fact that they do not support easy information exchange, which delays decision-making [5, 6]. It is worth noting that building information modelling (BIM) was developed to better manage the facility life cycle. BIM creates a model of individual building components, including the interactions with the external environment. All physical information and restrictions of the building or facility are included in the model [4]. A significant limitation of the BIM system is that it cannot offer information in real time for immediate operational action. As opposed to BIM, which centres on buildings, digital twin modelling is a more intelligent and sophisticated building model focusing more on human interactions with buildings through real-time data collection and transmission on the building's present condition. Over time, a building's digital twin will evolve in response to the physical change in the building throughout its life [7].

The 21st-century industry world is constantly seeking diverse ways to shrink costs and time while boosting productivity and efficiency [8]. Utilising digital twin is a veritable means of achieving that in the building sector. It is equipped to create an alternate virtual building and the facilities contained therein and then subject it to different real-life situations and occurrences through simulations. This will help in better prediction of the future, which will enhance decision-making and in turn, reduce operational cost and downtime while simultaneously enhancing building efficiency and productivity. From the above discussion, it is evident that the established management system in the built environment for facility management is reactive in nature – it attends the situations as they occur, increasing maintenance costs and downtime. There is a need for management systems to be proactive – they should predict and find ways to mitigate problems before their occurrence. This study, therefore, investigate ways that digital twin technology can be used to make facility management systems proactive in nature.

The research study ultimately aims to establish a smart management plan for buildings and facilities using digital twin. The study intends to revolutionise management practices to meet up with the fourth industrial revolution in the 21st-century world.

2 Methodical Structure of the Study

According to the research motivations outlined in the introduction, this study aims to develop a digital twin-based smart management plan for buildings and facilities. This effort will investigate how digital twin technology can be utilised to create proactive facility management systems. In order to accommodate the fourth industrial revolution of the twenty-first-century world, building management practices must be revolutionised. This study was conducted using reviews from relevant literature published on digital twin, facility management, building management systems and the built environment.

The methodology employed is a comprehensive and methodical literature review on the concept and its application to management practices in the built environment. In particular, a search was conducted in the Scopus Database for all publications published between 2015 and 2020 that included a combination of the terms "Digital Twin" and "Buildings" or "Built Environment" or "Infrastructure" or "Facility Management" in their titles, abstracts, or keywords. The only language considered was English; the type of publication (journal articles, conference papers, etc.) did not matter in the selection for inclusion. The reason for excluding publications before 2015 was that the main focus of the study was the application of Digital Twin to the built environment in relation to the fourth industrial revolution. No relevant publications are to be found prior to the year 2015 with respect to these topics. The study also reviewed extant archived literature from other sources to develop sufficient background knowledge for the evolution of digitalisation within the built environment.

The paper is structured as follows; Sect. 1 constructed a background to the study that developed to highlight the aim of the research. Section 2 discussed the structure which the study followed. Section 3 discussed the concept of digitalisation and digital twin. Section 4 extensively reviewed the leap from BIM to digital twin. Section 5 explored how built environment assets and facility management systems can be improved through digital twin. Section 6 explored previous use of digital twin for building and facility management. Section 7 developed a framework for facility management using digital twin, this is themed digital twin-based smart facility management. Section 8 describes the strategic process of the smart management plan. Section 9 concluded the study, highlighting the major findings of the study.

3 Digitalisation and Digital Twin

Digitalisation in industry sense has evolved across four phases. The first is digital enablement which involves the invention and usage of computers for scientific computing, it essentially entails converting physical documents into virtual formats. Digital assistance involves using computer-aided applications and systems to ease and efficiently perform tasks. Digital interlinks and control which involve the use of the internet to ease communication. Lastly, cyber-physical interlinkages encompass the use of new generation technologies such as AI, IoT, big data, cloud computing, digital twin, etc. to ease industry level activities [3, 9]. Figure 1 shows the evolution of digitalisation highlighting the processes and timeline.

Digital twin technology was birthed in 2010 when the United States National Aeronautics and Space Administration (NASA) focused its research on adopting the technology and its operation as their technology strategy for the future exploration of space [10, 11]. With its pioneer success in the aeronautic industry, digital twin became a key paradigm in the era of industry computation, the internet of things (IoT), and the fourth industrial revolution in general [4].

Studies have noted that digital twin is dynamic in nature as it is the basis of cyber-physical technology. Digital twin refers to a physical asset and a digitised model of that asset that can intercommunicate through forward and backward interactions in order to co-progress in unison [13]. Modern technologies in digitisation have allowed the holistic collection and storage of data from the physical asset to ensure accurate conformity of the virtual model in real-time [14].

The value of digital twin to the world is almost immeasurable since the technology devises a dynamic means to replicate models of physical assets in a virtual form. This replication conforms to the physical structure, position, situation, arrangement, attitude, condition, and kinesis [12]. A true replication of the physical world in digital form can be achieved through sensor-based data gathering, 3D computing, big data statistics, artificial intelligence and machine learning. This system can then be used

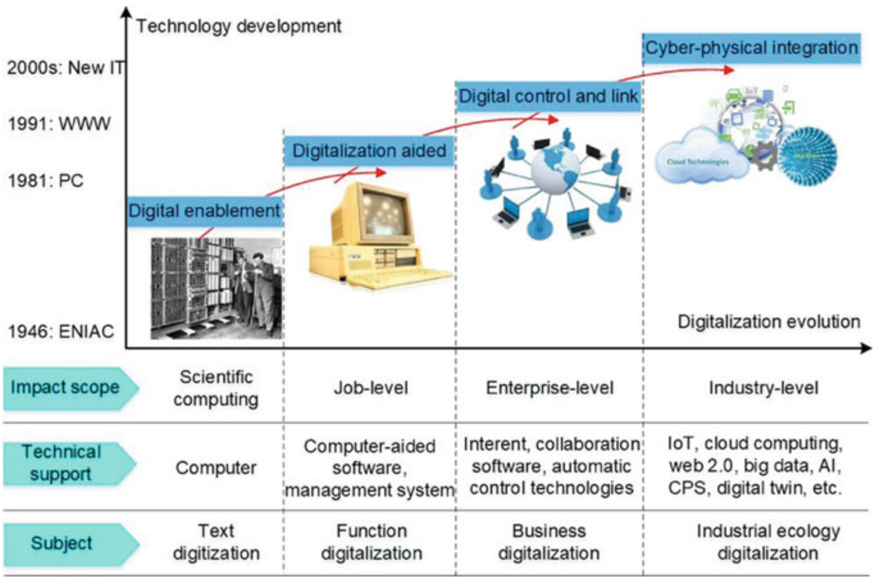

Fig. 1 Process of digitalisation [12]

for various activities, including system observation, diagnosis, forecasting, as well as enhancement.

Digital twin can specifically aid in decision-making in numerous industry fields since it can examine current trends, analyse past challenges, and project future uncertainties [15]. Also, both operational and administrative, orientation, training, and development of workers, can be performed through virtual models that the digital twin offers since the model is a true representation of the physical structure, attributes and behaviour of a real-life asset in real-time [16].

Digital twin also aids in understanding complex systems and procedures as it can use simulation and virtual reality means to breakdown physical assets and process them into smaller manageable parts [12]. A more advanced benefit of digital twin is the collection and digitisation of industry experts' knowledge, capabilities, and experience. This knowledge is stored and can be conveyed and modified to mitigate the knowledge gap in a particular field [12].

There are five aspects of digital twin: physical entities, virtual models, twin data, services, and connections. Physical entities are the assets in the physical world for which virtual models are to be created. Virtual models are the true digital duplication of the physical entity in real-time [13]. Digital twin data is the force behind the technology. The data are usually in multiple dimensions and are heterogeneous in nature. While some are sourced from the physical assets, others are formulated by the digital models through simulation. Data could also be sourced from the system's process and expert's knowledge [17]. Digital twin services encompass the wide array of activities that can be accomplished through the digital twin technology. These activities might include observation, diagnosis, forecasting, management, and enhancement. And lastly, digital twin connections refer to the interlinkage between the physical assets and their virtual replicas as well as the data and services. The connection allows efficient operation, complex analysis, and multifaceted simulation. There are six facets of connections in digital twin technology; each interlinks the other four dimensions pairwise [12, 13].

4 The Leap: From BIM to Digital Twin

The recent trends of incorporating IoT-powered sensors into built environment facilities has given unfettered opportunities to acquire building performance, management, and maintenance data in real time. And when this data is subjected to appropriate analysis and simulation, it would be useful in enhancing the operational efficiency of the components that makes up the built environment. It is worth noting that smart and intelligent buildings and, by extension, smart and intelligent cities require unrestricted access to data and processed information to function efficiently. Therefore, it is safe to assert that digital twin is a vital step to efficiently and sustainably attaining smartness in the built environment [18].

The application of digital twin technology to the built environment field will enhance the design process, optimise building operation in relation to the external

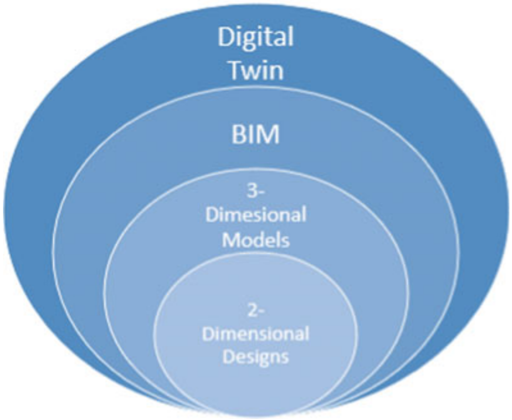

Fig. 2 Evolution of digital construction designs and models [19]

environment and also improve failure and fatigue prognosis [11]. Currently, numerous research studies are ongoing to improve modelling and simulations in built environment assets. The outcome of these studies will be channelled into strengthening digital twin applications in the built environment [19]. In construction engineering, digital building designs have gradually evolved from 2 and 3-dimensional designs to building information modelling, as shown in Fig. 2. However, it is important to note that building information modelling is the basis of digital twin in the built environment [19].

The concept of building information modelling entails accurately designing a 4 or 5-dimensional model which is diametrically for a proposed building or facility. All attributes of the proposed construction project are incorporated into the model, and the extent of the individual attributes is determined by associated physical boundaries [20]. A model of individual building components is created and their interactions with the external environment through BIM. All physical information and restrictions of the building or facility are included in the model. They can be subjected to trackable changes since the model is collectively created for different built environment professionals through the use of sophisticated architectural ICT tools (Jung, 2017). Figure 3 reveals the transformation of BIM into digital twin. Recent practices have seen the introduction of BIM integrated complementary technologies like Geographic Information Systems (GIS), Computer-Aided Facility Management (CAFM), Construction Project Management (CPMS), and Computerized Maintenance Management System (CMMS) [4].

BIM models the design of buildings and facilities in which individual building components are created and their interactions with the external environment. All physical information and restrictions of the building or facility are included in the model [4]. A significant limitation of the BIM system is that it cannot offer real-time information for immediate operational action. As opposed to BIM, which centres on buildings, a digital twin is a more intelligent and sophisticated building model that focuses more on human interaction with buildings through real-time data collection

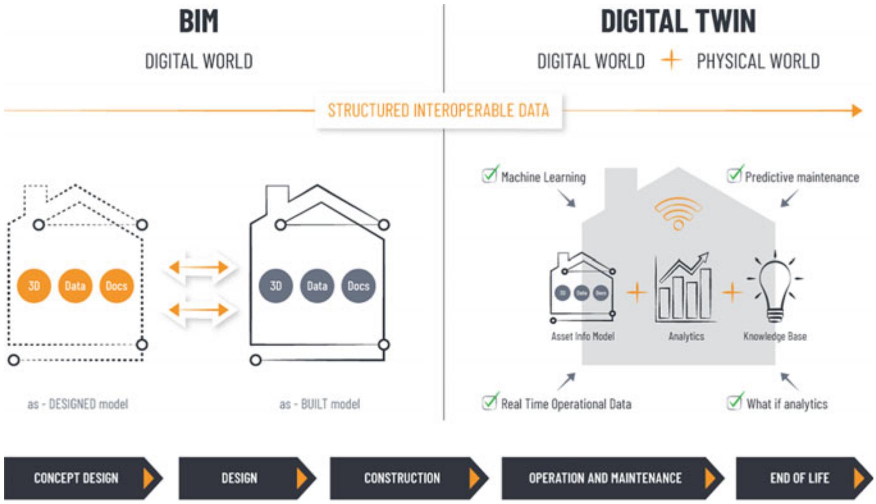

Fig. 3 BIM and Digital Twin Model Building

and transmission of the building's present condition. Over time, A building's digital twin will evolve in response to the physical change in the building throughout its life [7].

Digital twin in the built environment encompasses the design, construction, and operational stages of the building. Hence, Rogers (2019) termed digital twin as 'BIM on steroids', explaining that technology's possibilities in the built environment are currently boundless. Despite the sophistication of the BIM system, there are scores of construction information that transcends the scope of BIM, which digital twin in the built environment addresses. Building information modelling (BIM) can be revolutionised into digital twin for the built environment, which introduces dynamic elements. These elements include IoT integration in buildings and infrastructures, automation in construction, and building management systems. These elements help collect, collate, store, analyse, simulate and disseminate vital building information [4].

5 Facility Management and Digital Twin

The building and real estate field of study has always received profound interest from various professional fields, including architecture, cartography, economics, engineering, law, and management [22]. In essence, a building as an asset can be assessed from different viewpoints. As an element of science, buildings encompass all physical attributes and the legal, economic, and institutional interest inherent in them. Similarly, contemporary property management points to the fact that buildings should not merely be regarded as being only a physical entity but also as a medium of fulling management objectives [22].

Noor & Pitt (2009) reported that the intention of facility management from an economic perspective involves improving productivity and organisational revenue, which is accomplished by continuously creating avenues for cutting costs through executing a series of processes that are in line with achieving organisational goals. Effectively managing a building and the facilities contained therein usually involves verities of professionals who are required to work in concert with each other to achieve facility management objectives [6].

Traditionally, numerous professionals, managers, and artisans of varying specialised disciplines are involved in executing facility management activities. With the considerable number of personnel usually involved, efficient information exchange and management systems are required for efficient building and facilities management [24]. Incorporating information technology into facility management has offered various opportunities, which entails a more thorough analysis of day-to-day building operations. These operations include prompt estimation and identification of defects; better risk management practice; better estimation of potential operational system failures, and improved avenues for the safety of lives and property [25].

Over time, various systems have been utilised for facility management practices, which include Building Automation System (BAS); Computer-Aided Facility Management (CAFM); Computerized Maintenance Management System (CMMS); Energy Management System (EMS); Electronic Document Management System (EMDS) [5]. Practical and research evidence has confirmed the usefulness of these systems. However, they do not support easy information exchange, which delays decision making and causes unwarranted actions or inactions, making these ICT-aided systems less than efficient for facility management [6]. The development of BIM was a game-changer for the building sector, especially in facility management. A more efficient documentation and information conveyance system was utilised to improve the management of facilities [25].

The ideology behind digital twins is developed based on previous concepts and technologies. From a generally accepted perspective, digital twin is seen as a new-age Building Information Model incorporated with internet-supported sensors to ensure a real-time model update through data transfer from the building. The data collected and transferred in real time must be interpreted through analytics and AI in order to enhance decision-making [26]. For facility management, digital twin can be applied to making operational decisions and organising maintenance, remodelling, and upgrading. A digital twin platform can serve as a communication interface between the stakeholders during any stage within the facility's life cycle. Digital twin will ensure that interactions between building stakeholders are effective and help decrease unnecessary red tapes, rework, and energy demand [4].

6 Previous Use of Digital Twin for Facility Management

There are two identified existing models related to the study. As shown in Fig. 4, the first was developed by Nasaruddin et al. (2018) and was named 'Conversion of physical room to its digital representation'.

This model shows that there are seven distinct hubs, which all emanate from the building manufacturer's specifications. The framework indicates that the building manufacturer's specification is used to produce the physical space for which the digital twin is required. Data from the physical space are gathered through sensors, and these data are subjected to analytical algorithms that simulate visual representation. This representation is directly transmitted to the user interface, which shows the digital twin representation.

The second model related to the study was developed by Nie et al. (2019) and was tagged 'Digital twin-based building management service and prediction model'. The model consists of four hubs: physical building, digital twin, building operations service, and building prediction service platform; these are shown in Fig. 5.

The physical building is the primary source of data within the system, which are transmitted in real-time. The building's digital twin hub is the virtual building, which integrates models to create a digital replica of the physical building. Simulation results are derived and transmitted from this hub.

The building operations service hub incorporates a cluster of new-age technologies needed to observe, forecast, and properly manage a facility. It incorporates the management service hub and the predictive service hub. The big data process uses a collection of applications to proactively predict unforeseen interference with the operations of the building. This prediction can optimise decision making to improve building management and performance.

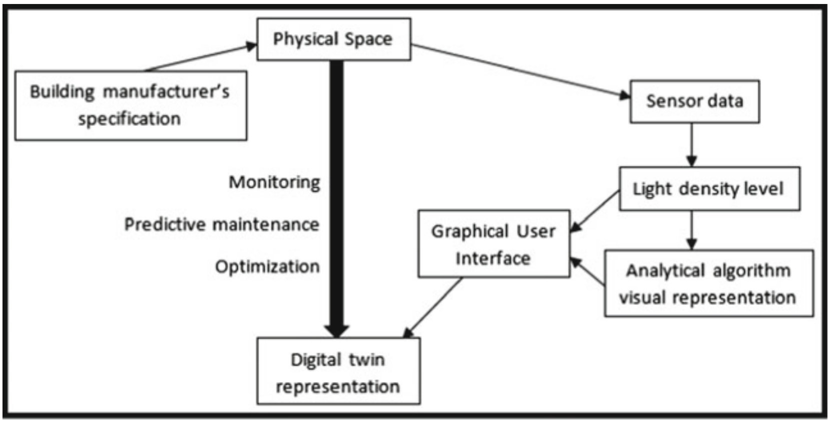

Fig. 4 Model for the conversion of a physical room to its digital representation

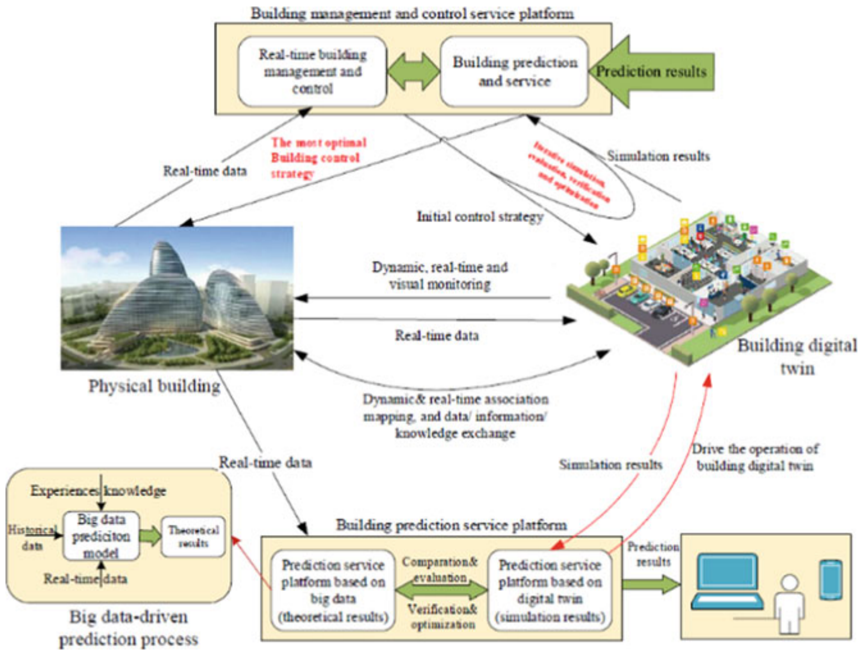

Fig. 5 Model for the conversion of a physical room to its digital representation

7 Digital Twin-Based Smart Management Plan

A critical review of both identified existing models related to the proposed study revealed some issues that need to be addressed. Both models did not account for the collation and storage of data gathered by the system. The storage of such data is vital for big data analytics and future simulations. Furthermore, the models did not consider benchmarking standards already established for both basic and ICT-aided facility management. Lastly, both models did not consider the importance of user perception and feedback systems; however, to ensure efficiency, there is a need to gather feedback from users. All these were taken into consideration when conceptualising this research and included in the model named Digital Twin Based Smart Management Plan, as shown in Fig. 6.

The Digital Twin Based Smart Management Plan consists of eight hubs. The virtual replica is a digital representation of the physical building which allows for real-time data exchange and visual monitoring. Data from the virtual hub is subjected to big data analytics and results are applied to the data obtained from the physical building as well as simulation results to optimise facility management practices. In addition, historical data and feedback from users of the smart management plan also make up inputs to the optimised management practices. At the apex, the smart management plan is a product of optimised management practices, historical data, and benchmarking standards for facility management. Finally, the perception

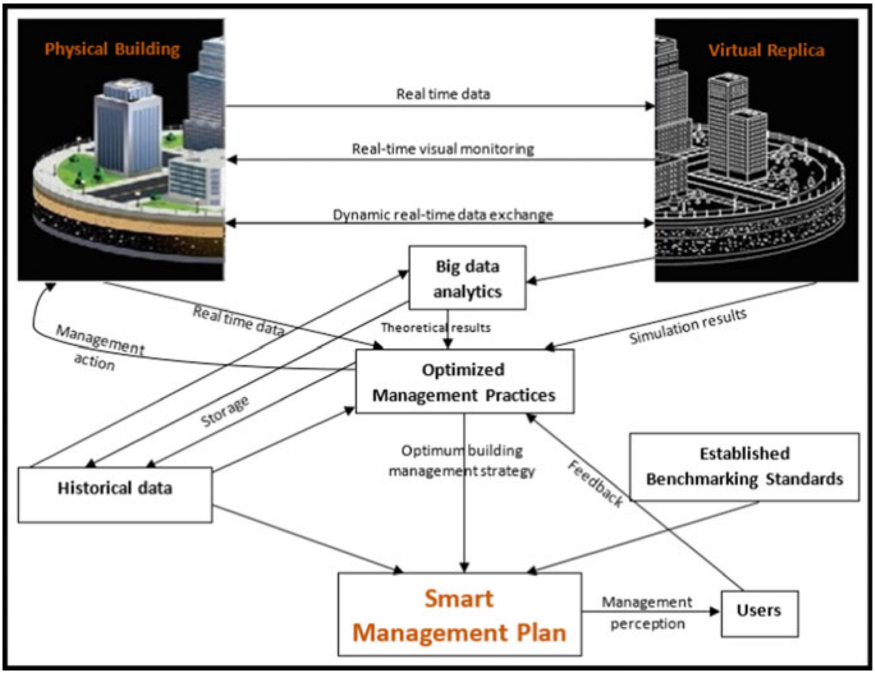

Fig. 6 Digital twin-based smart management plan

of facility managers who are the users of the smart management plan are recorded and feedback backs are offered back into the system to continually optimise management practices. This model ensures complete interaction among the process, people, place, and device.

8 Strategic Process for the Smart Management Plan

The digital twin based smart management plan can be implemented in four phases. These follows the principles of creating a digital twin. This strategic process is represented in Fig. 7.

The first phase of the process is initiation. The initiation phase entails defining the product's scope, the building's digital twin. The digital twin-based smart management plan includes monitoring various parameters that help in predictive maintenance, developing a business model to schedule predictive maintenance better, and developing a financial model to help reduce maintenance costs. The initiation phase also entails defining the requirements of the digital twin model. The requirement must cover data collection from the building and mode of sorting and analysing the collected data.

Fig. 7 Strategic process for the smart management plan

The second phase of the process is modelling. Modelling entails creating a definite and exact virtual twin model of the physical building. The modelling phase also entails linking the modelled virtual twin with existing data & systems of the building. This includes the interactions and functionalities of the building and its environment. The third phase of the process is utilisation. Utilisation entails developing effective and efficient communication between the physical building and its virtual twin. This will involve establishing connecting protocol and standards, security, middleware, Storage, and data analytics based on user interface needs. The fourth and final phase of the process is reuse. The reuse phase entails establishing an efficient information management system to create a platform for easy reuse of all collated and analysed data.

9 Conclusion

The 21st-century industry world is constantly seeking diverse ways to shrink costs and time while boosting productivity and efficiency. Utilising digital twin technology is a veritable means of achieving that in the building sector. This will help in better prediction of the future, which will enhance decision making and in turn, reduce operational cost and downtime while simultaneously enhancing building efficiency and productivity. This study, therefore, investigates ways that digital twin technology can be used to make facility management systems proactive in nature.

A framework for management was conceptualised through this research and named 'Digital Twin Based Smart Management Plan'. The Digital Twin-Based Smart Management Plan consists of eight hubs. The virtual replica is a digital representation of the physical building, allowing for real-time data exchange and visual monitoring. Data from the virtual hub is subjected to big data analytics, and results are applied to the data obtained from the physical building as well as simulation results to optimise facility management practices. In addition, historical data and feedback from users of the smart management plan also make up inputs to the optimised management practices. At the apex, the smart management plan is a product of optimised management practices, historical data, and benchmarking standards for facility management. Finally, the perceptions of facility managers who are the users of the smart management plan are recorded, and feedback are offered back into the system to continually optimise management practices. This framework ensures complete interaction among the process, people, place, and device.

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Ontology-Based Construction Process Library for Process States Inference

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Abstract This paper presents a new approach for modeling construction state inferencing rules using Semantic Web ontologies. This approach focuses on facilitating the shareability of the rules with ontology formalized meta information and SHACL-based rule body. Meanwhile, using the DiCon ontology as a unique terminology box, the rule could be reused directly for different construction data sources. The modeled rules would thus be collected as a shared library so that different users could search and reuse the rule in the library. The proposed ontology and CPL framework modeled were tested in an example case to demonstrate the usage of the ontology and framework.

Keywords Ontology · Rule · Construction Process Library · Inference · SHACL · Construction Digital Twins (DTC)

1 Introduction

Monitoring the construction process is always essential for the stakeholders to understand the actual situation on the construction site, minimize the costs, and reduce the impact of variation [1, 2]. However, the traditional manual inspections for progress tracking heavily depends on experienced inspectors [3], and always result in incomplete, inaccurate, and belated information [4]. So far, there has been a dramatically

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increasing adoption of information and communication technologies (ICTs) for automatically collecting process data, which has facilitated the problem of lacking accurate and digitalized construction process data and providing the data foundation for establishing the digital twins of the construction process [5]. For example, the sensing and IoT technologies [6–9], the indoor positioning systems [10, 11], radio frequency identification (RFID)[12], Laser scanning [13], and image/video-based technologies [14–17].

All these implementations could provide real-time or semi-real-time data to reflect the state of different flows of the construction process on the operation level. However, it can be alleged that the raw data collected by these systems still require further interpretation to obtain direct information for the stakeholders. Traditionally, they require experienced labor to manually analyze and interpret the data into meaningful construction process information. Such manual data analysis is time-consuming and costly to achieve and process state information. However, the current technologies for analysis or interpretation of these systems are still not mature for automation [2]. For example, although the recent Computer Vision (CV) implementation of the construction image and videos can automatically retrieve the entities and features in the image scene [18], the approach to utilize this information to infer the higher-level process state still needs further development.

With the increasing adoption of the Semantic web ontologies in the construction sector, these digital construction process data from different ICTs systems can be not only integrated as ontology-based semantic digital twins [19] but also represented by formalized machine-readable format [20]. The data of different process flows reflects the state of the different entities in the process and could be mapped to rule-represented domain knowledge about features and constraints of the different construction process states. Therefore, upon the machine-readable data, semantic inference could be considered as one potential approach to automatically interpret the data. And new facts not captured by the original ontology would be generated to provide the stakeholders with direct information about the construction process state.

The rule-based inference has received increasing attention from scholars in the construction sector. Scholars have explored the utilization of rules in inference [21], information extraction [22], and validation/checking [23, 24]. However, to our knowledge, the rule-based inference for the construction process state has not been explored deeply. There is lacking a generic approach to developing process state inference rules. Moreover, as the representation of the domain knowledge, the developed rules should be able to share and reuse by potential users. But the shareability of the rules is neglected in the previous efforts. Several aspects have limited the sharing and reusing of the rules. First, the rules are formed and serialized in different representations, which leads to the difficulty of collecting and managing the rules. Second, rules and data need to have a unique ontology to define the vocabulary, to guarantee the genericity of the rules in different cases. Third, the developed rules are lacking necessary information as background descriptions. Consequently, it increases the difficulty for the users to search the rules for practical uses and have the collection of the rule as a library.

To address the limitation of the above problem, we propose an ontology-based approach to build the library of reusable construction process state inference rules in this paper. First, we proposed an ontology called DiCon-CPL, which aims to provide a structured representation to form the construction process rule for sharing and reusing. The ontology consists of two parts, the first part is to describe the meta information of the rule to support the potential user to search the rule based on their demands. The second part is the rule body that is developed by using Shape Constraint Language (SHACL) [25] and with contents from the DiCon ontology [26]. The SHACL provides the formalized and conductible rule body, and the DiCon provides the unique terminologies about the construction process and related digital data that could associate with the rules and instance data. Furthermore, as developed with structured and formalized representation, the rules can be thus stored as an RDF graph to establish the construction process library (CPL). CPL is our conceptual platform open library designed as a sharable knowledge base, which collects the rule-represented domain knowledge of inferring construction process state, regarding different the digital data collected during from sites. A use case that follows the framework has also demonstrated the workflow of generating the CPL rules and conducting the inference of construction process state information.

The content of the paper is organized as followed. The Sect. 2 introduced the background of the current collection of construction process data and the implementation of semantic web ontology and rules. In the Sect. 3, the development of the proposed DiCon-CPL ontology is discussed, followed by the description of the CPL framework in the Sect. 4. In the Sect. 5, an example of implementing the DiCon-CPL and CPL framework to build up the process state inferencing rules with the indoor positioning system is demonstrated. At last, the discussion, limitation, and conclusion of this paper are given in the Sects. 6 and 7.

2 Background

Nowadays, there is increasing implementation of Semantic Web ontologies in the construction domain. Ontology is "an explicit formal specification of a conceptualization" [27], in which the domain knowledge is modeled by Description Logic (DL) [28] as concepts, properties, and the interrelationships between the concepts, thus it could represent the structure of information and domain knowledge [29, 30]. One major focus of implementing ontology in the construction domain is to solve the problem of data integration [31]. Information heterogeneity is one common domain issue [32]. The use of ontology could facilitate this problem since it allows the interrelation of all kinds of information [20]. Recently in the construction domain, ontologies have been developed to facilitate information integration and improve interoperability [33–35]. Our research team has also proposed the DiCon in the previous work [26]. The DiCon is a shared ontology suite that comprehensively describes the construction process, along with the alignment of the different digital data sources. The DiCon also provide the alignment with related ontologies to reuse them to associate with the different ICT data.

Besides information integration, ontology could provide a formalized vocabulary of concepts with explicit definitions and machine-processable semantics. Such semantics could transform into rules as a simplistic model to express knowledge and infer implicit knowledge and information [36]. Rule-based systems emerged along with the implementation of building information modeling (BIM) in the construction domain, which applies rules, constraints, or conditions to check the design [37]. With ontology implementation, rule-based inference has been more effective due to the machine-readable semantics and logical rules [20]. There is a research trajectory of combining ontology and rules in the construction sector. Terkaj and Šojić [38] addressed the rule-enhanced IFC to OWL conversion. Zhang et al. [39] proposed a construction safety ontology to formalize the safety management knowledge and a set of rules was developed to infer for job hazard detection. Wu et al. [40] addressed an ontological knowledge base for concrete bridge rehabilitation, in which they propose an ontology to improve information integration, and a set of rules were developed based on ontology to model the constraints of the bridge rehabilitation. Wang [41] proposed an ontology-based framework to support the operation and maintenance of the building, with a set of rules developed to infer key indexes and information about the maintenance. These previous works have demonstrated how the rules could be implemented in the construction domain to support the derivation of implicit information.

One recent semantic rule modeling trend is using the Shape Constraint Language (SHACL) [25]. SHACL is a World Wide Web Consortium (W3C) specification that is designed to validate RDF data graphs with shape graphs based on a set of conditions. SHACL rules upon SHACL are to form a lightweight RDF vocabulary for creating rules that can be used to derive inferred RDF triples from existing asserted triples [42]. Compared to other rule languages like Semantic Web Rule Language (SWRL), SHACL has more flexibility of expressed in the form of an RDF graph with RDF vocabulary to describe shapes data validation and can also be used for general purpose rule-based inferencing [43]. Moreover, as the successor of SPIN, SHACL support the SPARQL function as an advanced feature of using the SPARQL-based constraints to declare SPARQL-based target [42, 44]. The use of SHACL in the AEC industry is also an emerging track of research that several scholars have explored the usage of SHACL in constraint checking and information retrieval. Soman et al. [45] defined construction scheduling constraints with SHACL to check the constraint violation of the construction schedule. Oraskari et al. [46] presented a SHACL-based checking of the conformance of Linked Building Data. Hamdan et al. [47] used the predefined SHACL rules based on domain experience about structural damage image features to classify the detected anomalies automatically. Cao et al. [48] proposed a set of manufacturing rules based on domain knowledge and related manufacturing documents formed in SHACL, to check if the design prototypes are manufacturable against the design requirements. These previous efforts show that the SHACL rule is one ideal solution that can be used to build up the body of the rules to conduct the inference. Meanwhile, it is suitable for sharing and reusing the rules, as SHACL is expressed in the form of RDF graphs, which can be stored as named graphs in the RDF store.

Undoubtedly, the current research efforts have paved the way for rule-based inference in the construction industry. However, from the literature review given above, it can be concluded that most of the research efforts mainly focus on the design, scheduling, and manufacturing phase, while little effort has been put on the operation level to infer the state information of the construction process. In addition, these previous studies only focus on the rule body construction but have neglected how to systematically share, reuse and store developed rules. Overall, a platform that contains the construction process knowledge with a unique rule representation is needed to provide easier access for potential users. Therefore, in this paper, we first developed an ontology to formalize the inference rules with the SHACL rule body and use the DiCon as the terminology box for describing the construction process and linking to the related data stream. Moreover, a conceptual platform called CPL is established to collect the formalized rules for potential reuse.

3 Construction Inferencing Rule Ontology

To establish the CPL with shareable and conductible rules of inferring the construction process states, first an ontology called DiCon-CPL is developed to formalize the rules. Following this section, the development and evaluation of the proposed ontology will be introduced.

The development methodology of the DiCon-CPL is followed by the SKEM approach [29]. Since we would reuse our previous research outcome, the DiCon ontologies [26] as the foundation, along with the SHACL. Thus, the development of the DiCon-CPL also takes the horizontal segmentation approach into account. The horizontal segmentation approach is addressed in the SOSA/SNN [49], which aims to develop complementary contents from new related domains by defining classes as well as properties and connecting them to the previous ontologies.

The first step is the specification, which aims to determine the purpose, scope, and requirements of the ontology. The DiCon-CPL is aimed at modeling the construction process inference rule that provides a formalized description of the rule and conductible rule body for the sharing and reusing purpose. The scope of DiCon-CPL ontology is going to cover the background information and body of the inference rules within the digital construction context. Based on the specified scope and purpose, the requirement of the ontology can be identified with set up a list of competency questions (CQs). These are more detailed specifications of the ontology requirements [50], that can be used to formalize the ontological model, concepts, hierarchy, and relations. The CQs of DiCon-CPL are presented in Table 1. These questions were also used for the ontology evaluation to check if the ontology covered the desired content and can represent the domain knowledge.

Following the specification, the next step is the conceptualization process in which all relevant terms of the concepts, class hierarchy, and class properties including

Table 1 The Competency Questions of the DiCon-CPL ontology

Competency Questions
• What kind of data source the rule has?
• What kind of knowledge source the rule is built on?
• What kind of discipline of construction the does rule focus on?
• What kind of process the rule is focused on?
• Who creates the rule?
• When was the rule created?
• What version is the rule?
• What kind of conductible body the rule has?

their range and domain in the ontology are defined to construct the ontological model. In the DiCon-CPL, the basic terminologies of higher-level concepts and properties are inherited from the DiCon ontology. In terms of the extended classes and properties, they are created with the dicr: namespace as the complementary to describe the rule information based on the horizontal segmentation approach. The ontological model is shown in the Fig. 1. The proposed ontology consists of two parts. The first part is the rule meta-information, which aims to provide a formal description of the developed rule with necessary rule background and provenance information. As discussed previously, a variety of rules would be generated for a different process, under different data contexts. Such complex circumstance leads to difficulty to classify the rules. Thus, rather than giving the classification of the rule, a structured description of background information would explain what the rule is about. Therefore, the potential users can search the demanding rules based on the meta information. As shown in the Fig. 1, the ontological model is that the *Rule* is created by a certain *Agent*, with a certain *DataService* as the ICT data source. Each of the Rule also has the *Creation Time* and *Version* information. As knowledge representation, the rules also have their source knowledge and discipline and may also have Constraints to referencing the exact values of specified properties.

The second part is the rule body, in which the SHACL is applied to model the body of the inference rule. SHACL provides the conductible body of the rule in RDF representation. In the SHACL, there are two types of shapes, including the Node Shape and Property Shape [25]. *Node shapes* refer to the shape constraints that act on subject resources (or concept instances) of a specific type (the type can be defined while modeling the constraints) in the data graph. While the *Property Shapes* are focusing on the properties or attributes of the classes or their instances. In the previous DiCon ontologies, higher-level concepts of Entities and Properties that are related to the construction process have been already defined, thus they can directly be the target class or properties of the SHACL shapes.

This ontology is further implemented as Semantic Web Ontology Language (OWL) by using the Protégé environment. OWL is a computational ontology language that is designed for ontology development, which is a W3C-recommended

Table 2 Example rule of inferring process state based on relative humidity

Rule

```
    expp:HumidityRule a dicr:Rule;
     dicr:hasCreationTime "2022-08-22"^^xsd:Date;
     dicr:hasKnowledgeSource "https://doi.org/10.1016/0040-6031(94)02387-4."^^xsd:anyURI;
     dicr:hasDataSource expp:RelativeHumiditySensorSystem;
     dicr:hasBody expp:HumidityRuleShape;
    dicr:hasBodyURL
"https://raw.githubusercontent.com/YZhengaa/ConstructionProcessLibrary/main/SHACLRules/RHrule2.ttl"^^xsd
:anyURI;
     dicr:hasDiscipline expp:IndoorConstruction .

    expp:HumidityRuleShape a sh:NodeShape,rdfs:Class;
    sh:targetClass dicp:Activity;
     sh:rule [
            a sh:SPARQLRule ;
            sh:prefixes expp: ;
            sh:prefixes sosa: ;
            sh:prefixes dicp: ;
            sh:prefixes bot: ;
            sh:prefixes dice: ;
            sh:prefixes rdfs: ;
            sh:message "Painting is able to conduct, RH satisfied." ;
            sh:construct """
                PREFIX expp: <http://example.aalto.fi#>
                PREFIX dicp: <https://w3id.org/digitalconstruction/0.5/Processes#>
                PREFIX sh: <http://www.w3.org/ns/shacl#>
                PREFIX sosa: <http://www.w3.org/ns/sosa/>
                PREFIX bot: <https://w3id.org/bot#>
                CONSTRUCT { $this expp:hasState expp:AbleToOperate}
                WHERE {
                    $this a dicp:Activity .
                    $this dicp:hasLocation ?location .
                    $this dicp:hasStartTime ?StartTime  .
                    $this dicp:hasEndTime ?EndTime  .
                    ?location a bot:Space .
                    ?location sosa:hosts ?sensor .
                    ?sensor a sosa:Sensor .
                    ?sensor sosa:madeObservation ?observation .
                    ?observation a sosa:Observation .
                    ?observation sosa:observedProperty expp:relativeHumidity .
                    ?observation sosa:hasSimpleResult ?value .
                    ?observation sosa:resultTime ?resultTime .
                    FILTER (?value < 85) .
                    FILTER (?resultTime < ?EndTime) .
                    FILTER (?resultTime > ?StartTime) .

                }
                """
     ];
      sh:rule [
            a sh:SPARQLRule ;
            sh:prefixes expp: ;
            sh:prefixes sosa: ;
            sh:prefixes dicp: ;
            sh:prefixes bot: ;
            sh:prefixes dice: ;
            sh:prefixes rdfs: ;
            sh:message "Painting is not able to conduct, RH unsatisfied." ;
            sh:construct """
                PREFIX expp: <http://example.aalto.fi#>
                PREFIX dicp: <https://w3id.org/digitalconstruction/0.5/Processes#>
                PREFIX sh: <http://www.w3.org/ns/shacl#>
                PREFIX sosa: <http://www.w3.org/ns/sosa/>
                PREFIX bot: <https://w3id.org/bot#>
                CONSTRUCT { $this expp:hasState expp:NotAbleToOperate}
                WHERE {
                    $this a dicp:Activity .
                    $this dicp:hasLocation ?location .
                    $this dicp:hasStartTime ?StartTime  .
                    $this dicp:hasEndTime ?EndTime  .
                    ?location a bot:Space .
                    ?location sosa:hosts ?sensor .
                    ?sensor a sosa:Sensor .
                    ?sensor sosa:madeObservation ?observation .
                    ?observation a sosa:Observation .
                    ?observation sosa:observedProperty expp:relativeHumidity .
                    ?observation sosa:hasSimpleResult ?value .
                    ?observation sosa:resultTime ?resultTime .
                    FILTER (?value > 85) .
                    FILTER (?resultTime < ?EndTime) .
                    FILTER (?resultTime > ?StartTime) .

                }
                """
     ].
```

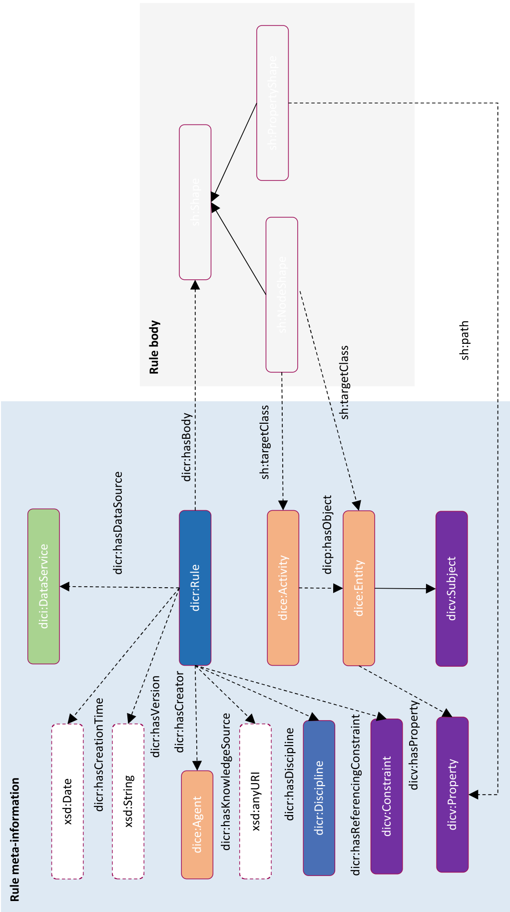

Fig. 1 The ontological model of the DiCon-CPL

ontology language [51]. Protégé is one of the most common tools of ontology development developed by Stanford University, which has a user interface with built-in reasoners to support ontology debugging.

The ontology evaluation is an essential process to check developed ontology fulfills all the requirements and purpose, and is consistent and usable [52]. In this research, the ontology evaluation consisted of automated consistency checking, answering the CQs verification, and an example as task-based evaluation. In terms of the automated consistency checking, which is completed by using the Protégé built-in reasoner, the result shows the DiCon-CPL is consistent without logical conflicts. In terms of answering the CQs, a set of SPARQL queries towards the ontology is conducted the check whether all the CQs can be answered. The CQ answering result indicates the developed ontology is satisfied with its requirements. And an example of using the DiCon-CPL to develop the rule will be illustrated in Sect. 5. Thus, according to the evaluation result, we can claim the developed ontology is consistent, satisfied the requirement, and is usable for further rule development.

4 The CPL Framework

To this end, the DiCon-CPL ontology can already formalize the construction process state inferencing rules with the meta-information and the SHACL rule body. To further support the modeling and sharing of the rules, in this paper, a conceptual framework called CPL is presented as shown in Fig. 2. This framework introduces the components of the rule-based inference system along with a detailed workflow of creating, sharing, and using the rules. The proposed framework applies to the knowledge base constitution addressed by Allemang and Hendler [53], which includes three parts: Terminological Box (TBox), Assertion Box (ABox), and Rule Box (RBox). The Tbox refers to the domain ontologies that describe the domain knowledge and information structure with explicit conceptualization, including the classes, properties, and axioms. In the CPL, the DiCon and DiCon-CPL ontologies are used as the TBox, since DiCon has a comprehensive description of the construction process and related digital data content. Associated with the Tbox, the ABox contains and represents the instance-level information. In the CPL, the Abox consists of digital data collected from construction sites via various digital systems and associated with the DiCon ontology to make the data integrated and machine-readable. Considering the data would be confidential, therefore, it would be held as local RDF graphs. In terms of RBox, contains the rules that indicate the implicit knowledge that is not included in the Tbox. In the CPL, the SHACL rules developed based on the DiCon-CPL are collected as a rule library to perform as the RBox for further process state inference.

Around these three components of the CPL, the workflow of state inference is built. The workflow consists of two user layers, in compliance with two different types of users of CPL: the user would develop and share the rules and the user who want to directly reuse the rules. First, both types of users should analyze which digital data source they have. This is because for different construction projects there are

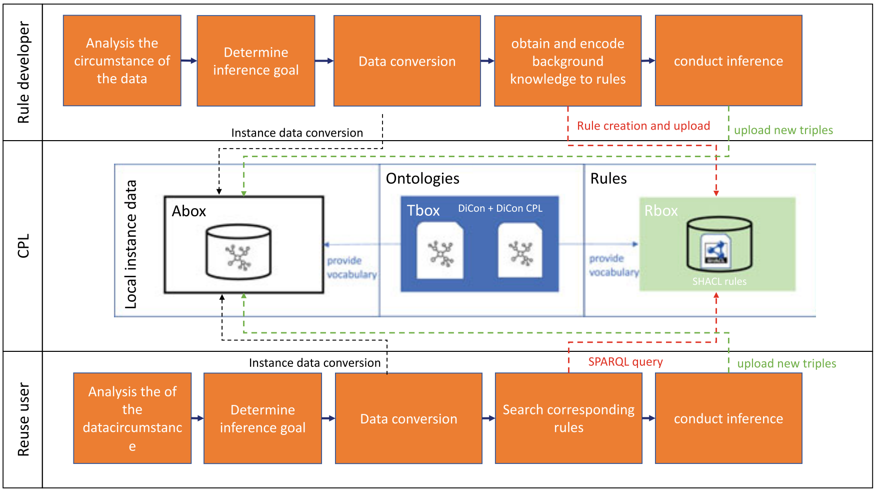

Fig. 2 The Framework of CPL Inference

different types of ICT implementations are applied on the site. Then they need to determine the inference goal, to find what target class and properties they are aiming for the inference. Then based on the Tbox, convert the data to local RDF graphs as the Abox. In terms of the rule developer, they applied the DiCon ontologies as the fundamental Tbox development and share the rule with the CPL. For the user who reuses the rules, they can conduct SPARQL queries based on their circumstance to find the suitable rules. And then apply the corresponding TBox of the rule to convert their data to local RDF graphs. At last, both types of users could execute the rule-based inference with their RDF serialized data to extract desired information. Such information will send back to Abox as the new triples.

5 Example

In this section, an example of using the framework proposed ontology and framework in this study are described to demonstrate the workflow of the construction of CPL. The example in the case study is given in the context of the indoor construction phase of a project that applied the indoor positioning system and IoT conditioning sensors. The tasks included drywall installation and painting. The stationary gateways of IPS and IoT humidity sensors are deployed in the different apartments and the portable Bluetooth beacons are attached to partitioners. The above source data are collected as tabular data and converted by using the DiCon as the RDF skeleton (Tbox) following the same path addressed in [26].

In response to the data content in hand, two types of rules to infer the process state are developed in this case following the CPL framework. The first type of rule is regarding the relative humidity sensor data. Based on the sensor data, the goal is to infer whether the relative humidity is satisfied to conduct the painting work in a certain location. We collect the domain knowledge that the painting task should avoid the condition when the relative humidity is over 85% because it will lead to the quality issue of the painting [54]. Based on this knowledge, a SHACL rule is developed and encoded. First, based on the DiCon-CPL, the meta information of the rule is created including CreationTime, KnowledgeSource, dataSource, BodyURL, and Discipline. Second, to model the rule body, the sh:NodeShape targets the class activity, and the SHACL-SPARQL functionality is used to first check the assigned location of the painting tasks are whether fit the relative humidity constraints. If the relative humidity is over 85, it is not able to operate the painting. Thus, a new triple that describes the task that is not able to operate will be added by the SPARQL CONSTRUCT function. Otherwise, it will add the statement that the task can operate. This provides the site manager with direct information on the variability that affects the operation. So, the manager could consider using equipment to reduce the relative humidity in the location to ensure the progress and quality of the task. The rule is shown in the following Table 2.

Second, based on the IPS data input, the inference aims to achieve the checking of the working states of the drywall installation process. In this case, the process is simplified based on the worker's presence [11], to check whether the necessary labor flow presented in the correct location as scheduled. We assume if the presence of the worker is in the correct location over the time threshold, the work is in progress because of the presence. Therefore, two conditions are considered to model the rule: 1. With the presence of the workers in the scheduled time and location of the task, and the duration of the worker's total presence is over the threshold (in this case 10 min), can be considered as the state of the task is *in progress as scheduled*; 2. Otherwise, refers to the task in the location is *not in progress as scheduled*. Based on these two conditions, we have modeled the rules with the meta information and SHACL node shapes that targets the activity class (as shown in Table 3). The SHACL-SPARQL functionality in this case is applied to find the presence of the workers in the scheduled location. FILTER operator is used to filter the presence of workers over the threshold. The CONSTRUCT function will create new statements that whether the work is in progress as scheduled.

All the developed rules are uploaded to a GitHub repository as the temporary location of the CPL Rbox to gain the URL for the rule body. For the potential user of the developed rule, they could search the demanding rule via SPARQL query of the metainformation. For example, the users who want to check the painting work state during the operation phase could reuse the humidity rule developed in the previous section. But they need to search for the usable rule in the CPL. The SPARQL query thus can be conducted to find the demanding rules. The SPARQL query is encoded following the logic to search the rules that are about the indoor construction discipline that has the data service of the humidity sensor. Thus, they can build the query shown in Table 4. The result also extracts the URL of the rule body that could be directly used in the inference.

Table 3 Example rule of inferring process state based on indoor positioning

Rule

```
expp:IndoorPositioningRule a dicr:Rule;
 dicr:hasCreationTime "2022-08-22"^^xsd:Date;
 dicr:hasDataSource expp:IndoorPositioningSystem;
 dicr:hasBody expp:IndoorPositioningRuleShape;
 dicr:hasBodyURL
"https://raw.githubusercontent.com/YZhengaa/ConstructionProcessLibrary/main/SHACLRules/RHRule3.ttl"^^xsd
:anyURI;
 dicr:hasDiscipline expp:IndoorConstruction .

expp:IndoorPositioningRuleShape a sh:NodeShape,rdfs:Class;
sh:targetClass dicp:Activity;
 sh:rule [
        a sh:SPARQLRule ;
        sh:prefixes expp: ;
        sh:prefixes sosa: ;
        sh:prefixes dicp: ;
        sh:prefixes bot: ;
        sh:prefixes dice: ;
        sh:prefixes rdfs: ;
        sh:message " Presence of worker is sufficient, activity is in progress as scheduled " ;
        sh:construct """
            PREFIX expp: <http://example.aalto.fi#>
            PREFIX dicp: <https://w3id.org/digitalconstruction/0.5/Processes#>
            PREFIX sh: <http://www.w3.org/ns/shacl#>
            PREFIX sosa: <http://www.w3.org/ns/sosa/>
            PREFIX bot: <https://w3id.org/bot#>
            CONSTRUCT { $this expp:hasState expp:InProgressAsScheduled }
            WHERE {
                $this a dicp:Activity .
                $this dicp:hasLocation ?location .
                $this dicp:hasStartTime ?StartTime  .
                $this dicp:hasEndTime ?EndTime  .
                ?location a bot:Space .
                ?location sosa:hosts ?gateway .
                ?gateway a sosa:Sensor .
                ?gateway sosa:madeObservation ?observation .
                ?observation a sosa:Observation .
                ?observation sosa:hasStartTime ?ObservationStartTime .
                ?observation sosa:hasEndTime ?ObservationEndTime .
                ?observation sosa:hasDuration ?duration

                FILTER   ((SUM(?duration)   >   10   ||?ObservationStartTime   >   ?ActivityStart-
Time||?ObservationEndTime <?ActivityEndTime) .
            }
            """
 ];
  sh:rule [
        a sh:SPARQLRule ;
        sh:prefixes expp: ;
        sh:prefixes sosa: ;
        sh:prefixes dicp: ;
        sh:prefixes bot: ;
        sh:prefixes dice: ;
        sh:prefixes rdfs: ;
        sh:message "Presence of worker is insufficient, activity is not in progress as scheduled;
        sh:construct """
            PREFIX expp: <http://example.aalto.fi#>
            PREFIX dicp: <https://w3id.org/digitalconstruction/0.5/Processes#>
            PREFIX sh: <http://www.w3.org/ns/shacl#>
            PREFIX sosa: <http://www.w3.org/ns/sosa/>
            PREFIX bot: <https://w3id.org/bot#>
            CONSTRUCT { $this expp:hasState expp:NotInProgressAsScheduled }
            WHERE {
                $this a dicp:Activity .
                $this dicp:hasLocation ?location .
                $this dicp:hasStartTime ?StartTime  .
                $this dicp:hasEndTime ?EndTime  .
                ?location a bot:Space .
                ?location sosa:hosts ?gateway .
                ?gateway a sosa:Sensor .
                ?gateway sosa:madeObservation ?observation .
                ?observation a sosa:Observation .
                ?observation sosa:hasStartTime ?ObservationStartTime .
                ?observation sosa:hasEndTime ?ObservationEndTime .
                ?observation sosa:hasDuration ?duration
                FILTER   (((SUM(?duration)   <   10   ||?ObservationStartTime   >   ?ActivityStart-
Time||?ObservationEndTime <?ActivityEndTime) .
            }
            """
 ].
```

By using the rule URI retrieved from the rule search part, the inference of relative humidity data can be conducted along with the converted local data. The inference of the process state is achieved in the Top Braid Composer with the URL of the rule body. The inference result is shown in Fig. 3. From the result, it can be seen that the tasks Activity 4, 5, and 6 can operate because they satisfy the humidity constraint.

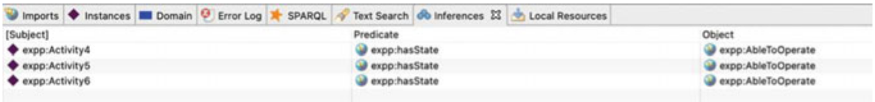

Fig. 3 The inference result in Top Braid Composer

Table 4 SPARQL query to search humidity rule

Query
SELECT ?HumidityRule ?HumidityRuleBody ?RuleBodyURL
WHERE {
?HumidityRule a dicr:Rule
?HumidityRule dicr:hasDataSource expp:RelativeHumiditySensorSystem
?HumidityRule dicr:hasDiscipline expp:IndoorConstruction
?HumidityRule dicr:hasBody ?HumidityRuleBody
?HumidityRule dicr:hasBodyURL ?RuleBodyURL

This example case validates the developed DiCon-CPL ontology in usability and illustrates the workflow of CPL rules that would be shared and reused for conducting the inference of the construction process state based on input ICT data streams. In particular, the example presents how the digital data could be automatically interpreted to provide direct process state information to the manager to gain situational awareness of the construction operation. Based on the such circumstance, the manager could quickly figure out the actual state and thus to respond the situation.

6 Discussion and Limitation

The contribution of this paper is threefold. First, the proposed DiCon-CPL ontology can provide an explicit description to ensure the shareability of the rules. This is due to DiCon-CPL has also modeled the meta information of the rules. In the rule development phase, such meta information would help the developer to formalize the rules to ensure the rule is developed correctly. In terms of the sharing phase, the meta information provides explicit information about the rules and thus supports the shared users to find and reuse the rules based on their demands via SPARQL to query the library. This fulfills the neglected point of the previous related rule efforts in the construction domain. Second, building upon the SHACL, the ruling body is conductible via the SHACL inference that can be directly used to infer the process state information, but is also easy to store and share as RDF graphs. This could also be considered one important aspect of the data processing phase of DTC [19]. The CPL concentrates the related domain knowledge into computer conductible rules to achieve automatic process state inference based on the digital data content. This enables meaningful applications to boost automated construction in the context of DTC. At last, the paper also reveals a framework to demonstrate the component and workflow of the CPL inference. For the rule developers, they could develop the rules by analyzing their data in hand and the inference goal, then encodes the rule with the information and body in SHACL. Then they can upload the RDF graph of the rule to the CPL or conduct the inference locally. In terms of the shared user, after they specify their rule demand, they can access the CPL by querying for the demanding rule and conducting the inference.

Admittedly, the present research has limitations that need to be addressed in the future. First, the proposed DiCon-CPL ontology is only evaluated by answering competency questions and consistency checking, which still need to be further evaluated via other approaches, for example, the expert workshop, to ensure usability for practical cases. Second, the CPL framework described in this paper is about manual rule development. There is still lacking effective automated approaches to convert unstructured text-formed knowledge (for example the operation manuals) to formal ontologies and rules [48]. This could be solved by implementing natural language processing along with the CPL ontology and rule construction. Third, the CPL is still under the conceptual and developing phase and the formal and practical library and the application has not been established yet. At last, although the example case has demonstrated how the ontology-based CPL rule would be developed and searched via SPARQL and conduct the inference to check the construction process state based on input IoT and IPS data, this example is a simplified case for demonstration purposes. The actual cases and the knowledge in the construction would be more specific and complex, which will require more rule modeling work, this is out of the scope of this paper. Our research group is now based on the CPL framework to develop the rules to support image interpretation combined with CV technologies.

7 Conclusion

This paper describes an ontology-based approach to defining construction process state inference rules in a consistent and formalized manner, to build up a construction process library as a shared knowledge base of the inference rules. The proposed ontology provides a richer description of rule meta-information for sharing the rule, and a conductible body based on the SHACL to allow the users to directly infer the process state. The example has demonstrated how the rules developed based on the DiCon-CPL could be searched based on SPARQL and use the SHACL validation to conduct the inference to provide an automated analysis to indicate the process state to the users. This paper also demonstrated the capability of semantic ontology towards knowledge management for the construction process under the DTC context. The described ontology-based approach of formalizing the rules could be applied to a similar sector in the construction domain, for example, the construction planning constraints [45] and design regulations [48], in which some constraints or rules have been modeled by scholars in SHACL but have limited shareability because of lacking meta information to classify them. There is also the freedom of using other ontologies as the Tbox if other domain ontologies need to be applied.

The CPL intends to be a platform for representing the construction domain knowledge into executable semantic rules and allow users throughout the world to create, reuse and share the rules to support information retrieval in the construction sector. However, the CPL is still in the conceptual phase and has not yet been used in construction practice. Thus, future work will also focus on providing a more efficient and easier approach to help the industrial user who is not familiar with the semantic web technologies to build up the rules.

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A Critical Review of Measuring the Modeling Productivity of Building Information Modeling

Sanghyun Shin, Suhyung Jang, Hyunsung Roh, and Ghang Lee

Abstract This study aims to identify indicators to measure the productivity of building information modeling (BIM) through a critical literature review of previous studies on BIM productivity and the factors used in the studies. Measuring BIM productivity, to which end quite a few efforts have been made, is important for efficient workforce management. The authors reviewed 14 papers collated from Scopus and Google Scholar. Examples of topics included productivity factors related to 2D/3D design modeling. Previous studies on BIM productivity have followed the definition of productivity as output/input. The input and output of BIM productivity indicators were classified according to the research purpose of the 14 previous studies. Among the BIM productivity indicators suggested in 14 previous studies, the most frequently used BIM productivity indicators were output as time and input as the number of elements in the 3D model. Among the factors affecting BIM productivity, modeling time was the most commonly considered. Other factors included model quality, modeling behavior, project size, model size and model review.

Keywords Building Information modeling · BIM Productivity · Productivity Factor · Productivity Indicator

1 Introduction

During a building information modeling (BIM) project, efficient manpower management can be achieved by measuring the modeling productivity of each modeler [1]. Through the productivity analysis of each modeler, the project manager can carry out an assigned task flexibly and improve the efficiency of the project team [2]. Modeling

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productivity can be evaluated by analyzing the working pattern data of each modeler's BIM model. Identifying individuals' modeling productivity makes it possible to estimate their performance in a specific period or on a project type to manage the project manhour efficiently [1]. Modeling workers can also self-diagnose their shortcomings through productivity analysis and improve their modeling productivity by sharing the command patterns of highly productive workers [3].

Productivity is the ratio of output per input [4]. This paper refers to an index used to represent productivity as "productivity indicator" and inputs and outputs of productivity as "factors".

In BIM productivity, no dominant indicator is used as the output of BIM productivity. Accordingly, determining how to select and measure factors that affect BIM productivity, such as quality, accuracy, and quantity of output, remains a difficult task [5]. BIM productivity indicators and factors are used in various ways, depending on the research purpose. The indicator of BIM productivity is still complicated and difficult due to the complexity of BIM projects because of the absence of standardized and integrated productivity indicators [6]. Therefore, it is necessary to identify and consider BIM productivity factors along with BIM productivity indicators. This study focuses on identifying and classifying BIM productivity indicators and factors. This study has two specific research questions:

1. What "BIM productivity indicators" were used in previous studies?
2. What "factors" were considered as inputs and outputs for measuring BIM productivity in previous studies?

Previous studies were collected and filtered using a systematic literature review method—the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) protocol [7]. Section 2 describes how the PRISMA protocol was employed in this study. Section 3 reviews the selected literature and identifies BIM productivity indicators and the factors affecting the BIM productivity indicator. Section 4 provides conclusions in response to the research questions.

2 Literature Review Method

The PRISMA protocol, the systematic review method that this study deployed, consists of four stages: identification, screening, eligibility, and inclusion [7]. The following subsections describe how previous studies were collected and filtered according to the four stages.

2.1 Data Identification

To collect research papers that dealt with "the productivity of modeling" or "BIM productivity in construction project", two databases, Scopus and Google Scholar, were selected. A total of 180 papers from 2005 to 2022 were collected through keyword searches. From Scopus, 155 results were obtained using the keywords "*((BIM) OR (3D modeling)) AND (productivity) AND ((measure) OR (assess) OR (evaluate))*." In the case of Google Scholar, 25 results were obtained using "BIM productivity measure" and "measurement of BIM productivity" as keywords. Through this process, researchers' interest in BIM productivity is found to have increased steadily since 2005 and risen sharply since 2013. It is shown that research on BIM productivity analysis has been going on for more than 15 years, and an increasing number of researchers are becoming interested.

2.2 Data Screening, Eligibility, and Inclusion

In the screening step, 128 papers were excluded through a manual review of the titles and abstracts. Four of the excluded cases were papers collected in duplicate from the Scopus and Google Scholar databases. The other 124 cases were excluded for the following reasons: 1) irrelevance with construction, and 2) systematic review papers provided a small amount of insight into the method of measuring BIM productivity.

In the eligibility step, all 52 papers were thoroughly reviewed and excluded from the analysis for the following reasons. Studies on the measurement of worker productivity at construction sites and on the measurement of productivity throughout the construction project process were excluded because they were not related to the modeling productivity measurement method. Moreover, studies on 2D design productivity measurement were excluded because this paper mainly focuses on the productivity measurement of BIM and 3D modeling. As a result, 36 papers were excluded, and 14 were selected. The final 14 papers were reviewed in detail.

3 Analysis Results

The analysis results are reported in two subsections, each corresponding to each research question. Section 3.1 identifies the "productivity indicator" used for BIM productivity measurement and classifies the indicators according to the research purpose. Section 3.2 identifies the input and output "factors" used in the BIM productivity indicator.

To determine the trends of the 14 selected papers, the publication year was analyzed. Two papers were published each in 2005, 2018, and 2020, and one paper each in other years. This shows that research on BIM productivity does not increase but was steadily conducted from 2005 to 2021. Among the 14 selected papers, 3 (21%) are from conferences and 11 are from journals (79%). In terms of publication venue, three papers were published in "Automation in Construction", three papers in "Journal of Construction Engineering and Management", and two papers in "Applied Sciences".

3.1 *Productivity Indicators Used for BIM Productivity Measurement*

Table 1 summarizes the outputs and inputs of the BIM productivity indicators collected from 14 selected studies and classifies them by research purpose. The research purpose of the BIM productivity is divided into benchmark BIM performance, evaluate BIM project modeling productivity, evaluate BIM modeling worker productivity, and compare 2D drafting and 3D modeling productivity.

The outputs and inputs of the BIM productivity indicators are explained below by research purpose.

Evaluate BIM Project Modeling Productivity. Among the 14 studies, 8 studies (56%) measured BIM productivity to evaluate BIM project modeling productivity [2, 11–14, 8–10].

Table 1 Outputs and inputs of BIM productivity indicators of the selected 14 papers

Research purpose	Output of indicator	Input of indicator	Source
Evaluate BIM project modeling productivity	Number of elements in the 3D model	Week	[8, 9]
	Number of element changes	Week/Month	[8, 9]
	Model LoD	Number of coordination meetings	[8, 9]
	Work hours	1000 m^2 of modeled floor area	[10]
	Work hours	Number of elements in the 3D model	[2, 11]
	Work hours	Weight (ton) of elements in the 3D model	[12]
	Work hours	Measurement unit	[13]
	Total wall area	Project lead time (minute)	[14]
Evaluate BIM modeling worker productivity	Work days	Number of elements in the 3D model	[1]
	Work seconds	Command pattern	[3]
	Number of commands	Work hours	[15]
Compare 2D drafting and 3D modeling productivity	Work minutes	Number of drawings	[16]
	Work hours	1000 m^2 of modeled floor area	[5]
	Work hours	1000 m^2 of modeled floor area	[17]

Two studies [8, 9] were related to a cloud-based BIM application called building information modeling cloud score (BIMCS) for automatic data collection and performance benchmarks of BIM workers. BIMCS developed 20 indicators for performance benchmarks and divided them into modeling productivity, effectiveness, model quality, accuracy, usefulness, and economy categories. This paper includes only the three indicators in the modeling productivity category, which is the main focus of this paper. The first indicator of "number of modeling steps/number of elements" shows how many steps a modeler took to develop an element on average. BIMCS suggests that too many steps are inefficient in modeling an element, and, thus, the smaller the modeling steps per element, the higher the modeling productivity. The second indicator of "number of element changes/number of elements" is an indicator showing how many times an element is modified on average during modeling. BIMCS suggests that more corrections are inefficient, and, thus, the smaller the number of changes per element, the higher the modeling productivity. The last indicator of "model LoD/number of coordination meetings" indicates the average number of meetings required to increase LoD one level, and unlike the two indicators, the higher the value, the higher the modeling productivity.

Sacks et al. [10] presented productivity benchmark that can be applied to the implementation of projects in the use of BIM. Modeling productivity was measured through work hours per 1000 m^2 of modeled floor area for 6 projects from 3 precast companies. Shan et al. [12] measured the BIM project modeling productivity by dividing the work hours by the weight of the elements in the 3D model, and through this, the existing steel connection system and the proposed steel connection system were compared. Leite et al. [11] analyzed BIM productivity by dividing the work hours by the number of elements in the 3D model [11]. Zhang et al. [2] divided the number of elements in the 3D model by the work hours and multiplied it by the estimated budget for normalization. To measure the progress and productivity of the engineering process in more detail, Garcia et al. [13] set different measurement units for disciplines, for example, "linear foot of pipe" for piping, "per tag" for equipment, and "ton" for structural steel, and divided them by the work time. To measure the performance of the wall production line using the case of a residential house with panels, Brown et al. [14] analyzed the total wall area per project lead time (minute).

Evaluate BIM Modeling Worker Productivity. Among the 14 studies, 3 studies (21%) measured BIM productivity to evaluate BIM modeling worker productivity [1, 3, 15]. These studies aimed to measure the modeling productivity of individual modeling workers rather than the BIM project.

Forcael et al. [15] used "number of commands/work hour" as an indicator to analyze the modeler's behavior and productivity using the journal file, which is a modeling log of Revit, as data. Commands used for modeling were classified into contributory or non-contributory, and the execution ratio of contributory commands and real-time work were analyzed. Also using the BIM log as data, Zhang and Ashuri [3] identified five patterns of the commands used for modeling and the time taken for each command pattern. Yarmohammadi and Castro-Lacouture [1] measured the time taken to model different types of elements, the number of modifications, and the number of errors through a custom-developed Revit plugin to identify the optimal design team configuration.

Compare 2D Drafting and 3D Modeling Productivity. Among the 14 studies, 3 (21%) measured BIM productivity to compare 2D drafting and 3D modeling productivity [5, 16, 17]. Sacks and Barak [5, 17] compared the productivity of 2D drafting and 3D modeling in structural engineering design and detailed work of concrete building structures based on the time taken to draft or model 1000 m^2 of floor area and 1 m^3 of concrete, potential benefits, and cost savings in the introduction of BIM. You and Nam [16] analyzed the difference in productivity between 2D drafting and 3D modeling for steel frame prefabrication in a plant facility construction project by measuring the time required to produce one drawing.

4 Productivity Factors Affecting BIM Productivity Indicator

Table 2 shows the factors that affect the BIM productivity indicator of 14 selected studies and data that measured the factors.

Model quality is a factor group that indicates how error-free a model is. It can be judged by the clashes and errors occurring within the 3D model. In the case of a clash, it is possible to determine which elements were clashed and whether the clash was positive or negative through automatic clash detection [11]. In the case of an error, analysis can be done based on data from the journal file extracted through an application developed using the Autodesk Revit application programming interface (API). Through this, the number of errors, types of errors, and location of the drawings

Table 2 BIM productivity factors of 14 selected papers

Factor group	Factor	Source
Model quality	Clash	[11]
	Modeling error	[1]
Modeling behavior	Number of modifications of an element	[1, 8, 9]
	Command pattern	[3]
Project size	Floor area	[10, 17]
	Wall area	[14]
	Number of drawings	[16]
	Project estimated budget	[2]
Model size	Number of elements in a BIM model	[2, 8, 9, 11, 13]
	Number of command executions	[15]
Model review	Number of coordination meetings	[8, 9]
Modeling time	Time (month/week/hour/minute/second)	[1–3, 5, 8–11, 13–17]

where the errors occurred can be identified while the modeler is performing BIM modeling [1].

Modeling behavior is a factor group that represents the way in which a modeler authors a model. This factor group includes the number of modifications of an element [1, 8, 9], the number of project data entries [8, 9], the number of command executions [15], and command patterns [3].

Project size is a factor group that represents the overall project size, such as the floor area [10, 17], the wall area [14], number of drawings [16], and the project estimated budget [2]. The project size factors were used mostly as a normalization factor.

The model size factors were used as both an input or output. The largest number of studies that used the number of elements in the 3D model to represent the model size [2, 8, 9, 11, 13]. These studies measured BIM productivity through the work hours it took for a modeler to model elements in a 3D model. The size of the model was likewise judged through the number of commands that the modeler used in the modeling process and used as a factor of productivity [15].

The model-review factor group represents the degree of effort to review a model or design. In this group, only one factor—the number of coordination meetings [8, 9]—was considered in the previous studies.

Modeling time was used as a factor in the analysis of BIM productivity in all 14 studies. This factor refers to the workhours that the modeler worked for modeling. The different units of measurement for time—i.e., second, minute, hour, day, and week—were used in each study, according to the purpose. Among them, hour was the most used unit [2, 5, 10–12, 15, 17]. Other time units, such as second, minute, day, and week, were used relatively less frequently than hour [1, 3, 8, 9, 14, 16].

5 Conclusion

To identify and classify the indicators and factors of BIM productivity, this paper analyzed research papers on BIM productivity using the PRISMA protocol. Papers were collected by keyword search, and an analysis process was conducted focusing on modeling productivity analysis rather than the productivity analysis of an entire BIM project. From the review, it is clear that different indicators and factors are used in each study for each research purpose. The two research questions of this paper can be answered as follows.

Productivity Indicator Used to Measure BIM Productivity
Productivity indicators for measuring BIM productivity can be classified into three groups by research purpose: evaluate BIM project modeling productivity, evaluate BIM modeling worker productivity, and compare 2D drafting and 3D modeling productivity. Among the BIM productivity indicators, the most researched purpose was to evaluate BIM project modeling productivity, and the most used indicator is work time (modeling time) divided by the number of elements in the 3D model.

BIM productivity indicators vary according to the purpose of the study. To evaluate the modeling productivity of the BIM project, studies mainly measure the time spent modeling the elements of the BIM project. Conversely, to evaluate the productivity of each BIM modeler, studies mainly measured the modeling time per the number of used commands or the modeling time per the number of modeled elements. To compare 2D drafting and 3D modeling productivity, studies mainly measure the time taken to draft or model 1000 m^2 of floor area.

Factors Affecting BIM Productivity
A total of 12 factors were identified as BIM productivity factors from the 14 selected studies: work time (month/week/hour/minute/second) (100%), the number of elements in a BIM model (35%), the number of modifications of an element (21%), the number of coordination meetings (21%), floor area (21%), clash (7%), modeling error (7%), command pattern (7%), wall area (7%), the number of drawings (7%), project estimated budget (7%), and the number of command executions (7%). And these factors can be classified into 6 groups among the 14 studies: modeling time (100%), model size (42%), project size (35%), modeling behavior (28%), model quality (14%) and model review (14%).

The contents to be studied in the future are as follows. This study identified various BIM productivity indicators, but the correlation between them has not been studied yet. Also the identified indicators represent their own productivity value, but does not provide a single integrated BIM productivity value. An integrated BIM productivity measurement model is also required.

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Digital Twinning in Additive Manufacturing - Closing the Digital-Physical-Digital Loop by Automated Integration of Captured Geometric Data into Fabrication Information Models

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Abstract As part of the digitization of the AEC industry, the Digital Twin concept is becoming increasingly important. Originating in the manufacturing industry, the concept at its core involves a bidirectional coupling of the physical product and its digital counterpart with the aim of keeping the two in sync. Without appropriate capabilities to realize such synchronization, the concept always remained as an unattainable vision for the AEC industry. Adapting additive manufacturing (AM) for construction, however, creates unique opportunities to realize this vision by enabling automation in both directions, from digital to physical product and vice versa. As a fully automatable manufacturing method where robotic processes are typically controlled by the digital representation of the product, AM realizes the digital-to-physical link for this purpose. Conversely, based on the same digital representation of the product, the acquisition of the physical implementation of the manufacturing process can be automated, enabling the physical-to-digital connection. This paper uses three AM application scenarios to illustrate, on the one hand, the need for automating quality control and, on the other hand, to describe approaches for its realization. In particular, the benefits of synergy between automated quality control (QC) and fabrication information modeling (FIM) to form a digital-physical-digital loop are explored.

Keywords FIM · Digital twin · Cyber physical systems · Automated inspection

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1 Introduction

The concept of Digital Twin – originating from the manufacturing industry and increasingly being adopted in the AEC industry – comprises in its core a bidirectional coupling of the physical product and its digital replica with the goal of keeping both in sync [3]. Applying additive manufacturing in construction provides the unique opportunity for realizing the full Digital Twin vision by enabling automation in both directions, from the digital to physical and vice versa. As additive manufacturing is typically realized by means of robotic processes that are steered by the digital representation of the product, the digital-to-physical link can be directly implemented. The physical-digital link, on the other hand, can be realized by capturing the physical realization of the printing process and subsequently updating the digital twin.

In this paper, we report on both parts of the bidirectional linking between the digital and the physical twin: For the digital-to-physical part, we present Fabrication Information Models as a digital representation comprising all information necessary for driving the fabrication process in additive manufacturing. We discuss FIM as a means for interlinking building models with detailed manufacturing information such as printing paths, extrusion rates and material compositions. While a FIM abstracts from specific machinery and control languages, it can be utilized directly for robot control by automatic translation processes.

A well-known challenge of additive manufacturing with concrete and similar materials is the deviation of as-built component from as-designed model that necessitate thorough quality control (QC). While larger deviations are typically interpreted as a failed print, minor deviations are usually tolerated. Especially in these cases, it is of utmost importance to update the digital representation to allow consideration of the real geometry in downstream workflows, for example in assembly processes. This update of the digital representation procedure closes the digital loop and realizes the concept of digital twinning.

In this paper we describe in detail which information is needed and discuss a possible way to establish information exchange from the as-printed object (physical object) to the FIM model (digital object). This exchange of information is categorized by three scenarios from shotcrete 3D printing with an illustrative example for each case. These scenarios are defined based on various QC aspects during and after the fabrication process.

The first scenario concerns the status of the object before the surface finishing and edge trimming step where the object is still in its rough state. In this scenario, the QC consists of point-wise deviation analysis of the as-built point cloud to as-designed model as well as layer-wise inspection. The second scenario deals with the printed object after the surface finishing and edge trimming where the manufacturing process is finished. Thus, QC in this scenario can be executed by extracting geometric features such as boundaries, surfaces which are to be used for comparison and updating the corresponding information in FIM. The third scenario focuses on the assembly of different components using special joint features and thus on the mutual coordination of several components with each other. The third scenario focuses on the assembly of different components using special joint features and thus on the mutual coordination of several components with each other. In this case, QC takes on several tasks at once. On the one hand, the first component must be measured at the joint with an increased level of detail, and on the other hand, it must be ensured that the recorded joint geometry is transferred to the other component with an appropriate margin of tolerance.

In this context, we discuss the variety of digital representations necessary for closing the Digital Twin loop, involving process, volume and surface descriptions on different spatial and temporal scales.

2 Background

2.1 Shotcrete 3D Printing (SC3DP)

The Shotcrete 3D Printing (SC3DP) process represents an Additive Manufacturing (AM) method developed by Lindemann et al. [15]. In this method, the shotcrete process, which has long been used in tunnel construction, is fully automated by means of robotic guidance (cf. Fig. 1). As in the established shotcrete process, the concrete is pumped to the nozzle via a hose, accelerated from there by a stream of air and sprayed onto the intended area.

Comparable to AM methods, the shape and quantity of the sprayed concrete filament in the SC3DP process is adjusted by several parameters (see Fig. 1, right) [12]. However, with SC3DP, the form-defining AM parameters (filament width, w_F and layer height, h_F) have to be adjusted indirectly. The farther the spray cone of the AM system is above a certain position, the more material is applied there, and the further away the nozzle is from the point of application, the larger the base area of the spray cone. Therefore, the filament height can be set via the movement speed and the filament width via the nozzle distance [12].

In general, however, it should be noted that the other parameters mentioned in Fig. 1 can also have an influence on the height and width. Therefore, for a successful application of this AM method, a precise coordination of the involved parameters is necessary, which makes the planning of the robot control significantly more complex and errors can occur more easily during the execution. If, for example, the planned layer height is not reached while applying one layer, this also has a consequential effect on the next layer [14]. For this reason, it is essential to use automated control systems for SC3DP in order to use this technology more reliably.

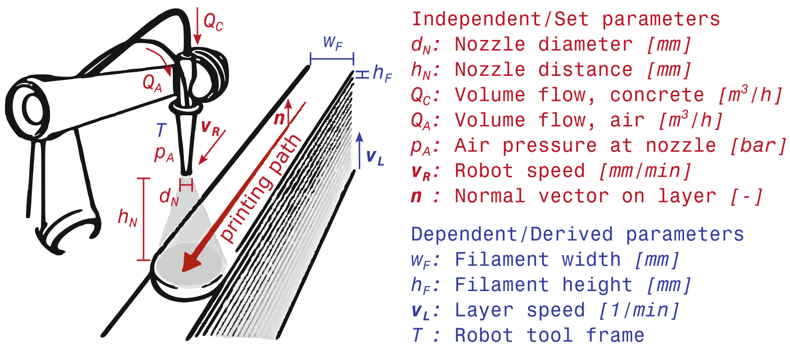


Fig. 1 Shotcrete 3D Printing (SC3DP) method with a selection of important parameters, after [12]

In turn, the SC3DP process offers many advantages that can be used to solve various problems in the application of AM. Among other things, this method makes it possible to integrate reinforcement in the component [9], allows to apply material directly on already existing geometries and enables a very high geometric freedom. Although SC3DP is a very coarse process that cannot produce detailed features, it can be used to print very fast and, depending on the concrete mix, the still-soft concrete can be easily detailed with finishing steps such as trimming and smoothing [15].

2.2 Fabrication Information Modeling

The term *Fabrication Information Modeling (FIM)* was introduced by Duro-Royo and Oxman [7] as "[…] a methodology designed to bridge the gap between virtual design tools and advanced digital fabrication tools". Based on this definition, Slepicka et al. [21] developed a FIM framework specifically for the construction industry that enables the use of AM methods driven by BIM data. With the help of the FIM framework, it is possible to component-wise extract BIM data in order to subsequently enrich it with all the information relevant for automated manufacturing. The framework is designed in such a way that the manufacturing information created is as universally valid as possible in order to be able to use this data with different manufacturing robots.

Figure 2 depicts the interaction of BIM, FIM and the manufacturing machine schematically. As clearly illustrated, FIM represents an intermediate layer between digital design and digital manufacturing. In addition, FIM can be used for many other use cases via appropriate interfaces. Among other things, the data can be converted directly into a simulation model that can be used to predict various properties (e.g., thermal transmittance, structural integrity, and others) of the component [1].

Using the BIM data as a basis, the geometry of a component is further refined in the FIM model so that its internal structure can be tailored according to the given

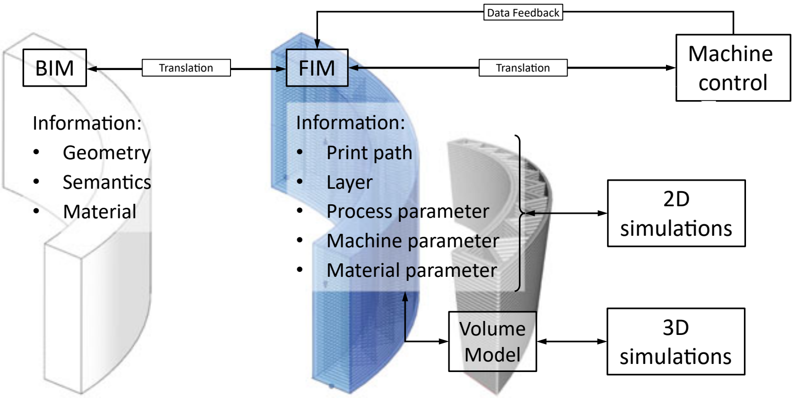


Fig. 2 From Digital Design to Manufacturing with Fabrication Information Modeling [21]

boundary conditions. Functional internals that were designed in the BIM model can be taken into account directly, so that many post-processing steps can be bypassed. In addition, information on the process flow can be designed in parallel to the fabrication information in order to predict material consumption and operating times.

In FIM, the outer geometry of the component is taken from the BIM model and, if not already designed in this way, converted into a Boundary Representation (B-Rep). Then the printing layers required for the process are modeled as separate entities to which the corresponding surface geometry (layer surface) is assigned. As the next step, the printing path is created for each layer in the parameter space of the layer surface and represented as a composite curve consisting of line, arc and/or spline segments. Finally, the relevant machine-, material- and process parameters are chosen or derived from the components geometry (cf. Sect. 2.1). Since the component geometry is specified from the digital design, defining filament width and height, a number of independent control variables must be inversely determined for the SC3DP process.

The B-Rep of the component in FIM not only represents the BIM geometry, but can also be understood as a bounding box within which all the printed material is to be located. By definition the layer surface corresponds to the upper surface of a printing layer and can be considered as a reference surface for the nozzle positioning and later for sensor data ("as-designed" to "as-printed" comparison). The printing path describes the center axis of the printing filaments upper surface (cf. Fig. 1) and thus represents an abstraction of the components expected print geometry. As stated in the previous section, the printing nozzle of a SC3DP machine has to be guided at a distance (h_N) normal ($\boldsymbol{n}$) to the respective layer surface (cf. Sect. 2.1 and Fig. 1). If the geometric information (path and layer surface) is planned in the robot's base coordinate system, the machine control can be derived directly, taking into account the selected process parameters.

2.3 Digital Twinning in Construction and Cyber Physical Systems

There are various conceptual descriptions for the term digital twin (DT), which in the original sense are based on the same core statement: A DT represents a digital image of a real object (or process) that already exists or will exist in the future, which is regularly updated to reflect the current state of the object (or process) (see literature review of Kitzinger et al. [13]). The DT representation must be available in an abstraction that is reasonable for the respective purpose but at the same time in a sufficient level of detail. One of the main purposes of a DT is to provide a comprehensive data basis for simulation, optimization and other planning tasks in order to make production, use, maintenance as well as demolition more efficient and sustainable [20].

However, one important component is missing if this concept is to be applied, namely how the processes involved in data exchange are linked to each other. A true digital twin can only be realized if its digital and physical sides are synchronized with every modification (no matter on which side) [13]. Thus, any modification to the physical side must be captured and transferred to the digital side, or conversely, any design change on the digital side must also be executed in reality.

Cyber-physical systems (CPS) are the underlying concept for realizing the circular flow of information just described. CPS are defined as “complex systems with organic integration and in-depth collaboration of computation, communications and control (3C) technology” [16]. In this sense, a CPS is a conjunction of technologies with which digital and physical part of a DT are linked. On the one hand, reality can be automatically captured and digitized and, on the other hand, conclusions can be automatically drawn from real events, enabling designs and the corresponding processes for their realization to be adapted. A decisive characteristic of CPS is that all information must be available on the respective side so that the system can be used throughout all phases of the life cycle of the corresponding object [10].

To enable this concept for AM in construction, mechanisms and algorithms for networking manufacturing processes (digital to physical) with sensor processes (physical to digital) must be developed, as shown in Fig. 3. For this purpose, both an automated derivation of information from the sensor feedback and a direct implementation of the feedback control by interpretation of this information must be realized. In other words, an integration of synchronized quality control (cf. Sect. 2.4) into the design and manufacturing process (FIM) is necessary.

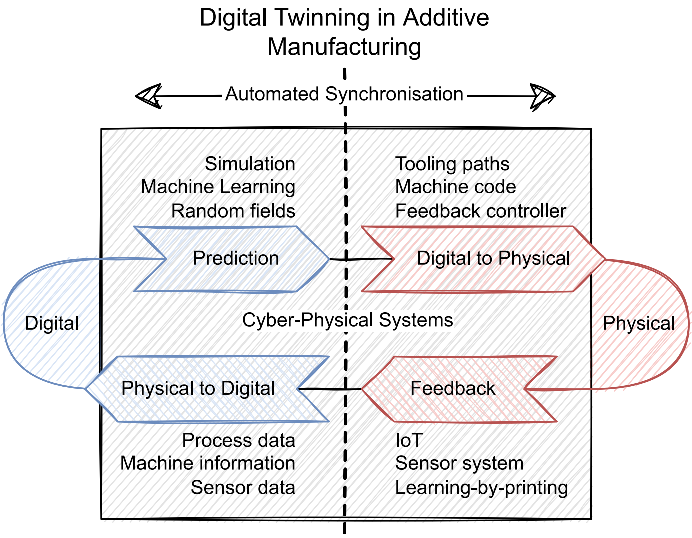


Fig. 3 Visualization of the circular flow of information during synchronization of the digital and physical sides of a digital twin

2.4 Quality Control for Additive Manufacturing

There is a lack of knowledge regarding the accuracy of concrete printing processes, as well as how they compare with each other [5]. As part of the digital fabrication process, a variety of stages are involved in the printing of an object [8]. As a result, quality control should be implemented both during and after each stage of the process. In this context, Kim et al. [11] investigate the current research on QC with different sensors. They point out that geometric defects may occur on concrete elements and that these defects can be detected before assembly.

Quality Control can be classified based on its application in the process, to *online*, *stage-wise* or *pre-assembly* (after surface finishing) control, and *assembly verification* [18]. In general, data is collected for each manufacturing step, from which features and attributes are extracted to provide meaningful information. However, different applications require different parameter settings and impose different boundary conditions. In Sect. 4 the different QC classes are illustrated on the basis of different scenarios.

While online control acquires sensor data in a continuous stream and is typically used to monitor process parameters, such as the nozzle distance (h_N, Fig. 1) [14], the other QC types are applied discontinuously at specific checkpoints. Stage-wise control of the printed object (referred to in [18] as layer-wise quality control) is performed at predefined epochs during manufacturing. Its main purpose is to ensure compliance with the requirements for the subsequent stages or processes and to capture the geometry at the end of the respective manufacturing stage for later use (production history). During stage-wise control two main checks are performed: Point-wise inspection and feature-wise inspection. These two inspection steps require the captured data to be aligned with their digital twin. As a reference for stage control, the FIM model provides the "as-designed" information of the component in the form of a B-Rep and the respective layer surfaces as NURBS-surface (cf. Sect. 2.2).

The pre-assembly control deals with extracting more specific features, such as edges and semantic information of the surface, after any post-processing stages. In contrast to stage control, the pre-assembly QC requires no alignment between the object and its digital model [18]. Finally, assembly verification is used to confirm that the component is assembled correctly.

The results from any kind of inspection must always be reported back to the FIM to update the model accordingly.

3 Methodology

As described in Sect. 2.2, FIM can be used as an intermediate layer to enable a link between digital design and digital manufacturing. Although this link allows manufacturing planning processes to be integrated with digital design and data exchange to be consolidated, this alone does not enable full automation of the manufacturing process. To achieve this, tools for the integration and automation of quality control (cf. Sect. 2.4) must be incorporated into the FIM framework to close the digital-physical-digital loop. This extension will evolve FIM into a cyber-physical system.

Figure 4 shows the necessary FIM extensions in the form of a flowchart, namely *online*, *stage* and *pre-assembly* control as well as *assembly verification*. In addition to the translation mechanisms already implemented in the FIM framework, tools for planning and evaluating scanning processes are being developed. The objective here is that the component being manufactured can be scanned completely and in high quality, either continuously during the printing process (online control), discontinuously at specific checkpoints in the manufacturing process (stage and pre-assembly control) or once after manufacturing and placement (verification), as described in

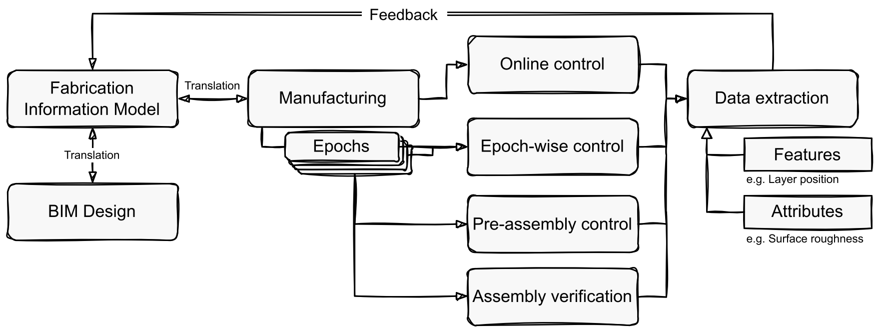


Fig. 4 FIM-Framework (cf. Fig. 2) with extensions for automated quality control

Sect. 2.4. From the collected scan data, it is intended that features can then be automatically recognized and checked against the "as-designed" model. Perceived deviations from the "as-designed" model should then either be automatically corrected by feedback or annotated accordingly in the FIM model.

FIM provides, as described in Sect. 2.2, not only the manufacturing recipe but also a list of geometric representations of the object that can be utilized by the QC processes and be enriched by the feedback. Knowing where material is to be applied can help plan ahead for optimal scanner positioning, and measuring where material is actually placed can help guide future manufacturing steps. Integrating the different QC types, described in Sect. 2.4, into the FIM framework will form a link between the digital and physical world and thus completes a digital-physical-digital loop.

In the experimental application (cf. Sect. 4), three selected scenarios are described to emphasise the importance of the combination of FIM and QC for different geometric shapes and different fabrication stages. The quality control in this study is mainly focused on geometric data acquisition and here mainly on terrestrial laser scanning (TLS). Other methods are, of course, applicable, but require a more detailed evaluation of the particular sensor capabilities and limitations, as well as the impact of the respective quantity being measured on the process.

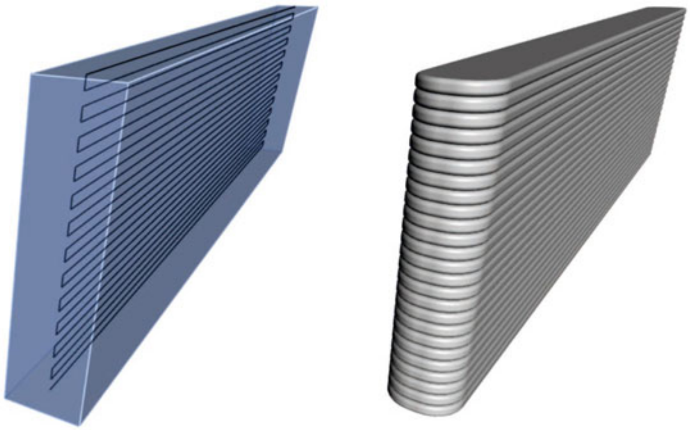
4 Experimental Application

In the following, three scenarios are used to illustrate possible use cases for automated quality control (QC) and at the same time discuss the corresponding problems. For all three scenarios, it will be explained how the production data is generated and which properties of the respective component are to be monitored. In all scenarios, the shotcrete printing method (SC3DP) is used as the fabrication method. Since simplified examples are shown in the scenarios, it is not necessary to consider the component semantics; only the geometric information is required for the FIM in this case.

4.1 Scenario 1: Simple Straight Concrete Wall

In scenario 1, the manufacturing process of a simple straight wall, with dimensions $1.6\,\text{m} \times 0.12\,\text{m} \times 0.45\,\text{m}$ (length × width × height), is to be monitored [14]. The wall is to be built in a single-stage manufacturing process and is not to be post-processed afterwards. The objective in this example is to monitor whether the printed material is within the planned boundary surfaces and to detect the exact location of each printing layer.

FIM: In order to generate the FIM model for this example, the geometry is first imported and translated into a B-Rep model as described in Sect. 2.2. After that,



(a) B-Rep and planned printing path of the simple straight wall. (b) Expected print result

Fig. 5 Digital model (FIM) of the simple straight concrete wall

the B-Rep is horizontally sliced into the individual layer surfaces at 15 mm intervals (layer height h_L), between which the material is applied. In FIM each layer is defined to be one base step. The subsequent path planning is done by fitting a printable filament onto each layer, which is done in this simple example simply by finding the center-line of the layer surface. To complete the robot motion all layers are connected with vertical lines, which represent the layer transitions.

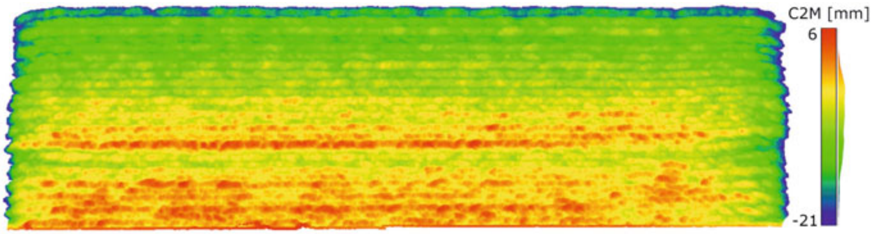
As shown in Fig. 5a, the printing path in this example consists of a straight horizontal line in each layer, along which material is applied, and the vertical layer transition, along which no material is deposited. Based on this, a prediction can be made about the printed filaments by sweeping an estimated cross-section along the horizontal curves of the path (cf. Fig. 5b).

QC: As mentioned before the wall in this example was not planned to be post-processed (see Fig. 6b) and only online and stage control were applied (cf. Sect. 2.4). The online control of this example was discussed in detail by Lachmayer et al. [14]. A tool-mounted laser profiler that measures the relative position of the robot tool to the top surface of the partially printed wall segment is used for a fine-grained control of the nozzle distance (see also Sect. 2.1). For the stage control illustrated in Fig. 6, a TLS mounted on a separate robot is used to capture the components geometry and position. By direct co-registration with the digital model and applying cloud to mesh (C2M) (or alternatively M3C2) algorithms [18], the deviation map (see Fig. 6a) is extracted, providing the deviation distance for every captured point (deviation map). In order to analyze the process in more detail, a manual segmentation into the individual layers is carried out as shwon in Fig. 6c.

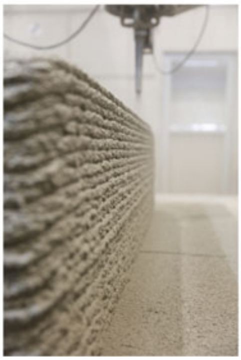
Analysis: As shown in Fig. 6, the finished component looks similar to its digital model (cf. Fig. 5), but differs in certain details. The most important deviations include the fact that the designed height is not met, the sides are realized rather inaccurately and the planned width is exceeded in many places (cf. Fig. 6a). In addition, the segmented point cloud (Fig. 6c) shows flaws on the level of individual layers. However, all of these results were created manually, long after the process was complete. Integrating quality control into FIM could not only automate the evaluation of measurements, but also initiate processes to counteract the previously mentioned problems.

If the recorded geometry is compared with the digital model, it can be checked whether the component meets the requirements for the next production stage or whether further steps are necessary. In case of the shown example, the reached height was 429.77 mm and therefore additional 1.35 layers would need to be printed to reach the planned 450 mm. With FIM, this can be automated and the process could be extended directly, saving these changes directly in the model, needless to say.

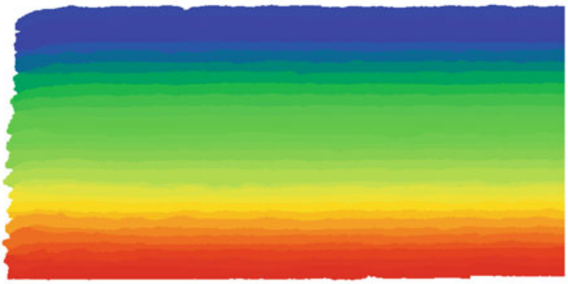
The labeled data shown in Fig. 6c was tediously created by hand, which was time-consuming and error-prone due to the fuzzy edges, and as a result still does not fully represent reality, as only 29 layers were counted (there should be 30). By automating the labeling process, this process could be performed much faster and less error-prone, while at the same time extracting the surface of the "as-manufactured"



(a) C2M distance between the point cloud and digital model.



(b) "As-manufactured"



(c) Manually labeled point cloud data.

Fig. 6 "As-manufactured" data for the simple Wall [6, 14] layer. The extracted layer surfaces could then be used to update the digital model and possibly utilized in advanced FEM analyses. It is worth noting that point-wise inspection can be used as a basis for the segmentation process (filament detection), as it provides a deviation map of the created object from its digital model. However, the sensor type, data quality as well as the filament feature detection methodology determines the quality of the segmentation process. Furthermore, another challenge corresponding to the filament detection is the differentiation process that detects the individual layers, as the filament borders may not always be separated clearly.

The heat map shown in Fig. 6a contains information about the surface quality of the simple wall example. As shown, the deviations are in the range of −2.1 to 0.6 cm, which might necessitate post-processing, such as surface smoothing, depending on the required tolerances of the object. Although not applied here, the dense geometric map of the rough surface can be used to create the machine control code for the smoothing motion. Even if the measurement data is processed directly, it may still be useful later, e.g. when used for predictions in similar projects. However, the amount of data collected using TLS is quite substantial, so abstraction of the data to an appropriate level must be considered. The point-wise inspection results, for example, can be approximated into pixel-based deviation maps that can be reported back to the FIM and applied to the B-Rep of the component. Another option would be to replace the point cloud data with a B-spline approximation, which not only increases data efficiency but also removes noise [19].

4.2 Scenario 2: Double Curved Reinforced Concrete Wall

For the second scenario, the real-size demonstrator [9] is used as example. This demonstrator is a double-curved reinforced wall that was built in several manufacturing stages and finally post-processed for a smooth surface (cf. Fig. 7).

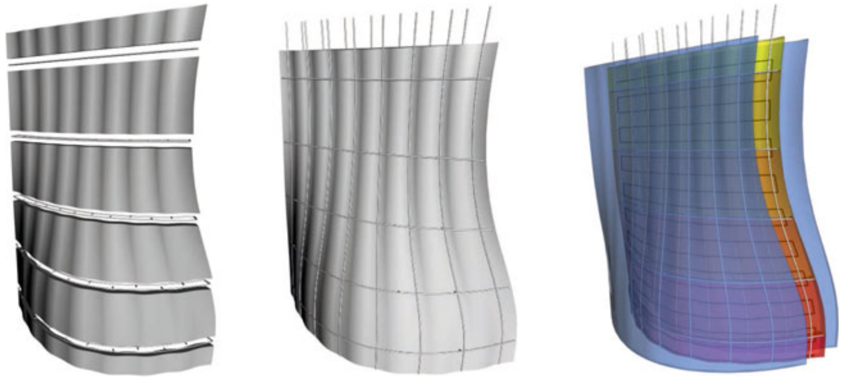
Noteworthy features of the demonstrator are, first, the geometric complexity and, second, the multi-scale details in the centimeter and meter range. Similar to the first scenario (Sect. 4.1), stage control was performed, but is not discussed in detail here to avoid repetition. More important for this scenario is pre-assembly control, which was performed after the edge trimming and surface finishing steps (cf. Sect. 2.1). After the post-processing, the object is expected to have a defined shape close to the designed model.

Fig. 7 Digital model of the double curved reinforced concrete wall example [9]

FIM: The manufacturing process of the shown example is, as previously stated, separated into different printing stages to enable the insertion of rebars. The following description is a slightly modified revision of Hack and Kloft's process description [9] in the context of FIM. As the first set of stages, the core structure is printed layer by layer, which is designed to contain pockets for the placement of reinforcement. At the end of each core structure stage (except the last), a horizontal layer of reinforcement is placed. Once the core structure is finished, the vertical rebars are added in the second stage and covered with the surface coating immediately afterwards in the third stage. Finally, in the last stage, the surface is post-processed using different sized rotating discs in three smoothing steps.

Each of the steps described above is represented in FIM as list of base steps, similar to the first scenario (cf. Sect. 4.1). First, the core structure is sliced into individual printing layers, each representing a base step and for each of which the printing instructions are generated (layer instruction). In addition, the placement of horizontal reinforcing bars is scheduled after a certain number of layers. Since each placement of horizontal rebars disrupts the printing process and the correct position of the rebars must be ensured, the production of the core structure is divided into further sub-stages, one sub-stage per rebar layer and per concrete segment (cf. Fig. 8a). Next, the vertical rebar placement is split into each individual placement step and grouped as the second stage (cf. Fig. 8b).

After that, the surface coating processes are designed similarly to the first stage and grouped as the third stage. Path planning is performed in this stage in the respective parameter space of the designed smooth faces of the component (finished state, Fig. 7). However, the substrate in this process corresponds to the respective side surface of the core structure, all of which are uneven, which is why the layer height is not constant. Finally, all smoothing steps are combined as the 4th and last stage (cf. Fig. 8c).



(a) Stage 1a–k: Core structure including horizontal rebars.

(b) Stage 2: Vertical rebar placement.

(c) Stage 3 & 4: Surface coating and finishing.

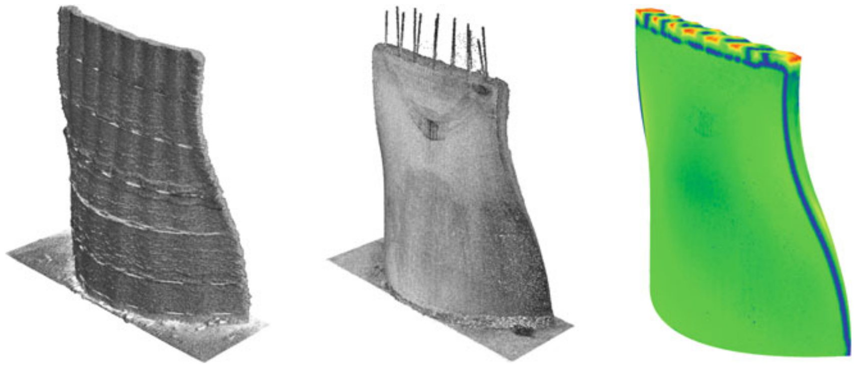
Fig. 8 Geometric representation of the different manufacturing stages for the double curved wall demonstrator [9]. **a** and **c** are shown as an exploded view for clarity.

Each (sub-)stage therefore represents a set of individual base steps, that can be executed in direct succession (continuous group). A continuous group can be manufactured without changing the robot tool, and QC can take place between each of these groups.

QC: This scenario is in many ways more complex than the previous case study, as it involves multi-stage manufacturing of a concrete and steel component including subtractive surface finishing. Each stage has been controlled using online and stage control and the finished wall was inspected with pre-assembly control [4]. As in the previous scenario, the online control was used to monitor the nozzle distance and thus stabilize the process. For the surface coating process before the final smoothing, stage control was used to generate a design basis (cf. Fig. 9a). Using the scan data a printing path was generated for the material application covering the installed rebars. The pre-assembly control at the end was performed to record the "as-manufactured" condition of the component after the surface finishing (cf. Fig. 9b) and compared with the digital model utilizing C2M algorithms (cf. Fig. 9c).

Analysis: Compared to the first scenario, the final product in this scenario displays much less deviation from the digital model (cf. Fig. 9c). It was possible to compensate for process- and material-related deviations by means of surface processing, so that deviations of less than 10 mm could be achieved [9]. However, some steps were carried out manually during the manufacturing process and the measurement data were evaluated using individually developed scripts.

Online and stage control was largely analogous to scenario 1. However, stage control could have been particularly useful in the first stage (cf. Fig. 8a) to ensure that the individual core segments (partial stages) were produced accurately and that the horizontal reinforcing bars were placed in the correct position (with the "as-built"



(a) Intermediate manufacturing stage. (b) Laser scan of the finished wall. (c) Deviation map.

Fig. 9 Laser scan data taken during the manufacturing of the double curved wall example [9] and processed deviation map [4]

position also being recorded). The same applies to the vertical rebars in the second stage (cf. Fig. 8b). The third stage (cf. Fig. 8c) was based solely on the measurement data from stage control.

Also in this example, automating the QC would speed up the process and more of the fabrication process could have been automated, such as the placement of reinforcement. However, the sensor selection for feature extraction and object detection in the stage control of this example needs further investigation. The previously mentioned detection of rebar is a difficult task for laser scanners because the signals received from the metals have a high reflectivity. In addition, the small shape of the rebars may result in a point cloud of poor quality due to noise.

The pre-assembly control in this example deals with extracting features from the printed object and comparing them with their digital counterpart [17]. The advantage of this inspection method is that the two data sets (digital and physical) do not have to be aligned because the object features can be compared directly. This feature eliminates the error factors associated with the alignment step. Any detected feature, such as boundary edges or surfaces, can be fed back into the FIM model as NURBS curves or surfaces. In addition to features, attributes such as flatness, smoothness, roughness, and others can be tested during pre-assembly inspection and fed back to FIM by annotation of the respective geometric element.

In general, the inspection cycles and feedback workflow enable increased automation of production. By using FIM as a central data repository, all collected measurement data can be accessed easily and efficiently. If there is a direct data feedback, a model can be adjusted in real time and in turn influence the production, i.e. a CPS can be realized (cf. Sect. 2.3).

4.3 Scenario 3: Key and Lock Joint Features

This example shows the manufacturing of a key and lock joint feature (cf. Fig. 10) that are to be assembled. FIM is not yet extended to represent such features, but conceptually these features can also be manufactured in a similar way as described in the previous scenarios.

FIM: Since a FIM model represents a single component, connection features, as shown in this example, act as an interface between different FIM models. Thus, one FIM model contains the key feature and another FIM model contains the fitting lock feature. This introduces the difficulty that the corresponding geometry must be designed across components.

The third scenario shows again components that have to be created in more than one manufacturing stage. Since the SC3DP process is not suitable for generating high-resolution geometries, an approximated shape must first be created, which can be adapted to the planned geometry with high accuracy in a subtractive post-processing stage. Thereby, it is important to make sure that the AM geometry fully incorporates the planned feature in order to limit the number of post-processing steps required.

For both components the AM process must be planned with a sufficiently oversized geometry. In addition, the trim geometries for both components must be fitted consistently with each other so that this joint does not affect the absolute position of the components. This also means that very small manufacturing tolerances must be considered.

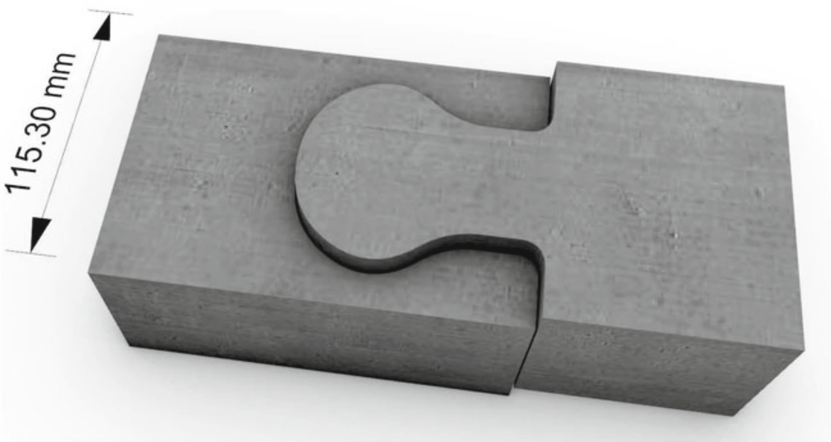


Fig. 10 Digital model of the Key and Lock joint [2]. It is meant to be a Demonstrator for a joining feature. Applied to a component the design may need to be resized

For this example, both sides were modeled as cuboids and a subtraction solid was created for each side. The subtraction solid for one side was planned freely and then used for the other side as a negative with some offset. For the complex geometry of the interface an extruded NURBS curve was defined.

QC: As in the previous scenarios, all the different types of quality control could be discussed in this scenario, but here the focus is on pre-assembly control Sect. 2.4 and in particular focused on the joint feature. To this end, the most important task is to detect features such as edges and surfaces in high detail at the points where different components are to be joined. In this example, the omega-shaped area represents the interface and must be captured on both sides of the joint, i.e. measured separately for each component involved. An assembly of the components involved is only possible if both recorded surfaces can be arranged with sufficient distance to each other.

Analysis: The two omega-shaped components were 3D printed just as in the previous examples. For the realization of the contact surface, material was removed accordingly after printing with a milling machine. In contrast to scenario 2, however, the material was not removed until the concrete had completely hardened. A difficulty in this example can be that the components have to be moved between the two manufacturing stages, so that the milling process has to be aligned with the repositioning of the components.

During the manufacture of components containing joints, the following errors, among others, can occur. On the one hand, the respective sides of the joint can be manufactured incorrectly so that they do not fit into each other. Secondly, the position of the joint may be incorrectly arranged on the component so that it fits together with its respective counterpart, but is then incorrectly positioned in a global sense.

The assembly shown in Fig. 11 exhibits the first of the two errors mentioned; although the components appear to be correct, they will not mate.

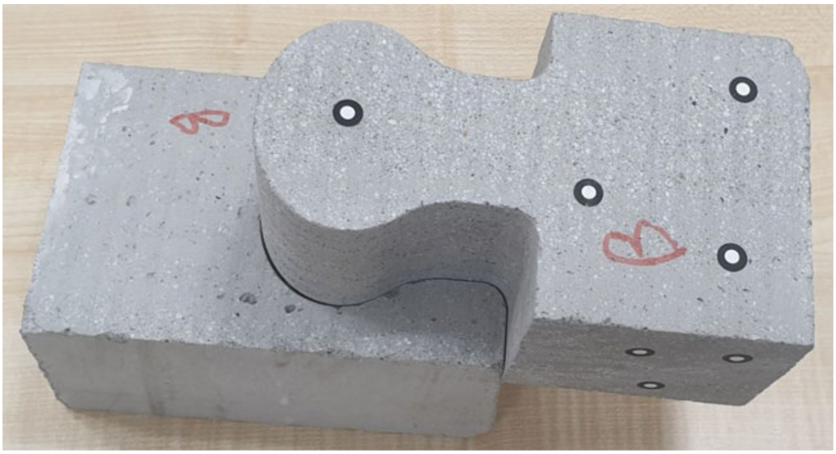


Fig. 11 3D printed specimen [2]

It can therefore be said that components containing joints require a very high degree of precision during manufacture, which makes a corresponding quality control absolutely essential. However, it can be problematic here that the selected sensor, i.e. TLS, can record the geometry in a resolution within the tolerance range of the joint. In addition, joints can only make up a small part of the component, which is why the sensor must be able to measure more densely in these parts of the component.

5 Conclusion and Outlook

A frequently cited advantage of AM is that it is a fully automatable manufacturing method that could help increase productivity in the construction industry. However, human supervision is still required for a meaningful use of this method according to the current state of the art. By itself and without appropriately programmed fail-safes, a robot will stubbornly execute its predefined program regardless of the outcome. It lacks the ability to detect, interpret and correct errors by itself.

In this study, different scenarios were investigated to determine the extent to which human supervision in the use of AM can be further reduced. For this purpose, we specifically investigated how automated QC can be implemented within FIM. In the scenarios it was shown that different types of QC are applicable depending on the process state and the desired component properties. Each demonstrated QC type has its own prerequisites, capabilities and requires a certain amount of preparation, such as the choice of sensor position (scan planning). In addition, for capturing certain materials and details in the required level of accuracy (LoA), sensor selection and settings must be optimized, e.g. when capturing the geometry of reflective metals. Thus, a good strategy for **sensor setup**, **information extraction** and **feedback** is crucial for QC automation.

As preparation, sensor examination and adjustment with regard to the requirements of the defined tolerances and the shape of the object is necessary to capture valuable data. In the case of TLS, laser footprint parameters such as range, angle of incidence and material properties, can have a decisive influence on the quality of the corresponding data. Using FIM for the planning and execution of the AM process, all these parameters can be accessed at any time provided appropriate FIM extensions are made.

For the extraction of relevant information and the corresponding feedback, a distinction must be made depending on the QC type. In the case of online control discussed in Sect. 4.1, a small local data set is processed immediately feeding back the obtained control value. The captured data (in the example a line profile) is obsolete at the latest after the next printing layer and does not need to be stored in FIM. During stage control, extracting information from the captured data involves direct co-registration of the captured data set with the geometric representation provided by FIM. The extracted point-wise information as well as the features are fed back to FIM to be used as a basis for planning the subsequent manufacturing stage. Finally, during pre-assembly control extracted features are extracted without co-registration and evaluated using FIM representations.

In addition, periodic inspection provides information on time-dependent effects during the manufacturing process, such as sagging and other changes in shape. Considering that the filament properties in the process are highly dependent on many different parameters such as material composition, nozzle spacing, nozzle diameter, extrusion speed, air pressure and robot speed, it is important to comprehensively document each manufacturing stage or sub-stage (cf. Sect. 4.2). This alone allows a meaningful comparison to be made with the design information and conclusions to be drawn about parameter influences on the process in order to improve future projects.

Finally, it must be noted that automation of information extraction and feedback of QC results to FIM (digital part of DT) represents an update routine that always points to the current state of the real component (physical part of DT) and thus realizes the physical-digital connection (cf. Sect. 2.3).

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Development of Knowledge Information Model for Highway Route Design

Koji Makanae

Abstract This paper shows a design structure schema for highway route design based on the conceptual pyramid information model and the connector model in previous studies. In the design structure schema, the design process is classified into four stages: Conceptual Design, Outline Design, Basic Design, and Recursive Design, and it shows that the highway design process can be viewed as a function of the designer's thought process. Moreover, a method for analyzing the fluctuation in highway distance was proposed. A distance-conversion table for each measurement that lengthens the highway can be linked to the dispositional information. Using this method, we can start compiling knowledge from the beginning about changes in distance and will be able to reproduce the route-selection process in a system.

Keywords Information management · Knowledge management · Route design · BIM · Knowledge continuity

1 Introduction

Building information modeling (BIM) is a technique continuously gaining popularity in the construction sector, and is increasingly being applied to public infrastructure. For example, U.S. CAD vendors in particular, are developing "BIM for Infrastructure" systems and working on their application in construction projects. Also, builingSMART, the BIM standards body, has established an infrastructure sub-committee, and is exploring applications of industry foundation classes (IFCs), which are the standards in building construction for railways and highways. Meanwhile, Japan is also following this trend: in 2012, a construction information modeling (BIM/CIM) concept was promoted by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), while construction-production systems using 3D models and

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ICT were developing fast. The BIM/CIM concept has also expanded into management, and can be expected to extend into information management that covers the construction lifecycle, including the maintenance management and handover to the next cycle. Till date, for BIMs in the construction sector, work has been done on knowledge-based BIM systems during project management [1].

By contrast, we proposed a conceptual model as a foundation for information management in the previous studies [2–4]. This paper summarizes the pyramid information model as a foundation for information management and the connector model for information, which can include knowledge and wisdom. Moreover, this paper shows a knowledge information schema and a method of compiling information for knowledge continuity for highway route design based on the conceptual model in the previous studies.

2 Modeling Infrastructure Information structure

Compared to other industries, public infrastructure is distinct, such that its work products are larger, and the lifecycles are longer, including production processes. These processes progress through stages of conceptual planning, detailed planning, surveying, designing, and fabrication. Among them, the design information is driven towards finer granularity and higher precision, ultimately forming the actual production on site. The authors in [2, 3] demonstrated that information structures in production processes followed a "pyramid" model moving from abstract to specific (Fig. 1), and an information-structure model along the time axis throughout the lifecycle.

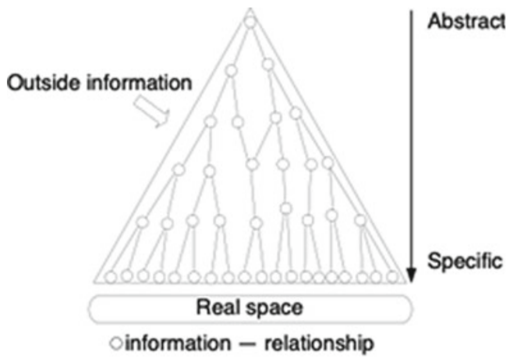

Fig. 1 The pyramid model of public-infrastructure information

3 An Information-Connector Model for Compiling Knowledge and Wisdom

In the pyramid model shown in Fig. 1, all generated information is connected to the thing itself in real space via links. But when viewing a production process at the micro scale, there also exits discarded information without any linkage to the thing itself. Taking a highway-design project as an example, when selecting an alignment, there are multiple possible routes connecting the starting and end points, each of whose draft designs will be produced. Each candidate route is evaluated for its pros and cons according to numerous factors, followed by a decision making, with only the selected candidate proceeding to the execution stage.

Although the course of this decision-making process will be documented in reports, it will not leave behind an information structure. However, such a process uses all the knowledge and wisdom of the people involved, and the basis for the decision (why a certain route was selected) may remain useful over the course of multiple lifecycles. The field of knowledge management uses a "data-information-knowledge-wisdom" (DIKW) pyramid [5], but when applied to infrastructure information management, there still exists a need for a way to collect and create knowledge and wisdom, not just data and information—the upper layers of DIKW.

A conceptual diagram of information connectors, including decision making is shown in Fig. 2. The individual connectors can be expressed as a "swelling of knowledge" when there are multiple options. Those bulges contain the decision-making process for one of the options. Compiling these decision-making processes leads to developing the rules of thumb, which can be used as a way of creating wisdom.

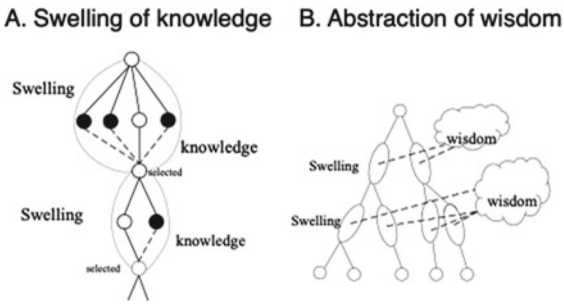

Fig. 2 The connector model of information, including knowledge and wisdom [4]

4 A Method of Compiling Information for Continuity of Knowledge

4.1 Preliminary Experiments in Knowledge Acquisition

To clarify the knowledge-acquisition process in highway design, in this study, we took a total of seven students from Miyagi University, without any knowledge or skill in highway design, as our subjects. In our experiment, we asked our subjects to draw highways before and after teaching them about highway design. The experimental procedure was as follows:

1. The subjects were presented with topographic maps showing only contour lines, with two points A and B indicated. The subjects drew routes connecting points A and B that they considered suitable.
2. Taking highways in a different region as a case, the subjects sat for a 10-min lecture on the main points on how to draw routes for highways (the route should connect points by the shortest distance possible, steep inclines should be taken into account, as well as complex topography should be avoided to prevent disasters.
3. Based on Step 2, the students drew suitable routes again (multiple routes were allowed).

Examples of the routes drawn in the experiment are shown in Fig. 3. The orange and red lines correspond to the routes a subject drew before and after the instruction, respectively. The black dotted lines show the actual route in the region, which is the result of numerous design constraints, while several routes drawn after the instruction approximated it. In the future, we will need to perform a numerical analysis of actual results and clarify the knowledge-acquisition process.

Fig. 3 Sample route drawn by an experiment subject (base map from web-based highway maker; Fukaura area)

4.2 Development of Design Structure Schema for Highway Route Design

In order to develop a knowledge structure schema required for highway route design, we analyzed an actual highway design process and flow analysis from the viewpoint of information distribution. The highway design process used as a reference is a large-scale mountain highway reconstruction project in Japan (Gassan Highway, 30.9 km long, 5 tunnels, 36 bridges, completed in 1981). Although the design at that time was paper-based and did not involve digital information, the flow construction was conducted considering the application of BIM. The resulting design structure schema is shown in Fig. 4. The design process is classified into four stages: Conceptual Design, Outline Design, Basic Design, and Recursive Design. Each stage encompasses the function f of human intellectual activity.

In the Conceptual Design stage, the basic information for highway route design (origin, destination, and waypoints) and the level of service of the highway are determined based on the design standard. Function f_1 outputs the origin, destination, and waypoints that should be set to realize the concept and the level of service of the highway to be built, based on a statistical analysis of regional and traffic conditions and geographical information.

The Outline Design stage defines the actual highway locations and the information underlying the cross-section configuration. The function f_{2A} defines the outline road alignment based on the terrain model, and the function f_{2C} defines the cross-section configuration based on the level of service.

The Basic Design is the process of defining the basic geometry of the highway structure using function f_3 based on more detailed terrain, geological, and environmental information. As in the previous process, the specific shape is defined by parameters. In most cases, the site for the highway is determined at this stage, and the land acquisition proceeds sequentially.

In the recursive design, sectioning is performed on the established highway alignment based on differences in structure type, and design is performed for each individual structure. The geometry is constructed using parameters according to the structural type, such as earthwork for function f_{4E}, bridge for f_{4B}, tunnel for f_{4T},.

As described above, the highway design process can be viewed as a function of the designer's thought process. Therefore, design object *Obj* can be shown as Eq. (1).

$$Obj = f_n(terrain,\ geology/environment,\ parameters\ (design\ conditions)) \quad (1)$$

The knowledge information modeling process is the definition of these functions. We plan to define these functions for the knowledge information model in the future.

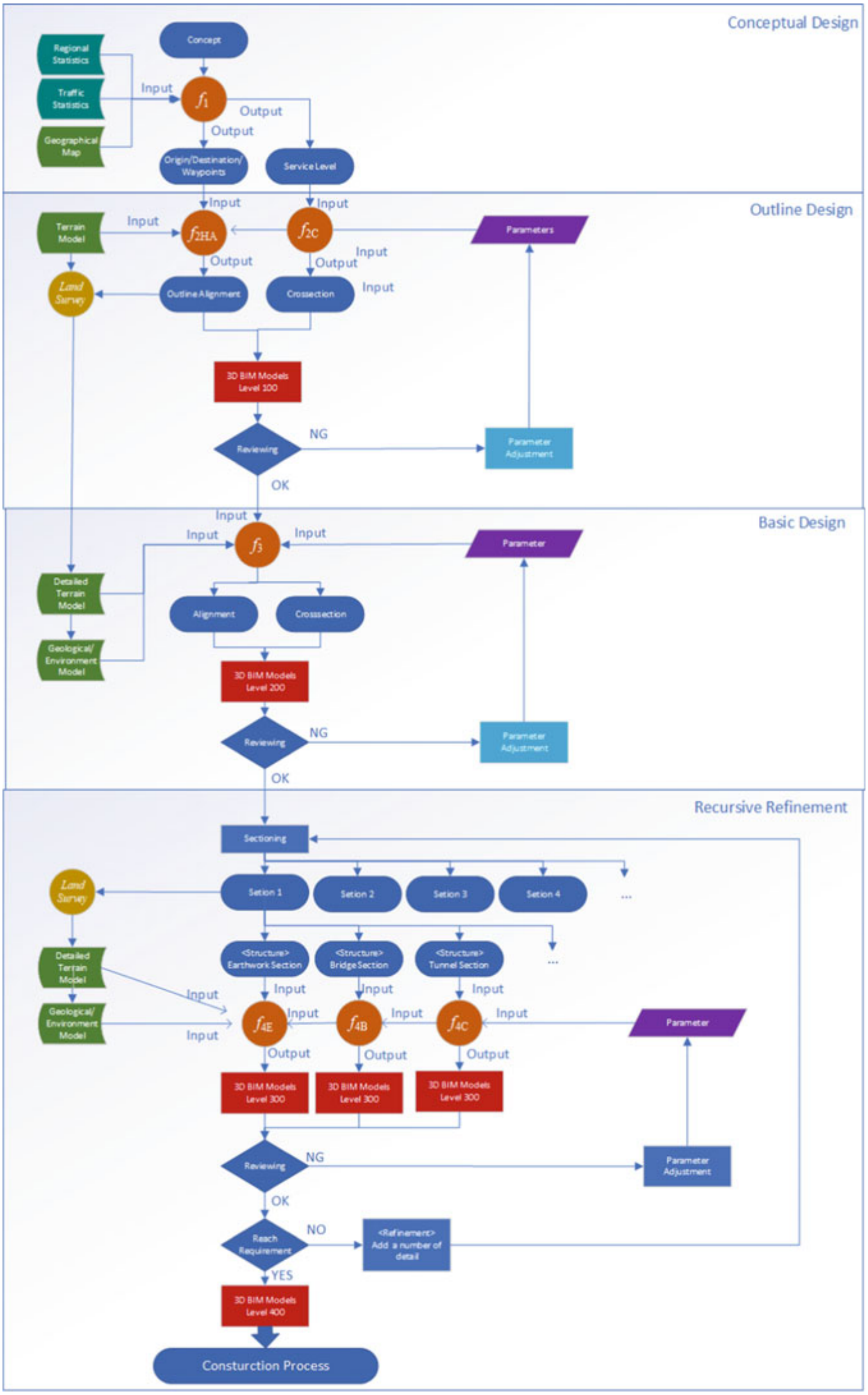

Fig. 4 Knowledge structure schema for highway route design

4.3 A Method of Compiling Information for Knowledge Continuity

When selecting a highway route, natural conditions such as topography, soil quality, climate, flora and fauna, and scenery, as well as societal conditions, such as the locations of existing highways, land use, schools and other facilities, will act as control points, while the goal is to lay out an optimized highway that satisfies these various conditions or minimizes their impact. In order to compile design dispositions (know-how) at the route design stage, connecting the map information consisting of curves that show the centerlines of highways is the main challenge. The geometric structure of a highway is defined as a single dimension representing the linear distance of the highway centerline. Similarly, distance is the central piece of information for specifying the position. Hence, connecting dispositional information and distance becomes desirable. However, at the route-selection stage, the centerline has yet to be decided to obtain the central piece of information, the distance.

An example of the route design process is shown in Fig. 5. Once the starting and end points have been set, the highway could be defined as a single straight line, but in reality, it may need to be a curve due to topographic and other constraints, thus, lengthening the highway compared to a straight line. Also, as shown in the example, if the highway involves tunnels or bridges, it may actually be shorter than following the topographic contours. In this study, as a method for analyzing the fluctuation in highway distance, we prepared a distance-conversion table for each measurement that has the effect of lengthening the highway, and proposed that this can be linked to the dispositional information. Using this method, we can start compiling knowledge

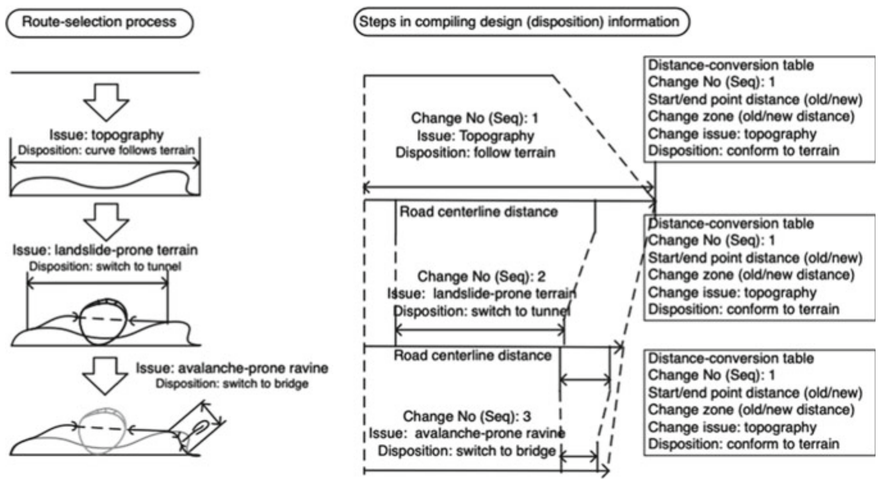

Fig. 5 Information-compilation process in route selection & design (disposition)

from the beginning about changes in distance, and will be able to reproduce the route-selection process in a system. In the future, a system that implements this method, as well as its continuous testing, will become necessary.

5 Conclusions

In this paper, we presented a knowledge structure schema required for highway route design and studied a way to compile information, including knowledge and wisdom. In the future, continuous work is necessary to build a system for compiling the design dispositions based on our proposed method. Also, more experiments and analyses of knowledge acquisition need to be done. Along with clarifying the knowledge-acquisition process, research needs to be carried out on ways to create knowledge and wisdom from the information compiled based on the expertise formed in this manner.

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The IFC-Tunnel Project – Extending the IFC Standard to Enable High-Quality Exchange of Tunnel Information Models

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Abstract The paper reports on the buildingSMART International project IFC-Tunnel that is developing an extension of the vendor-neutral data exchange standard Industry Foundation Classes (IFC). The paper highlights the importance of a well-defined development process and the involvement of international domain experts. It discusses in detail the requirements analysis conducted as well as its outcome in terms of the tunnel types and the use cases covered. It subsequently reports on the conceptual model that includes all proposed extensions and modifications, as well as the alpha version of the EXPRESS encoding which will be integrated into future versions of the IFC standard.

Keywords BIM · Tunnel Information Modeling · Industry Foundation Classes · Geology model · Geotechnical model · Underground Constructions · Voxel Geometry

1 Introduction

The international standard Industry Foundation Classes (IFC) is a vendor-neutral BIM data exchange standard providing a comprehensive data model that allows the detailed geometric and semantic description of buildings. It is in widespread

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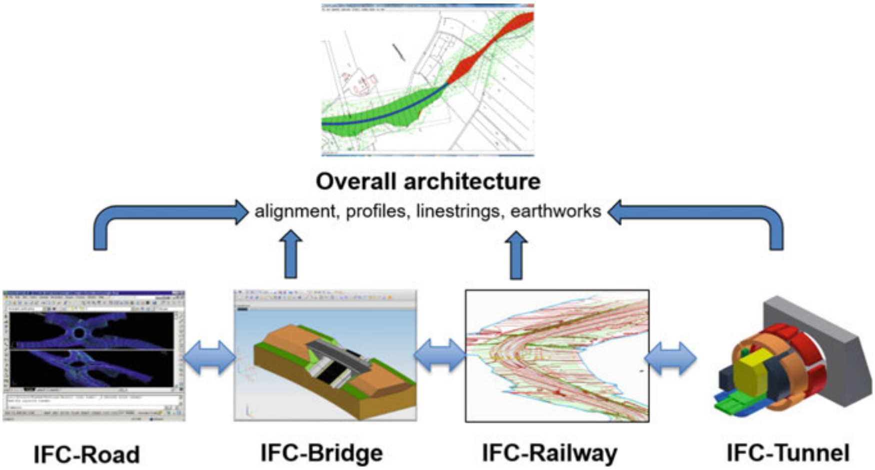

Fig. 1 Overview on the IFC-Infra extensions.

use for data exchange across different BIM software products. It is developed by the international non-profit organization buildingSMART and has been adopted as ISO 16739. Up to version 4.0, the IFC standard was mainly focused on buildings. However, due to increasing international demand, a substantial extension of the standard to support infrastructure facilities has been carried out.

To this end, the so-called Infra Room, a subdivision of buildingSMART International (bSI) with its own steering committee, was founded in 2013. It developed a roadmap and started a number of projects to develop the necessary extensions. The first project was IfcAlignment which defined extensions for describing the alignment of linear infrastructure assets [16]. On this basis, the IFC Infra Overall Architecture project was conducted in order to specify general principles to be followed by all Infrastructure extension projects. On top of that, the projects IFC-Bridge, IFC-Rail, IFC-Road and IFC-Tunnel have been initiated (Fig. 1).

In this paper, we report on the IFC-Tunnel project; its development process and the results.

2 The IFC-Tunnel Extension Project

In response to the urgent demand of international infrastructure stakeholders for extending IFC for tunnels, the standard development project was initiated by bSI Infrastructure Room. It started in January 2019 and will be completed by the end of 2022. Due to the short duration and the limited resources available, it was essential that the project focused on “low hanging” fruits; i.e. selecting use cases to be supported that bring the most value to the future users of the standard.

The IFC-Tunnel extension project followed the formal project execution guidelines of bSI that came into effect in 2015 [10] specifying the organizational structure and the development process.

2.1 The Organizational Structure

For each IFC extension project, a project team has to be formed. It consists of a group of international experts, preferably a combination of domain experts and IFC specialists. In the case of the IFC-Tunnel project, the project team was composed of more than 40 members originating from different parts of the world, including France, Switzerland, Austria, Norway, Sweden, Italy, Germany, and Japan.

To ensure a maximum efficiency, the project team was subdivided into the following working groups:

– Geology and Geotechnics,
– Excavation and Lining,
– Equipment and Systems,
– IFC experts

The individual subteams met on a bi-weekly basis complemented by whole-team meetings in irregular intervals. The project lead reported to the Infra Room Project Steering Committee (IRPSC) on a monthly basis, which monitors project progress and funds across all bSI infrastructure projects.

Panel meetings with external domain experts were hold in 6-months intervals to discuss the use cases and verify the development results.

2.2 The Development Process

As demanded by bSI guidelines, the IFC-Tunnel project implements the following development phases:

1. Requirements Analysis
2. Taxonomy Analysis
3. Conceptual model development
4. IFC schema extension proposal (draft)
5. Validation/Deployme
6. IFC schema extension proposal (final)
7. Formal acceptance

The following section will report in detail on each of these phases.

3 Requirements Analysis

An important lesson learned from more than 25 years of developing the open data standard IFC [15] is that it is of utmost importance to first define the scope and use cases to be covered by any extension project. This becomes even more obvious when considering (1) the large extent of the existing data model (IFC$\tilde{4}$.1 comprises 801 entities), (2) the limited time and resources available for the developing the extensions, and (3) the goal of lowering the effort for software implementation to enable a fast uptake of the standard.

The extensive requirements analysis performed by the project team resulted in the publication of the requirements analysis report [18], the content of which is summarized in the following subsections.

3.1 Tunnel Types Covered

Based on discussion with the expert panel and an analysis of the most widespread tunnel types constructed worldwide, the following construction methods were considered in the IFC-Tunnel project:

- Mechanized tunneling, using Tunnel Boring Machines (TBM)
- Drill-and-blast tunneling
- Cut-and-cover tunneling

Other construction methods, such jacked, immersed, and micro tunneling were investigated with lower priority.
From a usage point of view, the following tunnel types were decided to be in scope and having high priority:

- Road Tunnels
- Railway Tunnels
- Metro Tunnels
- Access Tunnels

With lower priority, the following usage types were investigated:

- Evacuation Tunnels
- Ventilation Tunnels
- Water Tunnels
- Pedestrian Tunnels
- Service Tunnels
- Underground facilities

3.2 Use Cases Covered

The project team performed an in-depth analysis of the use cases for a software vendor-independent tunnel data exchange format in order to identify those that are supposed to be supported by the extension, and those that are considered out-of-scope. The analysis included specifying the sending and the receiving application, rough descriptions of the required geometry representations and the semantic data as well as an assessment of the complexity of the realization of the required data structure. In addition, the priority of individual use case support was identified through intense consulting of the expert panel.

Based on a careful analysis of the benefits of the individual use cases and the complexity and effort involved with defining the necessary data structures, the project team decided to prioritize the following use cases for explicit consideration when designing the IFC-Tunnel extension:

– Initial state modelling
– Geologic factual data
– Geologic modelling
– Geotechnical modelling for design
– Geotechnical modelling for construction
– Exchange of alignment and major road/railway parameters
– Technical visualization
– Design coordination
– Design to design w. reference models
– Quantity Take-Off (general)
– Construction sequencing (4D modeling)
– Design to tender: Construction Model
– Design to tender: Geotechnical Model
– Design to construction
– Progress monitoring
– Geological documentation
– Quantity determination for billing/payment
– Handover to GIS
– Handover to AMS

Due to overly high complexity, the following use cases were decided to be out of scope of the fast-track project, but worth to be investigated in follow-up extension projects:

- Realistic visualization
- Safety visualization
- Structural and geomechanical analysis
- Air flow simulation
- Hydraulic simulation
- Standards compliance checking
- Prefabrication
- Scanning during construction
- Machine guidance and control
- Damages recording
- Settlement monitoring
- Design to Design (Full model logic)

3.3 Process Map

In compliance with the Information Delivery Manual (IDM) standard, the process map depicted in Fig. 2 has been developed to clearly identify the exchange requirements and associate them with dedicated data exchange scenarios. Its purpose is to provide a general reference workflow, i.e. deviations in national or regional processes are possible.

As processes related to geological assessment and geotechnical engineering are particularly important for tunneling projects, these processes are depicted in detail in Fig. 3.

3.4 Georeferencing

The proper usage of geodetic coordinate reference systems (CRS) plays an extraordinarily important role for the design and construction of tunnels due to their potentially very long expansions. Geodetic CRS apply a transformation to project the earth surface approximated by an ellipsoid onto a flat map (map projection). In the case of the Universal Transversal Mercator (UTM) projection, a cylindrical surface is used as projection surface. The projection and the height reduction to an ellipsoid introduces distortions in lengths (see Fig. 4). These distortions depend on the coordinate reference system applied and the location on the earth surface.

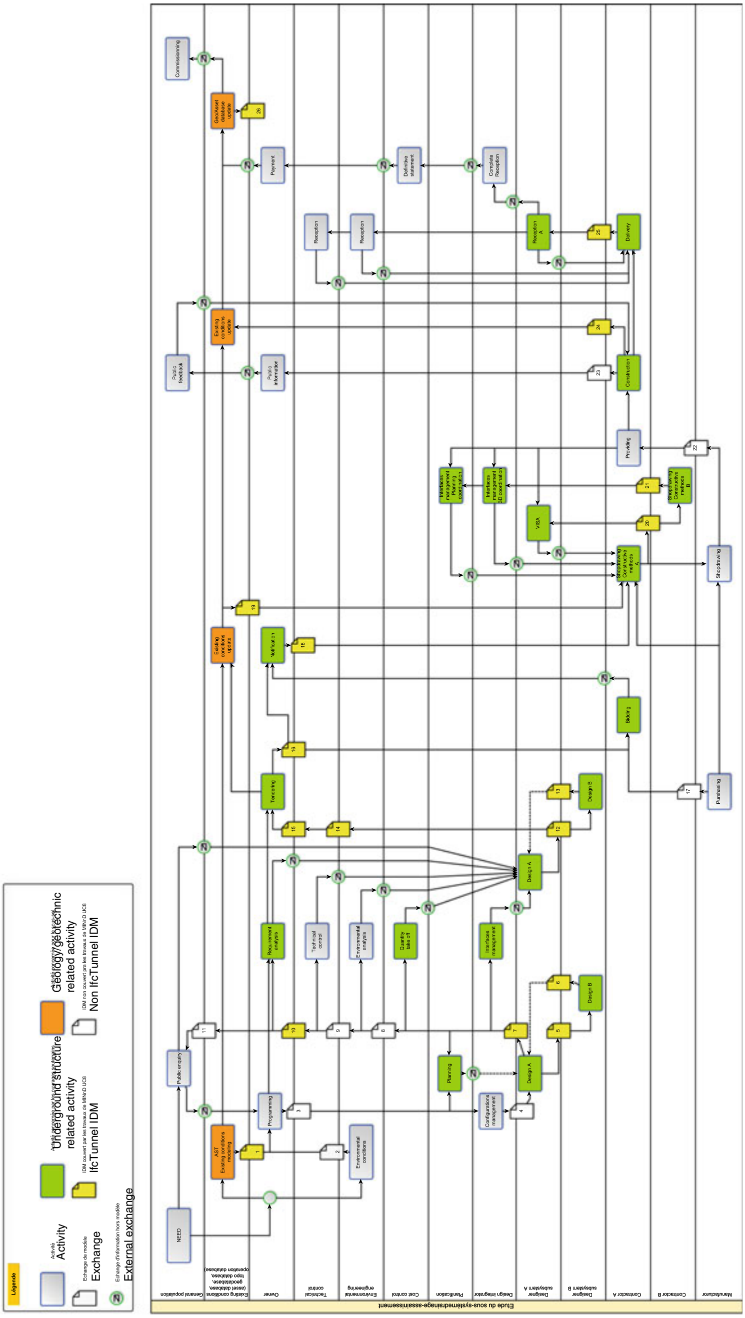

Fig. 2 BPMN Process map developed by the IFC-Tunnel project, based on prior work by the French MiND project.

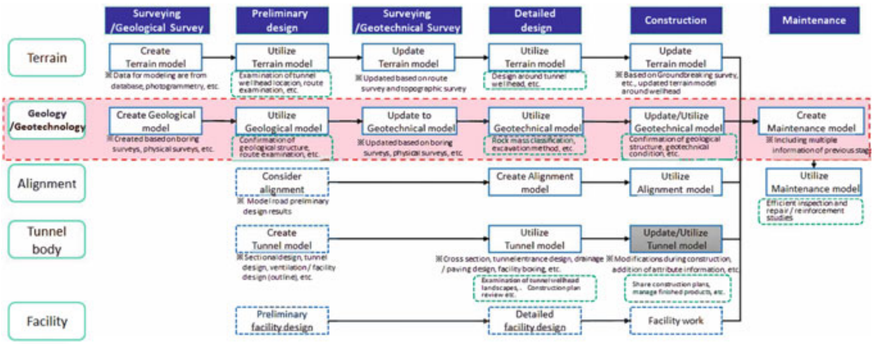

Fig. 3 The process map depicting the geotechnics-related processes.

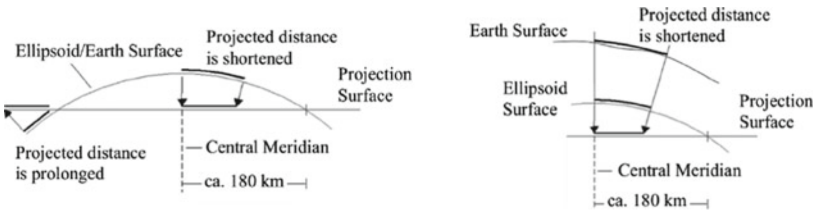

Fig. 4 The distortions induced by geodetic projection (left) and height reduction (right). Source: [13]

In consequence, tunnel models created in geodetic CRS are not 1:1 representations of the physical reality. This has to be taken into account for surveying, setting out, quantity take-off and any other kind of activity that translates model dimensions into the real world. Surveyors are experts in this field and can handle the required translations.

Data exchange standards, such as InfraGML, GeoSciML or CityGML, that are based on the Geographic Markup Language (GML) pay particular attention to the correct handling of geodetic reference systems by providing the necessary meta-data and by using exclusively coordinate values in the underlying geodetic CRS. This approach is also implemented by roadway and railway design systems.

BIM authoring systems for buildings are typically not able to handle geodetic CRS (large coordinates). For this reason, often a mere translation of the coordinate system is applied by defining a local coordinate system on a local point of origin. Typically, the geodetic coordinates are provided for this point of origin. However, if the local coordinate system is created by a mere translation (shifting in x and/or y direction by subtracting a fixed value from x and y coordinates), it remains a projected coordinate system with length distortions as described above. However, as now "small-value coordinates" are used, there is the severe risk that the tunnel model is erroneously interpreted as a distortion-free 1:1 model, potentially resulting in cost-intensive production or surveying errors on site.

Accordingly, for the proper use of the tunnel model represented by an IFC model, explicit information of the applied Coordinate Reference System is crucial. Very important is to allow the receiver of the model to unambiguously determine whether the model is distorted or not.

For short tunnels, also the use of a 1:1 modeling approach with an undistorted local coordinate system is possible. However, again this must be clearly specified in the IFC model. It is important to have in mind that for any data imported from GIS and other sources with geodetic CRS (e.g. digital terrain model), a re-projection must be applied to de-distort it.

For very large tunneling projects or for tunnels that cross national borders, project-specific CRS are applied that apply non-standard projections to minimize distortions between the projected CRS and the reality. A good example is the Brenner Base Tunnel that crosses the Austrian-Italian border and has its own CRS. This introduces the problem that for these project-specific CRS, no pre-defined EPSG codes exist.

The IFC Tunnel project analyzed the existing IFC4.3 standard that was submitted to ISO and identified a lack of this clarity of coordinate values in the IFC dataset. For this purpose, next to the IfcMapConversion entity which describes a conversion between local engineering coordinates from the IFC dataset to projected coordinates in the context of the IfcProjectedCRS as an EPSG code, three new entities were defined an proposed.

3.5 Alignment

The proper description of the alignment plays a major role for the digital representation of tunnels. A large number of use cases require the alignment to be represented as an explicit description as part of the IFC model to be exchanged. The alignment information is used for:

- procedural geometry descriptions where a cross-section is swept/extruded along an axis
- a linear reference system to position objects along the alignment

Both aspects are equally important. They are not necessarily implemented on the basis of the same geometric curve.

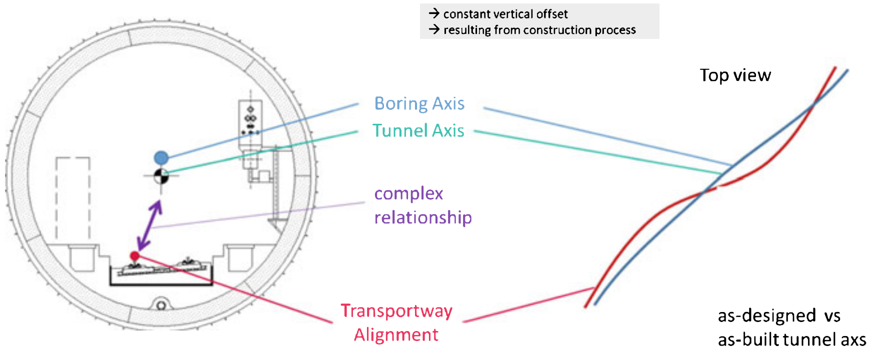

Fig. 5 Differences between the boring axis, the tunnel axis and the transport alignment.

Especially for TBM tunnels, it is important to distinguish between the different axes and underlying alignment curves (see Fig. 5):

1. the alignment of the roadway or railway encased by the tunne
2. the tunnel axis ("theoretical axis")
3. the boring axis

The differences between (2) and (3) results from the fact that there is vertical displacement of the ring after it has been installed due to the gravitational forces. The tunnel accordingly must be bored in an axis that has a vertical offset from the resulting tunnel axis.

While there are dependencies between (1) and (2), they are usually too complex to be described by the IFC model in an explicit manner. For the in-scope use cases (see Sect. 3) it is also not necessary to express this dependency.

According to the analysis conducted, the capabilities of IFC to describe alignments as introduced with IFC 4.1 and refined with IFC 4.3 are deemed sufficient for representing the axes of tunnel models and implement the identified use cases.

3.6 Geometry

The IFC data model supports a wide range of geometry representations. They can be broadly divided into

– **explicit representations** that describe the geometry of volume objects by their surface
– **implicit representations** (also called procedural descriptions) that describe the construction history, i.e. the operations applied to create the geometry

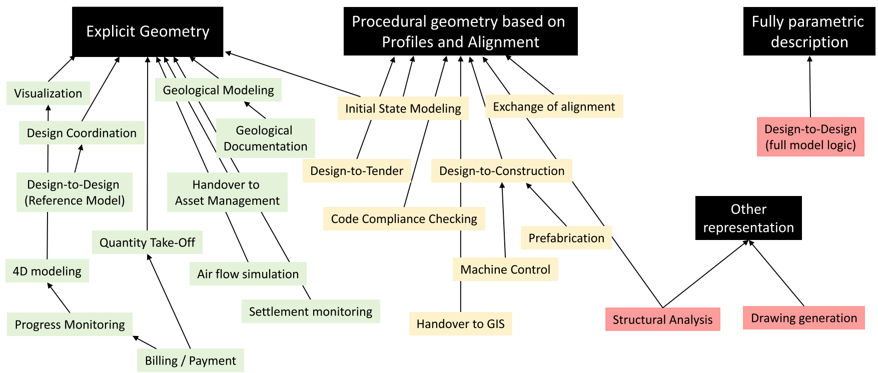

Fig. 6 Dependence of the use cases on specific geometry representations.

Both representations have their advantages and disadvantages and are suitable for different use cases. This is discussed in more detail in the following subsections.

The analysis revealed that the in-scope use cases require both, explicit BRep geometry as well as procedures geometry based on sweeps using profiles and alignment (Fig. 6).

Explicit Geometry. Explicit geometry representations describe the resulting geometry, but not the construction process. As such, they are well applicable for use cases that do not require the geometry to be modified after receiving it as an IFC model. By contrast, for design-to-design use cases where the (user of) the receiving application is supposed to change the model, explicit representations are of limited use.

The IFC standard provides multiple options for describing explicit geometry:

- triangle-based geometry (IfcTriangulatedFaceSet): a very common and wide-spread representation based only on triangles
- BRep geometry (IfcFacetedBRep): A representation that allows the proper description of non-triangular faces and the topology relations between faces, edges and vertices. All faces are planar and all edges are straight lines
- NURBS geometry (IfcAdvancedBRep): A representation that allows the description of solid objects with curved surfaces and curved edges on the basis of the mathematical description of Non-uniform rational B-Splines (NURBS).

Due to the construction methods applied, tunnel models typically have a high number of curved surfaces. This makes the application of NURBS geometry a natural choice. However, this representation is currently only to very low degree implemented by software vendors. Nevertheless, it is desirable for use cases with high accuracy demands and should be demanded from software vendors in the future.

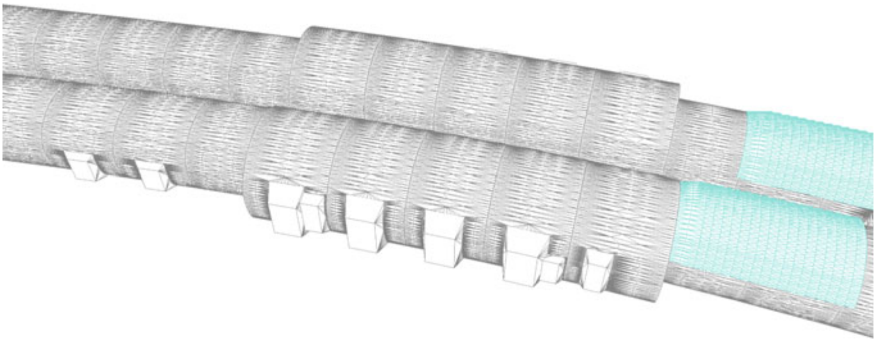

Fig. 7 A tunnel model with geometry described by IfcTriangulatedFaceSet with a large number of triangles

Accordingly, in most cases an approximation using triangle-based geometry will be applied (Fig. 7). It must be noted however, that due to this approximation, there are deviations between the real geometry and the one represented by the model. The size of the deviations depends on the refinement of the triangular mesh. At the same time, it must be noted that models with a large number of triangles are heavy in terms of file and storage size.

TBM tunnels are composed of a large number of repetitive (identical) elements, such as the ring segments. The geometry of these elements should be represented only once, and subsequently instantiated, placed and rotated by means of the IfcObjectType mechanism.

Procedural Geometry. Many of the high-priority use cases demand the usage of sweeps for representing the geometry of the tunnel, its elements and interior spaces. It was agreed by the project team that the usage of triangulated face sets is not appropriate for many use cases, due to the loss in accuracy and the excessive increase in data size.

Both, TBM tunnels as well as conventional tunnels can very well be described by procedural approaches based on the concept of sweeping a profile (cross-section) along an axis, as this reflects the typical construction methods. Many use cases accordingly depend on this notion and require the explicit description of the cross-section(s).

The use of procedural geometry is a requirement of any exchange scenarios that require the modification of the tunnel geometry at the receiving side. In comparison with a triangulated geometry description, a higher accuracy can be achieved by procedural descriptions while at the same time significantly lowering the data footprint (file size). However, the risk of diverging interpretations at the sending and the receiving application is higher, potentially resulting in erroneous geometry.

An important aspect to be considered is the fact that the profiles of conventional tunnels may change along the axis. Accordingly, the transition between the profiles must be clearly and unambiguously described by the IFC model, such that it is interpreted in the same way at both the sending and the receiving side.

For the procedural description of tunnel models, the following aspects have to be considered:

– the definition of the sweeping behavior,
– the description of the cross-section(s),
– the description of the sweeping axis,
– the description of interpolation between profiles,
– the description of spaces voiding the extrusion body

The entity IfcSectionedSolidHorizontal plays an important role. It has been introduced with IFC 4.1 as a result of the development activities in the IFC-Alignment and the IFC Infra Overall Architecture projects [6, 16]. The entity allows to perform sweeps along an alignment where the cross-section's y-vector is kept pointing in the global z direction, in contrast to the conventional IfcSweptAreaSolid where the cross-section is kept perpendicular to the sweeping path at any time. IfcSectionedSolidHorizontal has been introduced for correctly modeling elements of infrastructure facilities (roadway layers, bridge decks) and will be applied in this sense in the IFC-Tunnel extensions.

In practice, both IfcSweptAreaSolid and IfcSectionedSolidHorizontal are needed to define alignment-based geometry, depending on the construction method. TBM tunnels in most cases have a sweep geometry where the profile is perpendicular to the sweeping path, mainly due to the fact that prefabricated ring segments are used. Cut-and-cover tunnels on the other hand, are more likely to make use of IfcSectionedSolidHorizontal geometry as often they require cast-in-place processes which normally are oriented along the gravity axis (global z).

A particular requirement lies in the fact tunnels often have varying cross-sections along their axis. For a correct exchange of the sweep geometry, an unambiguous description of the interpolation between the profiles is necessary. To this end, guiding curves are used (Fig. 8).

Voxel Grids and Octrees for Representing Geological Data. There are specific use cases in the context of geological modelling [21] that require the use of voxel representations to allow for a fine-grained description of varying soil/rock properties with high spatial resolution (Fig. 9). Currently, such a geometry representation is not yet available in IFC. It should be considered to extend the IFC schema accordingly.

3.7 Geology and Geotechnics

The geological and geotechnical modeling of the underground plays an important role throughout all phases of a tunnel project and is relevant for several decisions and design solutions.

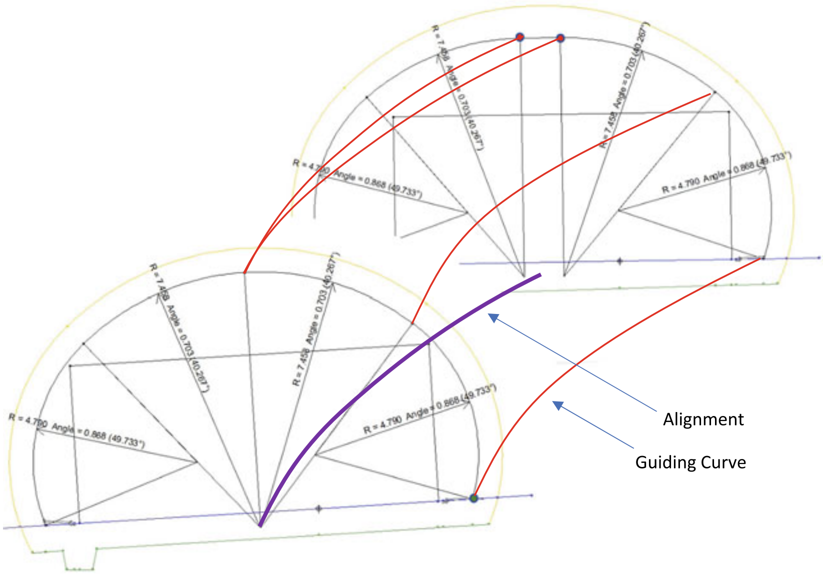

Fig. 8 A tunnel represented by a sweep with varying cross-sections. A particular challenge lies in the correct interpolation between the profiles. To this end, guiding curves are used.

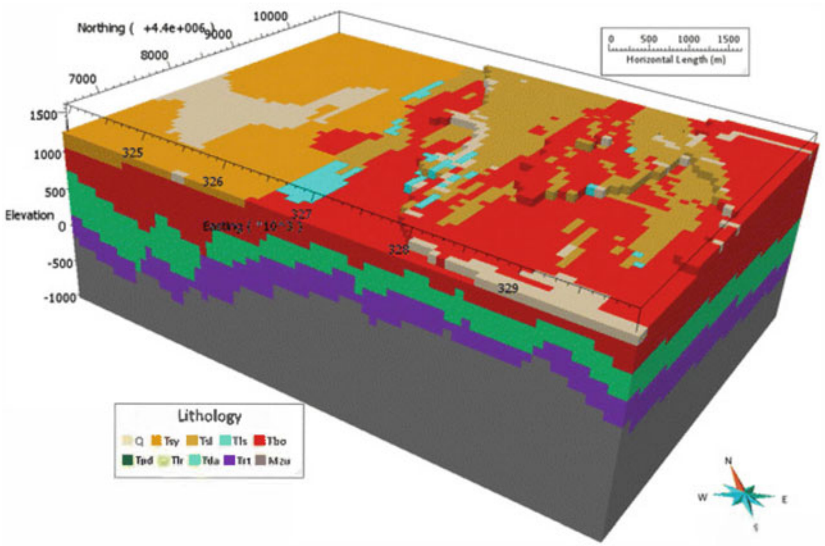

Fig. 9 Voxel representation of a geological model (Source: Witter et al. 2016 [21])

Several kinds of risks are associated with geological conditions and uncertainties in predictions of the ground conditions (interpreted models), which have a significant impact on the costs of tunnel projects.

Furthermore, in tunneling the ground material can be seen as a part of the building. For these reasons, the geological and geotechnical information must be described and represented in a standardized way, paying attention to the compatibility with IFC and existing standards of the geology and geotechnics disciplines. As IFC has developed to a widely applied industry standard and the integration of ground models into BIM design environments is requested frequently (not only, but especially in tunneling), such models should be covered by IFC.

This creates challenges for developing the IFC-Tunnel extension as the underground is not a man-made artefact, but a natural one and thus exhibits a rather complex structure, in terms of geometry and of spatially diverging properties: In general, there are no "standard-materials", but only artificial classifications superimposed to an inhomogeneous ground material.

Such classifications can be based on geological categories like e.g. age, stratigraphy and structural-tectonic position or lithology ("Geological model") or mechanical material properties and aspects relevant for design and construction ("geotechnical design models").

These classifications depend on the purpose and requirements in a (construction) project. Precise knowledge on the underground is only given by observation points (documentation, factual data). The modeling between these observation points represents the assumptions for design and provides the base for several applications:

- structural analysis (focus on mechanical properties)
- definition of construction and excavation methods
- material management etc.

This implies that commonly, different classification systems are used in parallel in tunneling projects, and the ground can be described in by different overlapping interpreted models.

Further, an interpretational model related to the planned facility (tunnel excavation/portal cut slopes) is used to summarize the expected conditions with key properties that describe the above aspects.

The nature of interpretational models for predictions involves vagueness and uncertainty. The developed schema includes several measures to describe and quantify this uncertainty, such as:

- multiple model scenarios related to a probabilistic analysis
- definition of value ranges for e.g. mechanical parameters
- visualization of the modeller's confidence by e.g. color coding
- an overlapping voxel model that describes the distribution of uncertainty of confidence in the model

The uncertainty is reduced throughout the project time with ongoing investigation and documentation of encountered conditions. Especially during project execution, comparison of encountered conditions to the prediction is one of the most important application for ground models. A well-defined "baseline model" that describes the expected conditions with e.g. value ranges regarding mechanical properties and distribution of materials enables a very efficient model-based evaluation of observations during construction. This provides the base for clear risk allocation in contracts and reduces the potential for disputes on unexpected ground conditions.

An as-built model of the encountered ground conditions, enriched with all the documentation collected during execution, can be provided after completion of excavation and ground improvement works. Such a standardized model can be stored in a structured way, and filtered content can be integrated in existing BIM environments for maintenance.

4 Taxonomy Analysis

After completing the requirements analysis phase, the tunnel taxonomy was compiled and analyzed in a comprehensive manner. The goal was to identify concepts specific to tunnel construction and to identify commonly used English terms for them. To this end, the following sources were analyzed:

- International Tunneling and Underground Space Association
- ISO and IEC standards on tunneling
- GeoSciML standard by OGC
- French MiND project documentation
- German DAUB guidelines on Tunnel BIM models
- and many others

In addition, the published results from various research projects were taken into account [1, 2, 4, 5, 7–9, 11, 12, 14, 17, 19, 20, 22, 23].

The information from the sources was subsequently merged and harmonized, first by using spreadsheets developed among the project team (see Fig. 10, later by mapping them into a UML conceptual model.

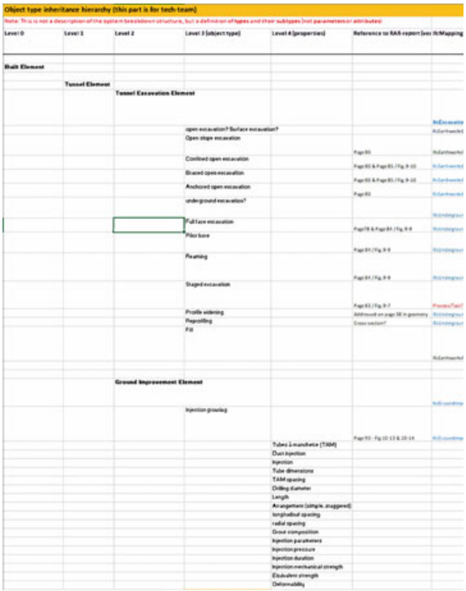

Fig. 10 A typical spreadsheet used by the project team for capturing and harmonizing the taxonomy of tunnel elements.

5 Conceptual Model Development

In the next step, the conceptual model was developed. The conceptual model describes the IFC extensions mostly by using UML diagrams in combination with documentation text. As opposed to the approach taken by OGC, the bSI conceptual model takes the particularities of the existing IFC data model into account and describes, for example, new sub-classes as refinements to existing IFC classes. It also defines pre-defined types, attributes and properties where appropriate.

The IFC-Tunnel project strictly followed the extension guidelines hat have been defined by the Infra Overall Architecture Project [6]. Among other restrictions, it demands to keep the number of new entities to a minimum and instead make a maximum use of existing classes. A good example is the wall of a cut-and-cover tunnel. It is not necessary to define a new class for it, instead the existing IfcWall can be used. However, it may be appropriate to extend the enumeration of the predefined types of an entity. Where necessary, the documentation was modified to include tunnel concepts.

Thanks to the principle described above, the resulting conceptual model only adds a minimum amount of new entities. At the same time however, a large number of new predefined types for a variety of entities were introduced. In the following UML diagrams the new PredefinedTypes have a cyan background color.

5.1 Spatial Element Extensions

In the IFC model, spatial structure elements are applied to capture the spatial hierarchy of a project. A significant extension allowing to cover not only buildings, but also infrastructure facilities was performed in Version 4.3 introducing the new entities IfcFacility and IfcFacilityPart, both as subtypes of IfcSpatialStructureElement.

The main new spatial entity introduced here is IfcTunnel, defined as subtype of IfcFacility. The PredefinedTypes defined for IfcTunnel are:

- ACCESSTUNNEL
- SHAFT
- UTILITIES
- RAILWAY
- ROAD
- PEDESTRIAN
- METRO
- BICYCLE
- BYPASS
- MAINTENANCE
- UNDERGROUND_FACILITIES
- RAMP

The existing IfcFacilityPart was extended by a new suclass IfcTunnelPart with the following predefined types:

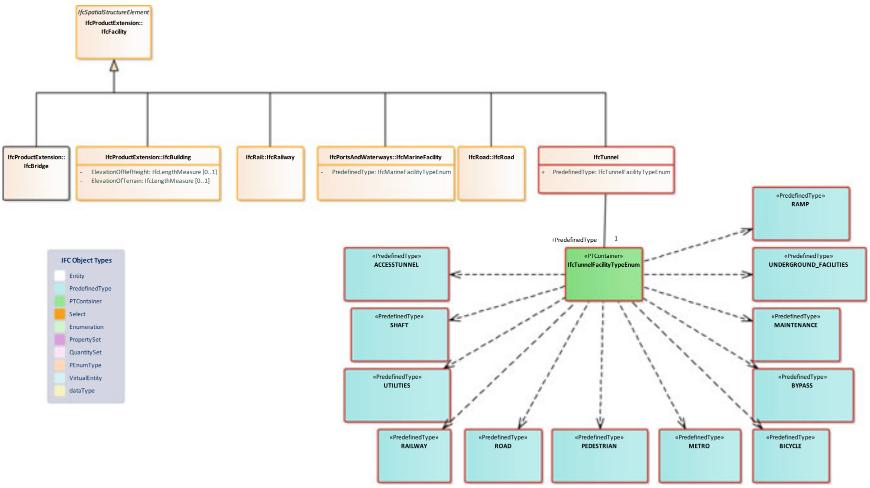

Fig. 11 Extension of the IFC model by the new class IfcTunnel depicted along with its predefined types (in cyan).

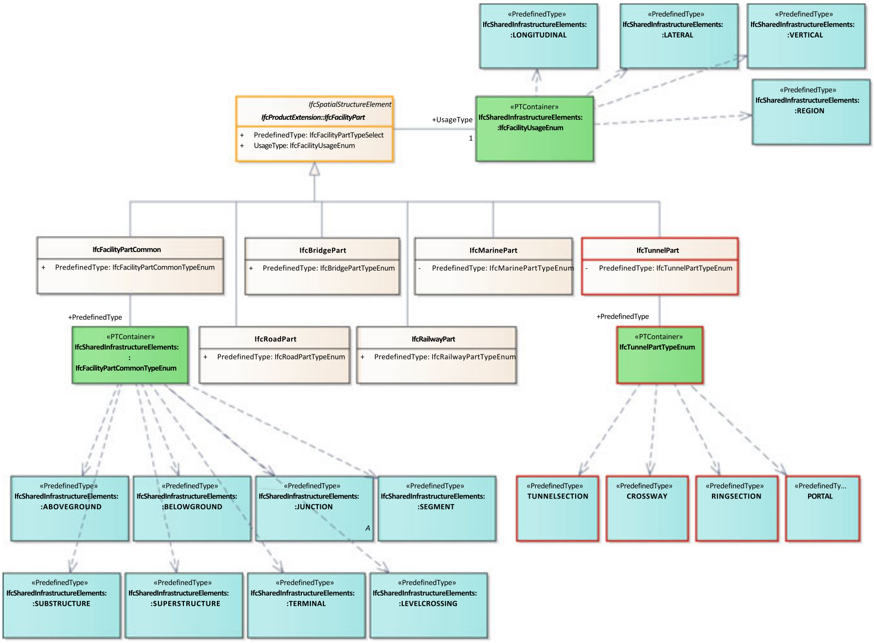

Fig. 12 Extension of the existing IfcFacilityPart by the new IfcTunnelPart (in red box) depicted with its predefined types (in cyan).

– TUNNELSECTION
– CROSSWAY
– RINGSECTION
– PORTAL

Figures 11 and 12 illustrate these extensions by means of UML diagrams.

5.2 *Spatial Zone Extensions*

Spatial zones play an important role in tunneling as they are often used as placeholders or reservations spaces. In contrast to IfcSpatialElement and its subclasses, instances of IfcSpatialZone do not have to be hierarchical and can be overlapping.

The existing IfcSpatialZone was hence extended by new PredefinedTypes which are depicted in Fig. 13 with a red-colored outline.

Fig. 13 Extension of the existing IfcSpatialZone by the new predefined types shown with a red box.

5.3 *Systems Extensions*

New predefined types were defined for the existing entity IfcBuiltSystem in order to support a suitable representation of systems in tunnels:

- TUNNEL_PRESUPPORT
- TUNNEL_SUPPORT
- TUNNEL_LINING
- FIREPROTECTION
- WATERPROOFING

For the existing entity IfcDistributionSystem the new PredefinedType SAFETY was added and the semantics of MONITORINGSYSTEM were extended.

Figure 14 depicts these extensions.

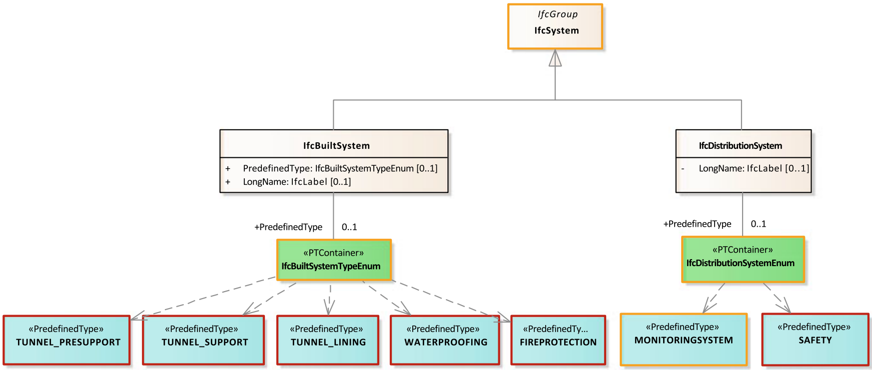

Fig. 14 The existing classes IfcBuiltSystem and IfcDistributionSystem along with their new predefined types (in cyan)

5.4 Built Element Extensions

The majority of the built elements of tunnels can be described by means of the existing entities. The following new entities were defined to describe tunnel-specific built elements:

– IfcFillElement
– IfcArchElement
– IfcGroundReinforcementElement

Figure 15 depicts the extensions in terms of the new entities and their predefined types. Apart from that, a large number of new predefined types were introduced for existing sub-classes of IfcBuiltElement that are not shown here.

5.5 Geology and Geotechnics

To allow the integration of geological, geotechnical, hydrogeological etc. models, the umbrella term GeoScienceModel was introduced and the new class IfcGeoScienceModel was introduced. It has the following PredefinedTypes:

– GEOTECHMODEL
– HYDROGEOMODEL
– GEOLOGYMODEL
– GEOTECHSYNTHESISMODEL
– PHYSICALPROPERTYDISTRIBUTIONMODEL

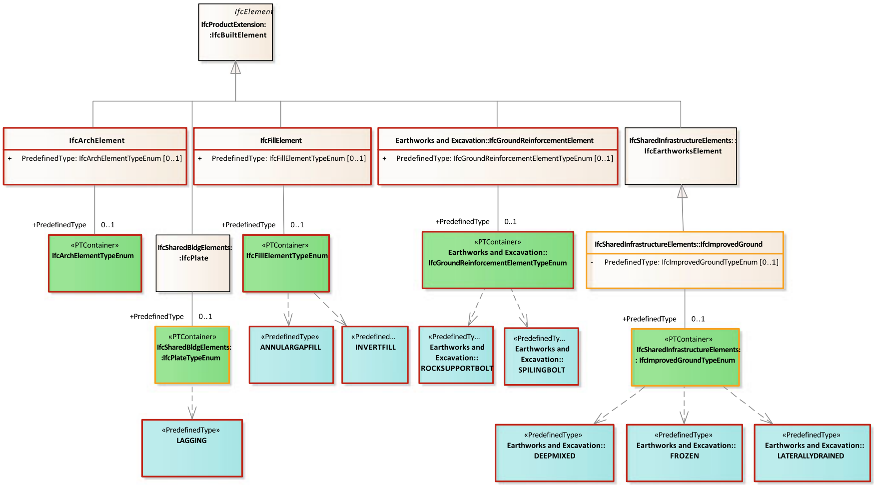

Fig. 15 Extension of the existing IfcBuiltElement by the new subclasses IfcArchElement, IfcFillElement and IfcGroundReinforcementElement depicted with their predefined types (in cyan). In addition it is proposed to modify the existing IfcImprovedGround and extend it by new PredefinedTypes.

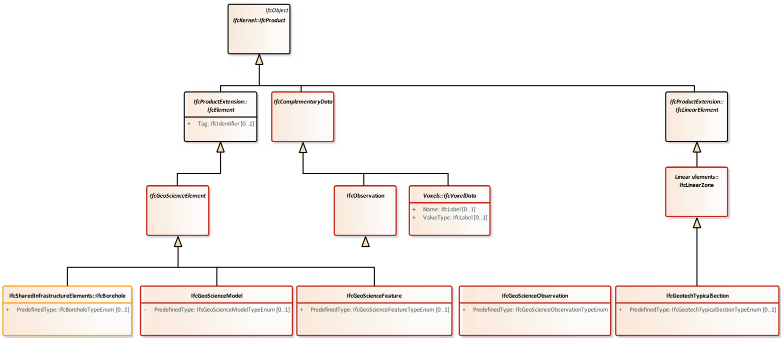

Fig. 16 Overview of the new classes introduced for describing a geological model in IFC and the associated observations.

– GEOHAZARDMODEL

The class IfcGeoScienceFeature was introduced to model individual features in the ground, such as folds or faults. The complete list of predefined types is shown in Fig. 17.

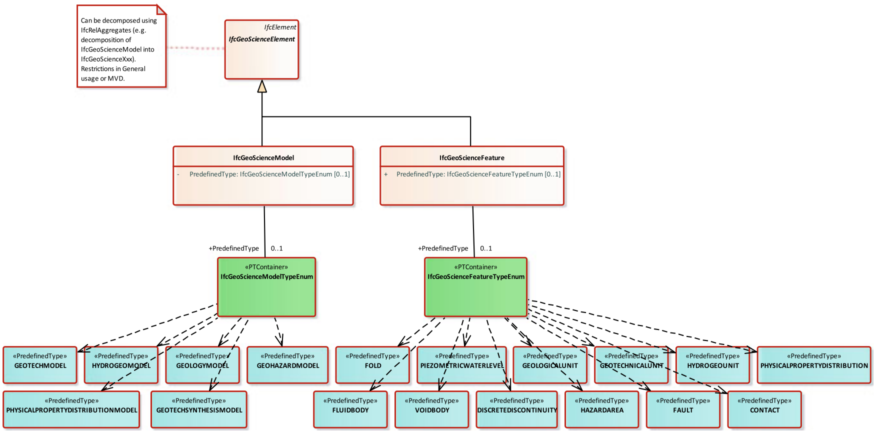

Fig. 17 The new classes IfcGeoScienceModel and IfcGeoScienceFeature and their predefined types (depicted in cyan)

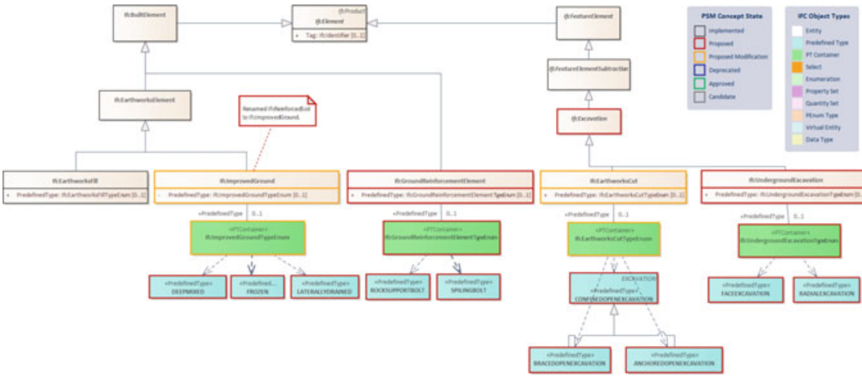

Fig. 18 The new classes IfcExcavation, IfcUndergroundExcavation and IfcGroundReinforcementElement along with their predefined types (in cyan)

5.6 Earthworks and Excavations

In order to cover the important aspect of tunnel-specific excavation the new class IfcUndergroundExcavation was introduced as subclass of the new abstract superclass IfcExcavation. The existing IfcEarthworksCut (mainly used for road and railway projects) is another subclass of IfcEarthworksCut (Fig. 18). The existing IfcReinforcedSoil was renamed to IfcImprovedGround to allow a wider range of applications. Accordingly, PredefinedTypes relevant for tunneling have been defined that are shown in the diagram (Fig. 16).

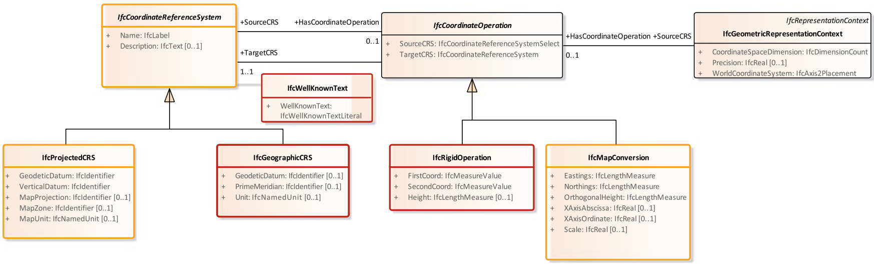

Fig. 19 The new classes IfcGeographicCRS and IfcRigidOperation. A IfcGeographicCRS is a CRS that uses a three-dimensional ellipsoid surface to determine locations on the Earth. IfcRigidOperation allows the definition of a local, yet distorted coordinated system when applied on a geodetic reference system such as UTM. This is often done in today's BIM practice to avoid large coordinates.

5.7 *Extended Georeferencing*

To fulfill the requirements described in Sect. 3.4 the IFC data model was extended by the new class IfcRigidOperation as a subclass of IfcCoordinateOperation. When applied to a projected coordinate reference system the effect is that of truncating the "big coordinate values" which is often done in today's real-world projects. In consequence of applying a mere translation and/or rotation, the coordinate system remains distorted (projected), i.e. all model distances have to be multiplied by a scale factor to get real-world distances.

If this is not intended, an instance of IfcMapConversion has to be applied, essentially inverting the projection of projected CRS to enable real-world dimensions and distances in the model.

Besides projected CRS also geographic CRS are now supported by the new class IfcGeographicCRS. Any location on Earth can be referenced by a point with longitude and latitude coordinates and the height above or below the ellipsoid. It serves as an alternative to projected CRS, such as Gauss-Krueger or UTM.

Figure 19 depicts the extensions. More details can be found in [11].

The new entity IfcWellKnownText allows flexible definitions of site-specific coordinate reference systems outside the bounds of existing databases such as EPSG. As stated in Sect. 3.4, customized CRS are frequently applied in large-scale tunnel projects, especially when realized across different countries. IfcWellKnownText implements the OGC standard "Well-known text representation of coordinate reference systems", which was adopted as ISO 19162:2019. The underlying literal must be formed according to ISO/IEC 13249.

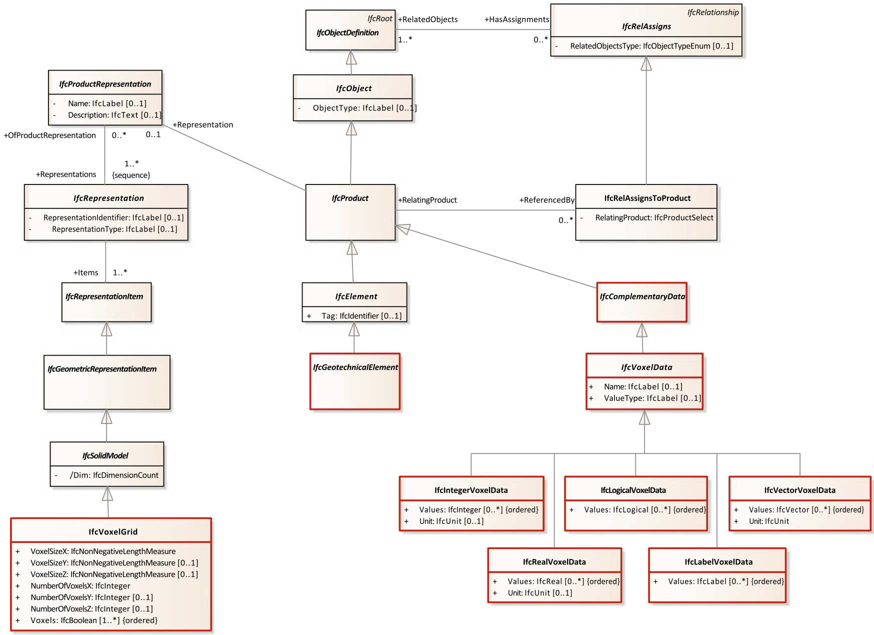

Fig. 20 The new classes IfcVoxelGrid and IfcVoxelData and their connection.

5.8 New Voxel Representation

The cover the requirements described in Sect. 3.7, the new entity IfcVoxelGrid has been introduced as a subclass of IfcSolidModel. It can be connected in a very flexible manner with one or multiple IfcVoxelData entities holding the actual values of the voxel grid. The classes and their connections are depicted in Fig. 20.

6 IFC Schema Extension (draft)

Based on the conceptual model, the actual extension of the IFC schema was realized. This was done by defining the corresponding EXPRESS schema. From the EXPRESS schema, all other data schemas supported by bSI are derived (ifcXML, ifcOWL, etc.). In addition, a comprehensive HTML documentation is generated. With respect to the latter, the project team created the documentation for new entities and updated those parts of the existing documentation where semantics were altered or extended.

The draft extension was published on GitHub[1] enabling direct feedback from the international community. In addition, the generated documentation was published on a dedicated website[2].

7 Validation and Deployment

To avoid ambiguities and identify deficiencies, the extension will be validated through prototypical implementations. To this end, software vendors from the tunneling domain are invited to join the deployment project that will develop and define a number of exchange scenarios and unit tests to be implemented by diverse vendors to validate the robustness of the extension.

8 IFC Schema Extension (final)

Once the errors and ambiguities identified in the course of the validation phase are fixed, the candidate standard of Version 4.4 will be published by buildingSMART International. It will undergo further validation before it becomes a final standard.

9 Handling of Properties

Properties play an important role in IFC-based data exchange. They are not part of the schema but are defined independently by means of the PropertySet mechanism [3]. This allows for a dynamic extension of the schema and enables to fulfill the data exchange needs on a national, regional or authority level without requiring international consensus (Fig. 21).

According to this principle, only a limited number of properties will be defined as international properties forming part of the final specification. However, there are well-defined mechanisms for handling national or authority-specific properties, for example by means of the buildingSMART Data Dictionary (bsDD).

[1] https://github.com/bSI-InfraRoom/IFC-Specification/projects/2.

[2] https://bsi-infraroom.github.io/IFC-Documentation-Tunnel/4_4_0_0/general/HTML/.

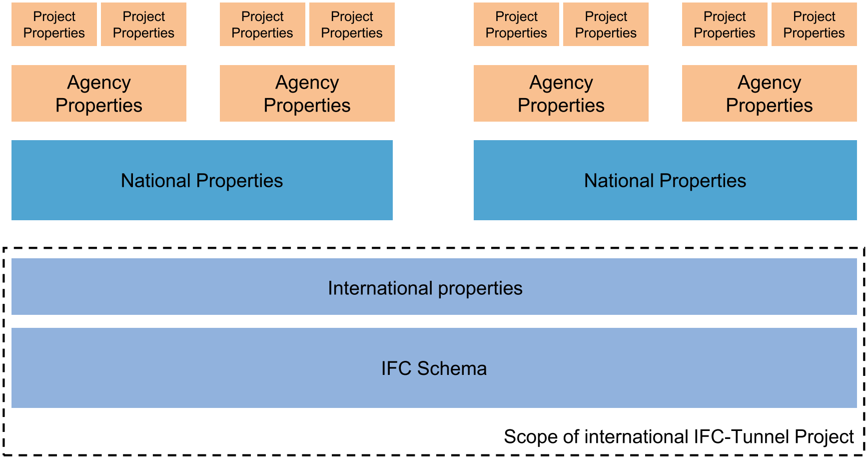

Fig. 21 The extension mechanisms of IFC allow the definition of properties on different levels.

10 Model View Definitions

As part of the deployment project, tunnel-specific Model View Definitions (MVD) will be specified that will allow software vendors to focus on those parts of the IFC schema that are relevant for their specific domain.

The following MVDs are planned to be specified:

- Tunnel Reference View (Tunnel RV)
- Tunnel Alignment-based Reference View (Tunnel ARV)
- Tunnel Design Transfer View (Tunnel DTV)
- Geology and Geotechnics View (GaGV)

11 Next Steps

The development phase was finished in October 2022. It will be followed by a deployment project where interested software vendors are invited to join a coordinated early implementation effort. In the frame of the project, the software vendors are receiving intensive support and gain the opportunity to provide direct feedback on the standard. If major deficiencies are detected in this process, the standard will be revised accordingly.

After successful completion, the official bSI standards adoption process is performed. Upon approval of the standards committee, the extension will be integrated into the official IFC 4.4 candidate standard and is subsequently set for vote by the national or regional chapters of buildingSMART International. If accepted, the standard will become the official IFC 4.4 release.

12 Discussion

The paper presented the extension of the vendor-neutral data format IFC developed in the course of the official buildingSMART International IFC-Tunnel project. The extension fulfilled a pressing request of the international BIM community to better support the data exchange of tunnel information models.

The project showed that is possible to successfully develop an extension of significant extent in a limited time of only 2 years. However, a stringent process had to be implemented to reach this goal. The most important prerequisite for the success of the project was the clear definition of the tunnel types to be included and the uses cases to be supported by the standardization effort. In this regard, it was essential to concentrate on the “low hanging fruits”, i.e. on the most widespread tunnel types and the most beneficial use cases with limited complexity.

The involvement of international domain experts through frequent online workshops proved to be a very helpful resource for the development process.

For the actual extension, the guidelines laid down by the IFC-Infra Overall Architecture project were carefully followed. Most importantly, new entities were only defined where necessary, i.e. where existing entities did not provide the semantics required for tunnel-specific concepts. In most cases, an extension of the predefined type enumerations was sufficient. This approach helps to keep the effort low for software vendors that already implemented previous versions of IFC when integrating the extensions.

With respect to properties, only a limited number were defined and became part of the official international specification.

13 Conclusion

The project has proven that the creation of a well-defined extension of IFC in limited time frame is possible. The formalized processes of buildingSMART International help to deliver a high quality product, ensuring both its technical validity and its applicability in the target domain.

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Finding Geometric and Topological Similarities in Building Elements for Large-Scale Pose Updates in Scan-vs-BIM

Fiona C. Collins, Alexander Braun, and André Borrmann

Abstract Information-rich BIM models are rarely usable off-the-shelf for operations tasks. Change decisions made on the construction site can lead to significant differences between the as-designed and as-built state of buildings. The responsibility for keeping the digital representation in sync with its physical twin is not defined and will likely only fully be assigned when automatic methods facilitate the geometric update process. To this end, previous research succeeded in (1) identifying if an element was erected at the time and position it was initially designed, and (2) updating the parametric design geometry to fit its LiDAR-measured as-built state under a set of assumptions and threshold values.

The research presented in this paper aims at updating the as-designed model in case of significant pose differences between the as-designed and as-built state. The method leverages graphs to encode the topological connectivity between geometric elements, once for the as-designed BIM model and once for the as-built point cloud. A similarity metric, namely the cosine distance, allows for a quantitative comparison of the topologically enriched point cloud clusters and their corresponding BIM element. The results show that a convincing type-wise similarity can be found in the feature space between the as-built point cloud clusters and the BIM elements. This similarity score becomes meaningful once the element's topological arrangements are included. An instance-wise similarity score of above 90% is achieved for matching-pairs of free-standing columns and allows for a large-scale pose update in the as-designed BIM model.

Keywords Scan-vs-BIM · Knowledge-driven as-built reconstruction · GNN

1 Introduction

Geometrically accurate and information-rich BIM models are indispensable in compliance-driven building projects. Whilst the information depth of such models increases with the growing adoption of digital planning methods, the risk of significant discrepancies during construction stays high. The slight geometric devi-

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ations accumulating during the on-site construction process can result in geometric conflicts [14] and require fast and reactive mitigation measures at the time and place of construction [15]. In most cases, the need for a belated change request results in delays, exceeding costs, and material waste for matching compliance initially set out for the project. Although most geometrical discrepancies are expected to stay within a specific tolerance range, it happens that the as-built construction shows building elements with significant positional differences from their as-designed representation in the BIM model. Geometric deviations challenge the delivery of reliable as-built design documents [1] and lead to significant model rework times.

Spatial and visual data acquired by LiDAR scans and cameras offer an accurate yet unstructured representation of the as-built status. The process of using the resulting point clouds for updating the as-designed BIM model is currently supported by point cloud semantic segmentation (PCSS) results. The point cloud shows clusters of points assigned to a set of semantic labels. In current based practice, a manual workflow follows to move the as-designed geometries into place. The match between the as-designed and its matching as-built point representation is the modeller's responsibility. Existing approaches have investigated BIM parametrization and show to automatically update elements for which the deviations lie within a certain threshold. This work aims to present a method for automatically finding geometric and topological similarity-based matches between the point cloud data (PCD) and as-planned BIM data in an encoded vector space. The results show the first step in extending the current research body of automated dynamic BIM model updates to cover large-scale pose deviations. More precisely, the method aims to break the limitation of tolerance (threshold) values. At the method's core lies the geometric and topological encoding with graph structures for either input format into a comparable vector space.

2 Background

2.1 Updating the as-planned

Finding matches between the as-designed BIM models and as-built point clouds has been a topic in the research fields of progress track and Scan-vs-BIM related contributions. The first focuses on detecting an element at a given moment and location in time to verify the overall construction progress. The second explores methods for geometrical updates in the as-designed BIM model. Accurately capturing the on-site construction progress has been vigorously investigated with spatial and visual data acquisition methods such as LiDAR scans and photos. A point cloud is either generated by Time-of-Flight sensors or photogrammetry and offers an accurate 3D geometric representation of the visible as-built construction. A control-point-based acquisition [13, 18] or an Iterative Closest Point (ICP) approach allows for point cloud to BIM registration. To validate the presence of a building element at a given point in time, Tuttas et al. [17] compare a set of metrics between the triangulated planes from 4D BIM elements and the local fitted planes from the point cloud that lie in the distance *d* from the object. Braun et al. [2] measure the point density within a stage-dependant threshold of a building element. Turkan et al. [16] compare the scanned point clouds with their orthogonal projection point on the as-planned surfaces. Braun et al. [3] enhance the detection by point surface comparison with an additional artificial intelligence (AI) approach involving a visibility analysis and element detection in images.

Having detected that an element is or is not present at a given time at its design location answers the use case of progress tracking. However, it might occur that the construction is well on time, yet the element is built with deviations from its designed geometric shape or pose. To that end, [13] introduce the concept of a Dyna-BIM (dynamic BIM) where both the element pose and the element shape in BIM are parameterized. Two metaheuristic optimization techniques show the ability of parametric slabs (in the article referred to as footings) to adapt to the as-built point cloud. In their approach, a previous point cloud processing crops the point cloud into segments of just the vicinity of each footing, thereby minimizing the effects of different footings on the optimization of one. For bridges, Mafipour et al. [11] further explore parametric shape fitting into point clouds previously processed with PCSS. All the above-explored automatic contributions are limited when it comes to large-scale deviations or rely on a previous point cloud slicing which induces assumptions about the element match. Bosché et al. [1] apply Circle Hough transform to compare as-planned piping systems to their as-built equivalent. Thanks to the shape prior they introduce, they can cover large-scale pose deviations to a certain degree. The described state-of-the-art is illustrated in Fig. 1 and Fig. 2.

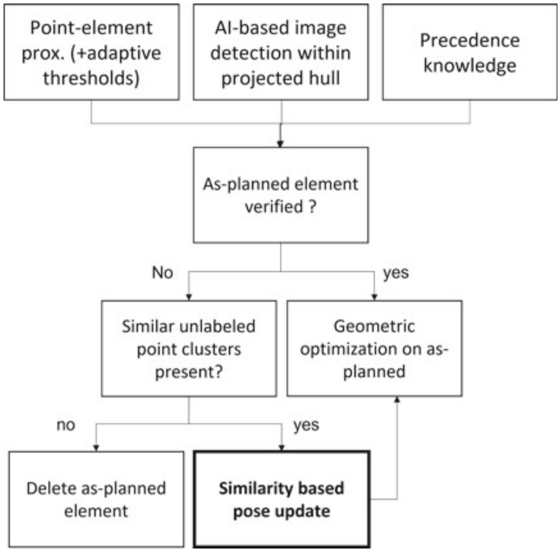


Fig. 1 State-of-the-art workflow for as-built progress track and design model fitting. The contribution of this work is highlighted in bolt.

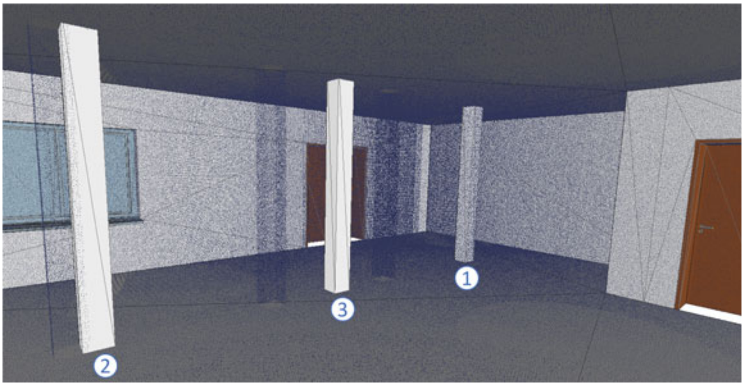


Fig. 2 As-built point cloud overlay with as-designed BIM model: 1) Column validated with point proximity, 2) Column validated with extended methods s.a. adaptive thresholds or with precedence knowledge 3) as-designed column not validated, two point clusters of potential columns remain.

2.2 *Spatial Relationships and Dependencies*

Using graphs to capture the relationship and dependencies between different building elements has been helpful as a concept. Characterized by their flexibility to represent complex relationships and heterogenous attributes, graphs have become the favored way of expressing information from BIM enriched with the insights of as-built point cloud acquisitions [22]. The connections (edges) allow for conditional semantic links between the elements (nodes), which host rich feature representations of the latter. Braun et al. [4], for instance, assemble a precedence relationship graph from as-planned BIM models where the technological temporal dependencies of an advancing construction are encoded as directed edges from an object (predecessor) to the depending object (successor). While recording the construction progress, the certainty of identifying a successor is significantly decreased if its corresponding predecessor has not been detected yet. Wang et al. [21] show that spatial encoding in a graph structure helps predict simple room layouts.

On the other hand, spatial encoding with graphs is also an important topic in AI research for performing PCSS. Graphs allow to encode both, local geometry [20] as well as topological element connections [10]. The super point graph approach suggested by [10] utilizes the hypothesis that a large amount of information needed for semantic element segmentation is contained in topological relationships.

2.3 *Similarity-Based Object Queries*

Retrieving the most similar data object based on the content of the query object has found many applications in other areas, such as content-based image retrieval

(CBIR) in search engines or Graph similarity search for chemical compound retrieval. Retrieving entities informed with global scene information has yielded better results than entity-based retrievals alone. Maheshwari et al. [12], for instance, show that encoding images as scene graphs allow the image match to return more intuitive results—e.g., capturing object interactions such as human-animal interaction.

Some research has focused on retrieving the best matching CAD geometry from a point cloud object in the context of buildings. Bosché et al. [1], for instance, use a similarity-based criterion integrating location, radius, and orientation for retrieving cylindrical MEP components. Wang et al. [19] retrieve the most similar CAD models from a furniture shape database to align them with the input point cloud. A set of rotation-invariant key point features is used. The mentioned approaches have a shortcoming in that contextual information is largely neglected.

2.4 Contribution

Little work exists on adequately updating as-designed BIM models geometrically to their as-built equivalent while preserving initial model semantics [13]. More specifically, no automatic method can capture large-scale pose deviations between the as-planned model and the as-built point cloud. In this work, the described benefits of spatial relationships are used in formulating topological graphs to create more informed matches between the as-designed and as-built representations. The contribution of this article is summarized as follows:

– A method to perform similarity-based matches to provide pose updates for the outdated as-designed model
– The formulation of a graph matching problem for two fundamentally different yet often jointly used data sources (as-designed BIM geometry and as-built point clouds)

3 Method

The proposed approach to find correspondence between as-built and as-designed building elements across large-scale pose deviations is presented in three steps: 1. Graph formulations 2. Topological enrichment with Graph Convolutional Networks (GCN) 2. Similarity computation. The straightforward next step of updating the as-designed element is out of the scope of this work.

3.1 Graph Formulation for as-Designed and as Built

The two corresponding yet different graphs are defined as G_{design} and G_{built} with the set of vertices V_{design}, V_{built} and edges E_{design}, E_{built} respectively.

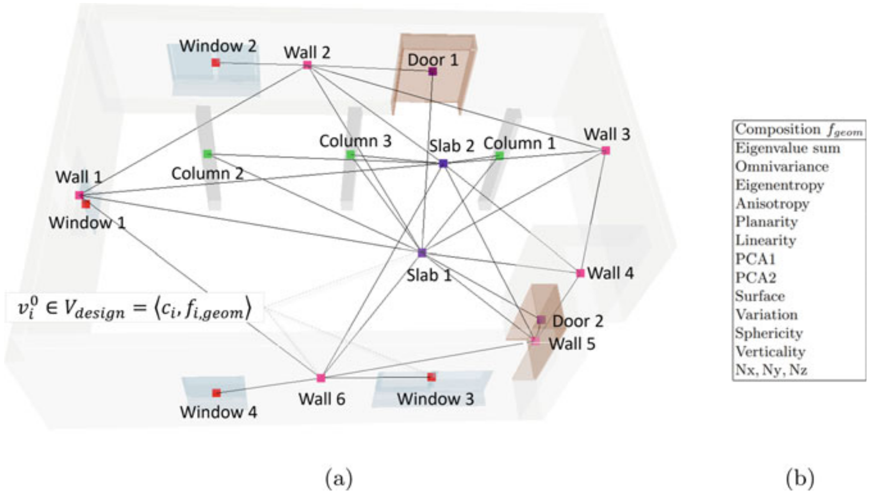
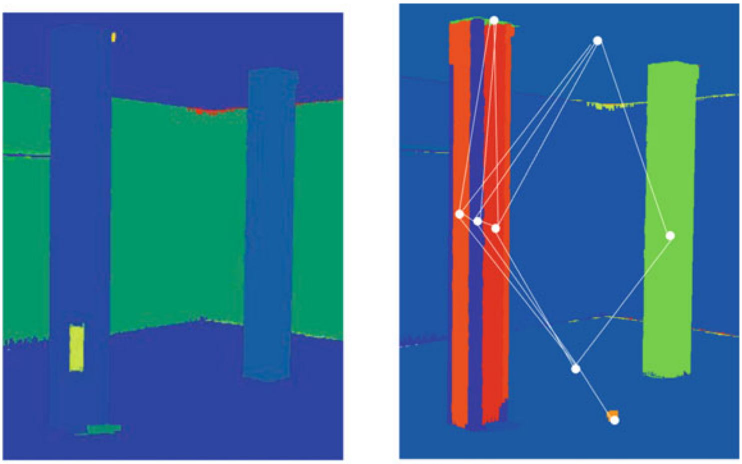


Fig. 3 Topological connections in graph representation of the as-designed model G_{design}. The nodes include the generated shape representation, and the edges denote "touching" elements. For a better visibility, the top slab is not included in the illustration.

$\boldsymbol{G_{design}}$**:** The building elements' shape characteristics and topological relationships are extracted from the BIM model represented as IFC[1] model to represent the as-designed facility in a graph format. The vertices $v_i = \langle c_i, f_{geom} \rangle \in V_{design}$ are defined as the elements geometrical centroids c_i and each include a set of features f_{geom}. The feature vector f_{geom} is a compact vector representation of the element's shape, summarized with a set of computed features as suggested by [7] (see Fig. 3b). The element's neighborhood information is extracted from the IFC files with the spatial query language QL4BIM suggested by [6] and the topological operator "touching". Accordingly, elements adjacent to each other will share an edge in G_{design}. The resulting graph is illustrated in Fig. 3a.

$\boldsymbol{G_{built}}$**:** To generate the graph-based as-built representation, we assume a segmented point cloud as an input. The preceding point cloud segmentation (PCS) assigns points to semantically homogeneous clusters. This step can be performed with a conventional geometric clustering algorithm or a supervised (semantic) segmentation using Artificial Neural Networks such as suggested by [9]. An as-built element might be represented by one or several point clusters. Furthermore, depending on the regularisation strength of the clustering method as well as the geometric noise and occlusions in the source point cloud, these clusters might be more or less fine-grained. Figure 4a and b show results of such clustering with different regularization strengths. For our experiments the noise level is set to 0.005 in the simulation, and the regularization strength in Landrieu and Simonovsky's [9] method to 0.08.

[1] Industry Foundation Classes – A standardized BIM data exchange format.



(a) Strong regularization

(b) Regularization r=0.08 and exemplary visualization of G_{built}.

Fig. 4 Point cloud geometric clustering results with the method by Landrieu and Simonovsky [10]

Similarly, as for the as-designed, the clusters' centroids c_i and the same set of features f_{geom} are computed for each cluster, forming the $v_i = \langle c_i, f_{geom} \rangle \in V_{built}$. To achieve the topological connectivity between the clusters, the graph formulation method from [10] is used. As the authors suggest, a symmetric Voronoi adjacency graph $G_{\text{voronoi}} = (P, E_{voronoi})$ is defined for the whole point cloud $P_{as-built}$ first. Two point clusters S_1 and S_2 are adjacent and marked with an edge in G_{built} if there is at least one edge in $E_{voronoi}$ with one end in S_1 and one end in S_2 (see Fig. 5).

The experimental set-up is structured according to two possible PCS results:

– One single point cluster represents one building element (idealistic setting)
– Several point clusters represent one building element (see Fig. 4b, left column)

3.2 *Topological Enrichment of both Graphs with GCNs*

In the graph formulation described above, the edges represent topology, yet the nodes' features contain no information about their neighborhood. In buildings, topology (here encoded as graph neighborhoods) is highly relevant for any type of scene interpretation. It is thus essential to include not only the elements shape characteristics but also what connectivity it has to its surroundings.

Furthermore, in this work, we use a similarity score based solely on the node features (see Sec. 3.3 for further detail). It is, therefore, necessary to propagate the

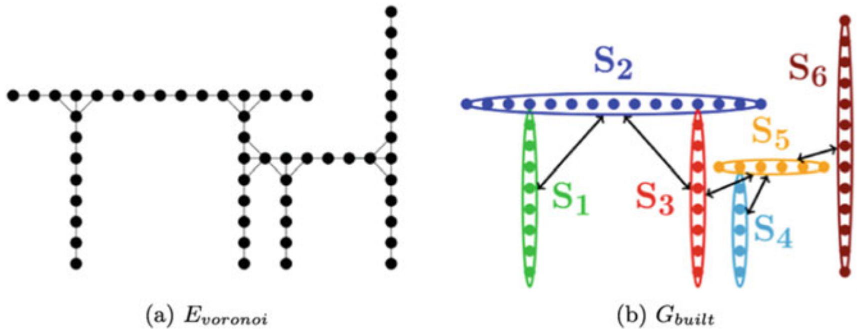


Fig. 5 Graph formulation as proposed by Landrieu and Simonovsky [10]

node features along the graph edges. Hence a 2-layered GCN as in [8] is assembled for message passing along the graph edges. The GCN learns to transform the input feature vector of node v_i together with an aggregate of the nodes neighboring messages to produce the predicted node label closest to the true label[2]. For a detailed description of GCNs, the reader is referred to [5]. Here the training is formulated as a fully-supervised node classification problem. Following an inductive training setting, the GCN is optimized on a set of 15 design graphs deduced from 15 different design models. Testing is performed on a different set of 4 design graphs. On average, the graphs contain 1300 nodes representing the classes Wall, Slab, Stairs, Door, Window, Furniture, Column, and Beam. Once the network achieves a balanced accuracy in node classification performance of over 85% on the test set, the network is used to perform inference on the showcase building presented in Sect. 4. The inference results are once computed for G_{design} and once for G_{built} without retraining, resulting in the node-wise feature vectors $f^{'}_{i,design}$ and $f^{'}_{i,built}$. The final node embedding vectors of the predictions can be regarded as an element representation, including shape characteristics and topology.

3.3 Similarity Computation

To find matching building elements between the as-designed model and the as-built point cloud, we compute the similarity between the nodes of the respective graphs. Computing the similarity score between the initial feature vectors $f_{i_{,design}}$ and $f_{i_{,built}}$ hints at how many geometrical similarities the two elements have. Comparing the enriched vectors $f^{'}_{i,design}$ with their corresponding $f^{'}_{i,built}$, topological characteristics will complement the shape representation and thus influence the similarity score. The cosine similarity is computed between pairs of features as shown in Eq. 1. Figure 6 illustrates how nodes between the two graphs are matched for a case when one point

[2] Wall, Slab, Stairs, Door, Window, Furniture, Column, and Beam.

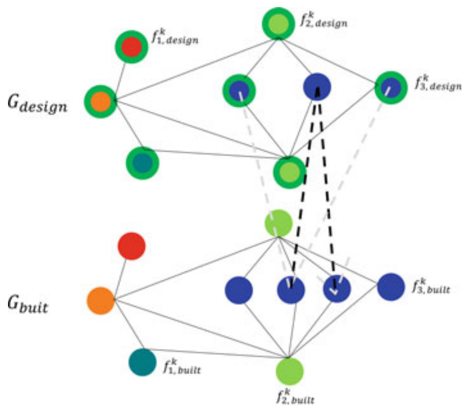


Fig. 6 Multi-fold graph correspondence between the as-designed and the as-built graph (schematic graphs follow the scenario outlined in Fig. 2). Nodes with green outlines are verified design elements according to state-of-the-art methods. For the unverified node, the most similar nodes in the as-built are found and indicated with black dashed lines. The other way around (grey dashed lines), the most similar design element is returned for each point cloud cluster.

cluster represents one building element. The analysis is conducted similarly when more than one point cloud clusters represent one building element.

In this research, we compute the node-wise similarity across all node pairs in the two graphs. Instead, in practice, the similarity computation could be limited to the unverified as-designed elements or the point clusters for which no design element was found in immediate proximity.

$$Sim(A, B) := \cos(\theta) = \frac{\mathbf{A} \cdot \mathbf{B}}{\|\mathbf{A}\| \|\mathbf{B}\|} = \frac{\sum_{i=1}^{n} a_i b_i}{\sqrt{\sum_{i=1}^{n} a_i^2} \sqrt{\sum_{i=1}^{n} b_i^2}} \tag{1}$$

where A and B stand for $f^k_{i,design}$ and $f^k_{i,built}$; the two feature vectors to be compared. Note that when k=0, $f^k_{i,design}$ is simply the input feature vector $f_{i,design}$.

In this research, we compute the node-wise similarity across all node pairs in the two graphs, resulting in quadratic complexity of the algorithm. In practice, however, the similarity computation could be limited to the unverified as-designed elements or the point clusters for which no design element was found in immediate proximity.

4 Experiments

The method is demonstrated for a simplistic showcase building consisting of walls, slabs, windows, doors, and columns. The BIM model used for the image material of this article is the same as used for the experiments (see Fig. 3a) and 2. To demonstrate the effectiveness of our method, we introduce pose deviations to the column elements. The columns all have typical thicknesses of 250 × 250mm, and their pose deviations were all made in the aligning direction of all columns. For column 2, a discrepancy of 0.2m is set between the as-designed and as-built status. Column 3 is duplicated, and either as-built column equivalent is situated at a 1m distance from its as-planned equivalent. We will refer to the respective as-built column equivalent with a subscripted alphabetic letter after the number.

The graphs are constructed as described in Sect. 3.1 and 3.1, before the similarity score is computed as described in Sect. 3.3 with or without topological enrichment (see Sect. 3.2. In two experiments, we set out to show (1) the importance of topology for the similarity score and (2) the methods' generalization potential to apply to the state-of-the-art clustering methods.

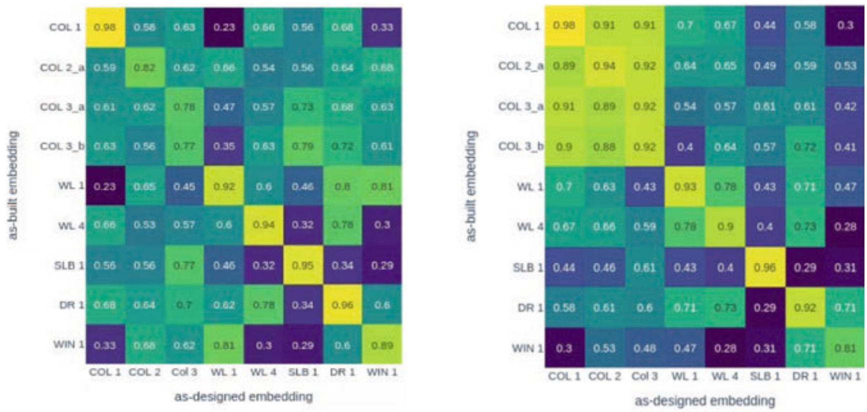
For simplification, a simulated point cloud is used as input instead of a real point cloud, complementing the as-designed BIM model. The LiDAR scan simulation tool of Winiwarter et al. [23] is used. For simulating the as-built capturing process, a conventional Terrestrial Laser Scanner (TLS) is defined, important hardware parameters are set and scan positions are placed.

4.1 Importance of Topology

In this experiment, we assume the point-cloud clusters to represent the BIM elements one-to-one. Some sophisticated point cloud clustering methods can achieve this when little noise and obstacles are present in scenes. The clustered as-built point cloud is compared to the as-designed BIM equivalent element-wise. Figure 7 shows the pair-wise results of the similarity score, once for the computed node features f_i (a) and once for the topologically enriched node features f_i' (b). The heatmaps are not rectangular since the as-built point cloud includes one additional column, as shown in Fig. 2.

Without topological enrichment, the similarity scores for matching and congruent pairs are noticeably high, with similarity scores around 95%. For elements where the majority of element faces are captured by the LiDAR scanner (e.g. for columns 4 large faces are captured) the score lies higher than for such that have unilateral occluded faces (e.g. walls, slabs where the LiDAR scanner captures only one visible face). However, for the elements with deviations, the similarity score decrease with the distance the column has moved (e.g., the similarity score of 2_a - 2 is slightly higher than the one of 3_a - 3). The centroid features have the biggest influence on the similarity score. If the pose discrepancies between the as-designed and as-built are significant, as outlined in the paper introduction, these scores will not suffice for similarity-based updates across large-scale distances.

When the node features of both graphs are enriched with topological information via graph convolutions, the results look more promising. The topological enrichment increased the similarity score of the non-congruent, yet the same columns averaged 80 to 92%. Since all the columns have a rectangular format and are modelled identically, the high similarity score of e.g. column 2_a* with column 1 and 3 is also explicable. From the results it can be deduced that column 2_a is indeed the same as column 2a and column 3_a and 3_b the same as column 3. The similarity scores across types mostly decrease further and are less correlated to the exact location. In some cases



(a) Feature comparison between $f_{i,design}$ and $f_{i,built}$

(b) Topologically enriched feature comparison between $f^{'}_{i,design}$ and $f^{'}_{i,built}$ features

Fig. 7 Computed cosine similarity scores. For visualization purposes, only a part of the elements is displayed. The brighter the color, the higher the similarity score. Abbreviations COL: Column, WL: Wall, SLB: Slab, DR: Door, WIN: Window.

the similarity score for wall - column pairs increases. The common connection to a slab element could cause this behaviour.

As suggested by the results above, it can be said that the topological most likely decreases the importance of the location-based features and increases the influence of the shape and topological features. In our experiments this happens in a favorable way such that the as-built columns can be matched with their as-designed equivalent.

4.2 Sub-element Clusters

For this experiment, a common output of a point clustering algorithm is used to formulate the graph. The used 2-layered GCN is capable of propagating feature information as far as two clusters. For evaluation, the similarity score was computed between all cluster embeddings (f_i or $f^{'}_i$) matching to one as-built ground truth and their matching as-designed element. Depending on how many clusters the algorithm made, the mean of all the similarity scores was computed. For the left column in Fig. 4b for example, the mean was calculated, whereas for the right column it was not neaded. The average per-type matching scores for each element cluster with it's matching as-designed embedding is reported in Table 1.

Table 1 Averaged similarity scores over all elements of the type based on shape alone and the addition of topological information (*).

Class	mean similarity (shape only)	mean similarity (including topology)
Slab	0.78	0.91
Column	0.45	0.78
Wall	0.62	0.9
Window	0.32	0.52
Door	0.56	0.61

Again it becomes visible that including topological information propagated across the edges of the graphs increases the similarity scores. With topological enrichment, the average scores for columns are slightly lower than for the other well-performing types, such as slabs and walls. Especially slabs and walls and, to a lesser degree also, columns are typically clustered in large point clusters due to their rather homogenous flat surfaces. This allows our 2-layered GCN to inform each cluster about the relevant across-building-element typologies.

Likewise windows and doors would typically show as multiple point clusters because of their frames which is most likely the reason for the worse results. Deeper graph networks might be able to increase the results in cases where finer segments are present in the clustered point cloud.

5 Conclusion and Outlook

The detection of the deviations between as-designed and as-built status to update the digital representation of the building under construction promises significant added value while remaining one of the main challenges of automation. However, the difficulty of reconstructing accurate information-rich BIM models from as-built point clouds can impede the usability of such reconstructed models. A combination of large-scale similarity-based pose updates and metaheuristic geometric optimization techniques could prove top-down approaches favorable over bottom-up reconstruction in terms of the information depth of the resulting models.

Our suggested method shows the first evidence that similarity-based geometry retrieval is very promising for solving Scan-vs-BIM problems with significant pose deviations and is apt to complement state-of-the-art methods. We propose using graph representations of both the as-designed model and the as-built representation, where node feature vectors reflect the individual element's characteristics and their adjacency relationships to other building elements. Based on this, we apply a cosine similarity metric to assess the similarity between the nodes of both graphs. This enables us to find matching pairs among the elements having deviations between as-designed and as-built, which subsequently allows updating the BIM model correspondingly. The method shows stable similarity scores above 90% for columns in simulated as-built representations. The method entirely relies on propagating topological information in a GCN inference scenario. Formulating the similarity score to include edge features instead of only features could further make the method more robust.

To fully prove the method as applicable, the experiments will be conducted on real PCD in the future. Given the extensive application fields of a similarity-based object (as presented in Sect. 2.3) retrieval from queries, the authors suggest formulating the graph matching as a learning problem. Thereby, even less obvious matching elements, such as in the case of severe occlusions, might be automized.

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Multimodel Framework for Digital Twin Empowerment

Nidhal Al-Sadoon, Raimar J. Scherer, and Karsten Menzel

Abstract In recent years, digital twins have become a more significant strategic trend in the construction industry. Stakeholders in the industry view it as a technology-driven innovation that has the potential to support the design, building, and operation of constructed assets, alongside advancements in other new-generation information technologies such as the Internet of Things (IoT), artificial intelligence (AI), big data, cloud computing, and edge computing. However, the construction project context generates various organizational and functional information through model-based domain-specific information models that require integration and analysis. Furthermore, commercial technologies enable the integration of real-time data sources with building information models (BIM), but these tools are often proprietary and incompatible with other applications. This lack of interoperability among heterogeneous data formats is a major obstacle to the reliable application of digital twins in the construction industry. To address this challenge, this study presents a multimodel framework developed using Information Container for Linked Document Delivery (ICDD) that can integrate multiple data models from autonomous and heterogeneous sources, including real-time data sources, in their original format at the system level. This framework enables stakeholders to analyze, exchange, and share linked information among the built asset stakeholders, relying on linked data and Semantic Web technologies.

Keywords BIM · Multimodel · Digital Twin · Linked data · Information Containers

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1 Introduction

Since two decades ago, when the concept of "digital twin" was first proposed by Dr. Michael Grieves, NASA coined the definition and function of it in 2010 [1]. Since then, with the emergence of new technologies, various industry sectors have been leveraging this concept in product manufacturing to optimize the operation and maintenance of physical assets, systems, and processes [2]. Increasingly, industries are shifting towards a smart manufacturing paradigm with multi-scale dynamic modeling, simulation, and intelligent decision-making. The collaboration and integration of advanced technologies such as building information modeling, artificial intelligence, and wireless networks into digital twins are becoming more prominent in the architecture, engineering, and construction industries. Digital twins are offered as a new technology-driven innovation to support the design, building, and operation of constructed assets [3].

On the one hand, BIM provides techniques, tools, and data schemas that allow for standardized semantic representation and systems. By utilizing real data, the digital twin enables the visualization, monitoring, and optimization of operational assets, processes, and resources that provide crucial, real-time information on performance and activity. On the other hand, BIM lacks semantic completeness in areas such as control systems, including sensor networks, social systems, and urban objects outside the scope of buildings, necessitating a holistic, scalable semantic approach that considers dynamic data at several levels [4]. Modern high-performance buildings have sophisticated monitoring systems and sensors installed to collect large amounts of data on their indoor environmental quality and energy usage that can be used to enhance their overall performance [5].

However, construction projects are unique endeavors in terms of project design, organization, and production facilities and processes. They are distinguished by many stakeholders, which has historically made it difficult to develop integrated information systems [6]. Although BIM applications have significantly improved architecture, engineering, and construction since they allow specialists to model all building design information into one three-dimensional BIM model, including 3D geometry, cost information, material information, etc. To contribute to overall industry collaboration, the Industry Foundation Classes (IFC) schema was released almost three decades ago as an open and neutral data structure for saving digital building descriptions and serves as a global standard for BIM data interchange. However, a single IFC file containing fundamental object information is insufficient for resourceful decision-making [7]. On the other hand, various model-based, domain-specific information models generate the building models, leaving the BIM lacking in terms of interoperability and automation. This poses a serious challenge for the development of a comprehensive construction digital twin. Model interoperability requirements have been partially met by commercial vendors, which facilitate seamless integration through import and export capabilities among BIM tools. However, in time, the number of tools and platforms shared among project actors can quickly become overwhelming [4].

Given these shortcomings and relying on Semantic Web technologies, this study presents a multimodel framework developed based on the ICDD standard ISO 21597 to integrate multiple data models, in their original format, from autonomous and heterogeneous sources, including real-time data sources, at their system-level and enables analyzing, exchanging, and sharing this linked information among the stakeholders of built assets. The framework aims to provide an information container that contains holistic linked information not only about a built asset itself but also about all related information sources throughout its lifecycle to enable more reliable decision-making and built asset management. This research is the first step towards developing a holistic, dynamic multimodel framework to link all related data models to the building model while evolving over the building lifecycle, starting from the conceptual design, passing through the construction phase, and ending with facility management.

2 Semantic Web Technologies for Digital Twin

The construction industry has greatly benefited from the implementation of digitalization, with Building Information Modeling (BIM) being a significant contributor. BIM was initially designed for the exchange of documents in proprietary formats using the Industry Foundation Classes (IFC) and has since evolved to encompass the management of built assets throughout their life cycle. However, BIM's current state is not entirely compatible with the integration of the Internet of Things (IoT) due to its legacy formats and standards, which restrict its capabilities in a Semantic Web environment [8]. Nevertheless, the emergence of web technologies such as RDF, OWL, and SPARQL offers the potential for a data- and web-based BIM paradigm, which is becoming increasingly viable. Due to its ability to enhance both interoperability and collaboration between disciplines, and its significant impact, the application of Semantic Web and Linked Data concepts in the AECO industry has already been extensively studied [9]. Pauwels argued that building data can be structured using Semantic Web technologies, which can facilitate interoperability and enable logical inferences and proofs. This has numerous benefits for the industry, including lossless data exchange and fully integrated systems [10]. Research by Abanda et al. [11] provides an in-depth overview of the trends in ontology and semantic web linked data over the last decade. The study highlights growing interest in the application of these technologies in the fields of risk analysis, project management knowledge sharing, and energy performance analysis, particularly in the construction sector.

One of the key benefits of using the Semantic Web and linked data is their ability to promote interoperability between various application domains, enabling seamless data exchange and collaboration [11]. Semantic Web technologies have the potential to greatly facilitate the integration of data from the AECO domain with data from other domains. One example of this is the use of geographic information systems (GIS) throughout the various stages of civil infrastructure projects. Over the past ten to fifteen years, the GIS community has increasingly turned to web and semantic web technologies. This shift has led to a greater abundance of GIS data available on the web, resulting in improved accessibility and usability of this data. By leveraging Semantic Web technologies, GIS data can be more easily integrated with other types of data from different domains, enabling more comprehensive analyses and informed decision-making [12].

An accurate Digital Twin (DT) model means data from diverse fields, such as dynamics, structural mechanics, acoustics, thermals, electromagnetics, materials science, control theory, and sensing and measurement technologies, should be integrated into the virtual space to make the models more accurate and closer to reality. The adoption of Semantic Web technologies has been identified as a promising approach to improving interoperability in the AEC sectors, resulting in a more integrated and efficient data exchange environment. These technologies enable the description of information in a format that can be easily understood by computers. In addition, Semantic Web technologies enable the linking of data from multiple domains, such as BIM, GIS, heritage, sensor data, simulation data, and smart cities, into a single web of linked building data. This approach facilitates better collaboration and data sharing among stakeholders involved in the construction industry, leading to improved project outcomes and overall efficiency [12, 13].

3 Approach

Compared to the manufacturing field, the construction industry consists of large groups of independent components, including designers, consultants, contractors, suppliers, and public agencies. These groups pass through different stages, resulting in complex interdependencies. Construction is an evolving system that develops every day through variations and developments in its physical structure, making it complex and not easily understood or predicted by an automated system. Given these challenges, we propose a dynamic multimodel-based approach for the implementation of a real-time data digital twin. First, we present the multimodel concept, then we propose the implementation framework.

3.1 Multimodel Concept

Architects, engineers, and construction professionals are increasingly using sophisticated computational models to address the behavior of multiple features and elements in the built environment at various levels of resolution and across different disciplinary domains. The basic idea of a multimodel is to combine distributed application models, or selected views of them, in a single exchangeable information resource. Within the resource, the application models are bound together by link models that explicitly specify the interdependencies among the application models, referencing the respective model elements by their identifier (ID). The resulting compound model represents a logical business object reflecting the results of a certain business activity, which can be stored in a persistent data store or serialized in a multimodel container.

The multimodel approach is a viable way to support information analysis and collaborative work across multiple application domains. It allows for joining discrete information from different software applications to inspect the coherence of related application models and create complementary analysis models. Instead of relying on the all-in-one model approach to achieve interoperability, the multimodel approach respects the individual application models maintained by different domain experts. Interoperability should be accomplished on demand in different software applications and supported by ontologies [6].

The combination of application models in multimodels provides a basis for a general methodology to interrelate, compare, analyze, and reuse any kind of information throughout construction projects. Using the multimodel approach outlined by [14], which enables connecting the domain models to a multimodel to perform cross-domain tasks formalized as a multimodel container (MMC), stakeholders can exchange and share linked information among themselves. The multimodel also enables filtering, querying, and reasoning among the models, along with the benefit of a shared data environment. This strategy also avoids the need to modify the linked models, which is crucial for standardized data models like the IFC.

Combining the Linked Building Data (LBD) approach with the multimodel approach, the ISO 21597 [15] enables an environment for the integration and reasoning of data on the Web, as well as dynamic semantics through ontology-based link model extensions. The ICDD provides structures and methods for the inter-linkage of heterogeneous data and their exchange between different applications as a closed solution to an engineering problem [16]. The standard specifies a container that stores documents and links otherwise disconnected data within those documents. The container of *.iccd format (compressed with ZIP) has a fixed structure, consisting of the relevant linked models and documents in a Payload Document folder and the linked models in a Payload Triples folder. Each container has an index file that specifies its content, based on the concept of the multimodel approach [16]. The index file and the Link Model schemas are defined in Part 1 of the standard via the two ontologies Container.rdf and LinkSet.rdf [10]. The internal structure of the ICDD comprises two ontologies: a container ontology, which defines the classes and properties used for the description of metadata about the container, and the linkset

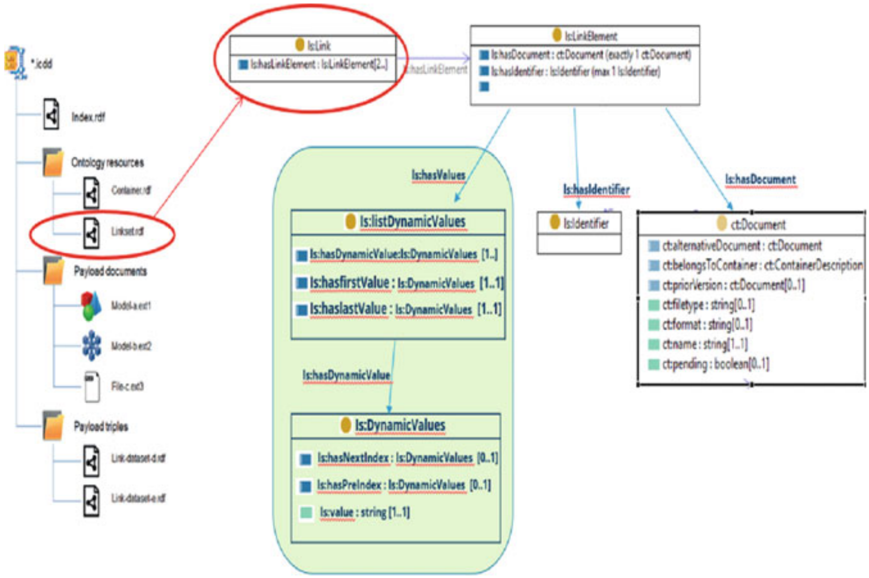

Fig. 1 Structure of ICDD container (the extended schema highlighted in green) [18]

ontology, which provides the definitions for the semantic links between documents. Figure 1 illustrates the structure of an ICDD container on the left, sourced from ISO 21597–1, and the extended ICDD framework on the right, which was developed by Al-Sadoon, N. to enable dynamicity for building elements. The Linkset ontology is extended so that multiple values could be explicitly allocated for any building element [17, 18].

3.2 *Multimodel Based Approach*

Optimizing the value of data can be achieved by implementing a well-designed framework, which facilitates a deeper understanding of performance data and highlights its true potential. To this end, we have developed a multimodel engine (MME), as depicted in Fig. 2, utilizing a multimodel approach. The engine is designed as a microservice, allowing for seamless communication with other applications and integration into cloud-based software via REST (Representational State Transfer) interfaces. The MME is equipped with several functionalities to accomplish the research objectives, including:

1. Create the multimodel container (MMC) based on the object classes and properties provided by the Container.rdf ontology that specify the contents of the container.

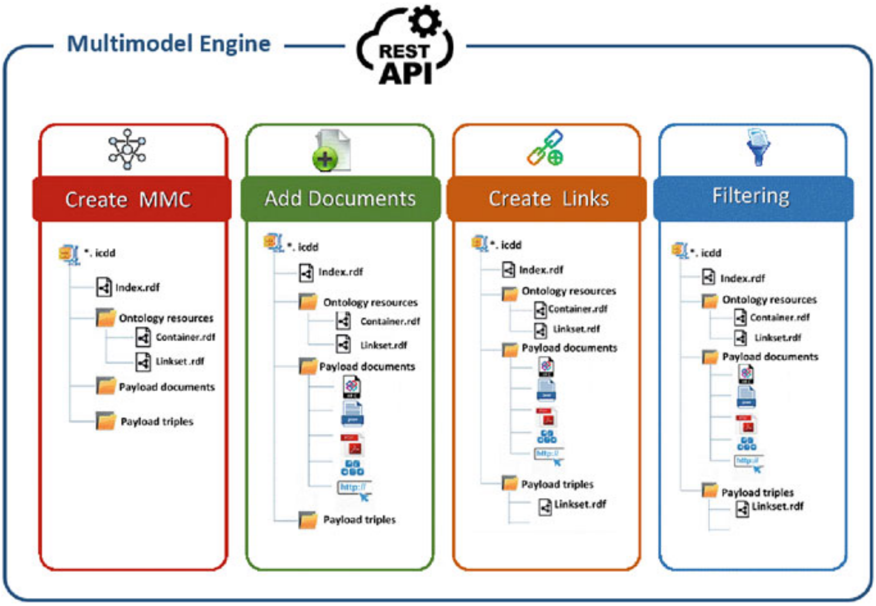

Fig. 2 Multimodel engine main functionalities

2. Add documents, which include all building information models and data sources. These documents could be internal or external (both added in their original format).
3. Perform a filtering function based on the end user requirements on the documents and elements within them.
4. Create links between the documents or objects within them based on the Linkset.rdf ontology.
5. Based on the extended dynamic ICDD [18], additional functionality was developed to enable the explicit assignment of multiple states to any building element.

As a shared data environment, the creation of a multimodel container in the form of *.icdd allows for searching, querying, and reasoning across various documents. It is worth noting that the construction industry is a constantly evolving field, and therefore, the versioning functionality [19] is a crucial feature. This will enable the versioning of documents and automatic updates of corresponding Linksets. The multimodel approach offers a standardized structure for loosely coupling heterogeneous data models, while the multimodel engine functionality provides a common environment for models, elements, and values. As a result, this approach adds value to the information and provides a comprehensive digital twin for the industry.

4 Approach Verification

To verify the proposed approach, an exemplary use case is carried out here. As a test case, a BIM model for building NUR31 on the Technische Universität Dresden campus is created using Autodesk Revit. It contains the building geometry and other building-relevant information. The 2nd floor of the building, where the Institute of Construction Informatics is located, is equipped with sensors to measure temperature and air quality, in addition to a weather sensor to gather outdoor environmental data. The approach is formalized by creating the multimodel engine using Python, OwlReady2, and SQLite. For validation, a prototype for a web-based graphical user interface application, currently under development, will be made available for the end-user to implement the multimodel engine functionalities. REST APIs are created to implement these functionalities. To test the APIs, the Postman application was chosen. In the following paragraphs, we describe how the implementation is carried out.

As stated in the research objective, the integration of multidisciplinary application models in their original formats from diverse sources, including real-time data sources at a system level, is proposed. The data model sources selected for integration into a Multidisciplinary Model Container (MMC) are from various domains, including sensors, web resources, and BIM model data. To establish the relationships between documents and their elements, the ICDD standard offers two main types of linking: Is:BinaryLink and Is:DirectedLink. The Is:Directed1toNLink, which is a subtype of the Is:DirectedLink, is the linking type used for implementation here. This type provides the mechanism to link one data model (or element from it) with multiple data models (or elements inside them). The main data model is the NUR31 building model in IFC format, while the other data models will be:

1. Real-time data model from weather sensor
2. Water Ground level at the site location as an Environmental model (GIS URL)
3. 2D Floor plan at level 2 NUR31 building as a JPG file
4. Soil Geotechnical Report as a PDF file
5. And URL for the building location on google map.

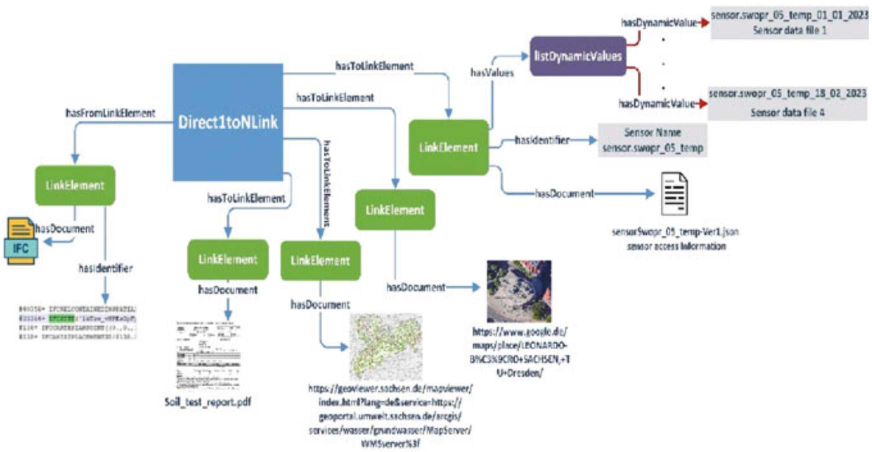

Fig. 3 Linking multiple data sources to a single building element (1 to N Link)

The multimodel engine functionalities progress as follows: First, the MMC is created, and then the data models mentioned above are uploaded into the container. It's worth mentioning here that the ICDD standard provides the specification to add the data models either to be uploaded and saved in the container or to define the corresponding URL (such as web resources) where the external data model is located. The next step is to create the links. We propose here that the end-user wants to link an element from the building model, which is the IfcSite, with the other data models. So, when the end-user implements the linking function, he must select the IfcSite element from the BIM model. Based on their selection, the multimodel engine will perform a filtering function in the IFC file to determine the GUID of the IfcSite element and assign it as hasFromLinkElement. Then the hasToLinkElement is defined accordingly by selecting the other data model, as shown in Fig. 3.

To increase efficiency and provide a more valuable In the multimodel container, additional functionality was added to access the sensor to retrieve sensor data and then save it in the Payload documents as a *.csv data model. Figure 5 illustrates the implementation of this function to retrieve weather sensor data for the period from January 1 to January 31, 2023. This process is repeated based on the end-user requirements. For example, here we retrieve four different weather sensor data sets. As these four datasets belong to a particular sensor, therefore, the extended Linkset.rdf ontology developed in [18] is adopted to add the aggregated sensor data models as multiple values within the listDynamicValues of the document folder 'sensor.swopr_05_temp.' as shown in Fig. 4.

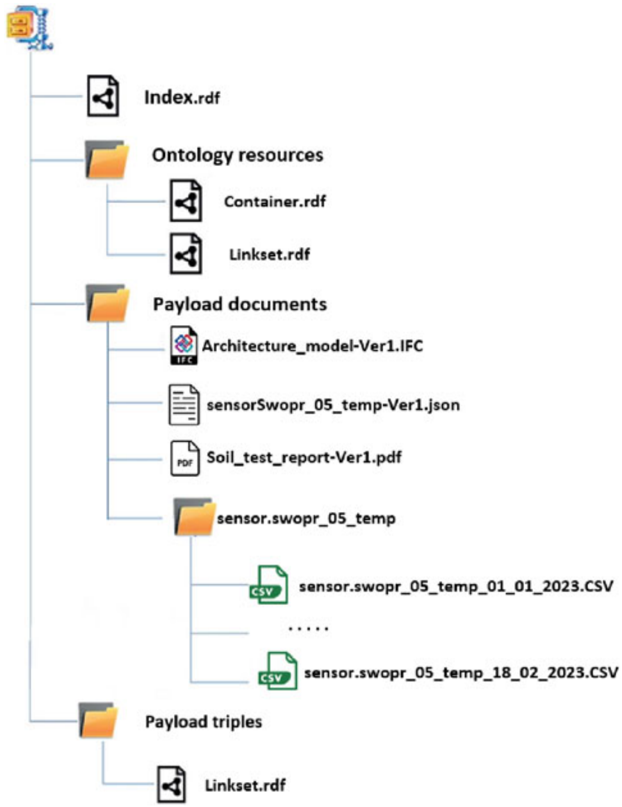

Fig. 4 ICDD structure for verification use case

It's worth noting that utilizing the listDynamicValues feature can allow for the creation of multiple files that contain aggregated data for each sensor. This approach enables the retrieval and storage of sensor data based on the anticipated usage by the end-user. After creating the multimodel container, adding the data models, and creating links, the container is ready to be shared, exchanged, and provides the capability to perform the functionalities of searching, querying, and reasoning across the documents based on domain-specific requirements. Figure 6 shows an example of retrieving linked data from the multimodel container.

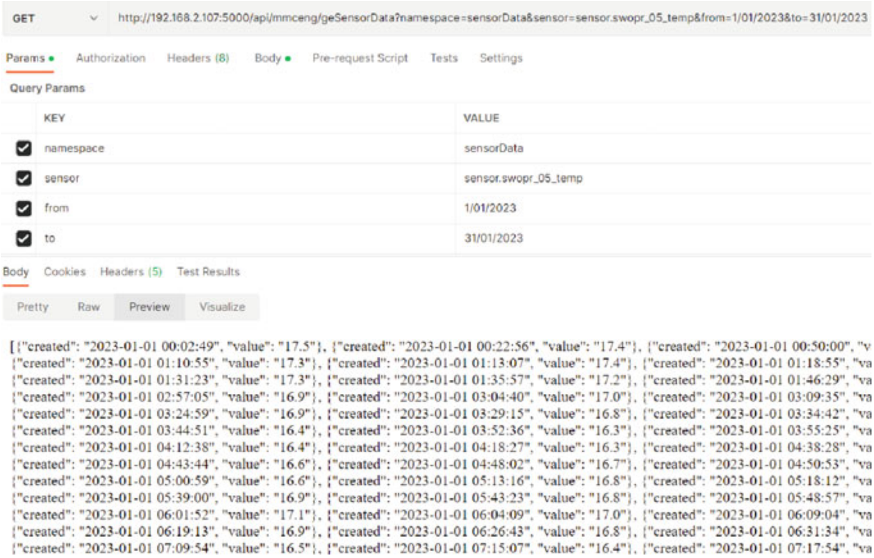

Fig. 5 API for sensor data retrieving

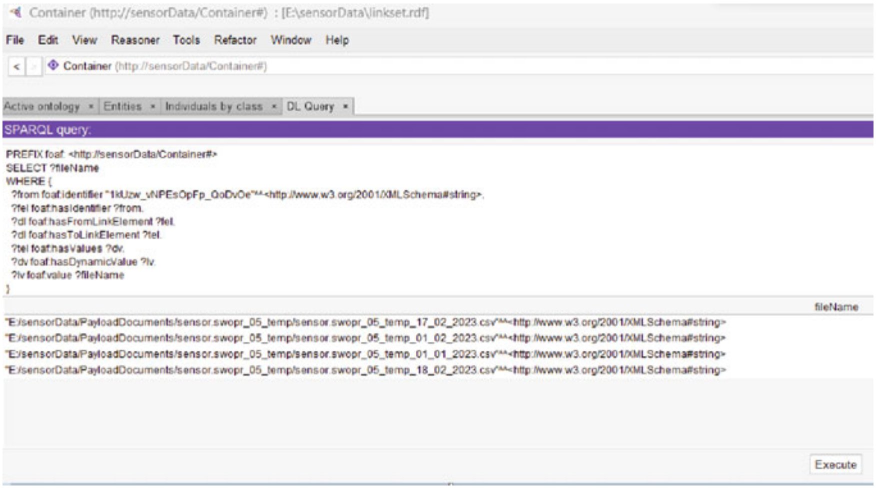

Fig. 6 Querying weather sensor files linked to IFC site

5 Conclusion and Future Work

As architects, engineers, and contractors adopt the new generation of information technologies at a rapid pace, the demands for collaboration and coordination are increasing, resulting in an enormous amount of information and multiple fragmented data models. Thus, in order to fully utilize this information and manipulate it throughout the building lifecycle to create and maintain digital twins, this study proposes the multimodel approach to link all distributed data models that could be produced from design to decommissioning. The developed dynamic multimodel framework allows the correlation of data generated from heterogeneous sources (tools, sensors, buildings, etc.) with BIM models on an object level while maintaining the format of the original data sources. By doing so, it sets up a holistic knowledge base of semantically linked information that can be deployed by machine learning, deep learning, data mining, and analysis capabilities to support holistic decision-making. An experimental use case has been implemented for an existing building as part of the evaluation of the proposed approach, which is planned to support web-based advanced smart services for digital twin empowerment in the iECO [20] research project. Further development in future work will be to create a common platform to connect building information models with readily available data from multiple systems using the extended ICDD framework. This will assign multiple data sources to BIM elements and add versioning functionality that enables the versioning of the elementary models, particularly the BIM model, throughout the building lifecycle. Hence, developing such a dynamic ontology-based approach for linking BIM data with multiple data sources at the building element level aims to facilitate interaction between different datasets and provide the opportunity to perform evaluations across multiple systems, thus supporting smarter decision-making processes. This will undoubtedly pave the way for more reliable digital twins.

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Achieving Macro-Level Bim Adoption in the South African Construction Industry: Key Stakeholders and Constraints

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Abstract Building information modelling (BIM) adoption in the construction industry has become a fundamental ingredient for best practices globally. The benefits have been established In many BIM leading countries. However, due to many challenges, most developing countries are still struggling to achieve industry-wide diffusion. On this premise, this study assessed the profound constraints to the adoption of BIM in the South African construction industry. The study identified the key constraints to BIM adoption in the South African construction industry through a quantitative research approach. It also identified the critical stakeholders that must drive widespread BIM adoption in the South African construction industry. The data was collected from construction industry professionals using a well-structured questionnaire. The key constraints to BIM implementation in the South African construction industry were identified based on the data collected and analysed. The study also identified the key stakeholders for BIM implementation in the South African context. Among other recommendations, the study recommends that the government provide a conducive business environment to enable the implementation by stakeholders.

Keywords BIM diffusion · Construction industry · Developing countries · Stakeholders

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1 Introduction

The underlying intent of industry 4.0 and its attendant emerging technologies is to achieve industry best practices and improve the construction industry's productivity, efficiency and seamless product delivery process. However, achieving this transition is dependent on the ability to overcome barriers. One of the central technologies identified for the transformation and productivity of the construction industry is building information modelling (BIM) [1]. However, there have been various constraints to be submerged and make the transition from the status quo to the new status quo of efficiency according to the Satir's model of change [13] in the light of BIM adoption. Various researchers have extensively researched the barriers to BIM adoption. This has been studied at the individual, project, organisational and industry levels. For instance, [27] modelled various indicators at the industry, organisation and project levels. Another perspective on the classification of BIM barriers is actor, process, knowledge, and planning [2, 28]. In addition, the constraints can be organisational, technical, and economical, among others. Table 1 presents barriers to BIM implementation in literature. These barriers cuts across various countries. Overcoming the identified impediments are essential to achieving BIM implementation. However, the first step is the identification of the barriers.

Table 1 Barriers to BIM implementation in the construction industry

S/N	**Barriers**	**References**
1	Resistance to change	[4, 10, 22, 31, 32]
2	High cost of implementation	[10, 26, 32, 2, 14, 1]
3	Training requirement	[10, 26, 31]
4	Data inadequacies	[25]
5	Interoperability Challenge	[18, 25, 31, 32]
6	Insufficient BIM awareness	[12, 22, 23, 25]
7	Outdated infrastructure	[22]
8	Absence of legal framework	[22, 31]
9	Collaboration among stakeholders	[17, 24]
10	Lack of competence	[23]
11	Incompatibility with existing industry standards	[32]
12	Lack of transparency	[12]
13	Lack of government support/ policy	[26, 3]
14	Uncertainty about ROI	[15]
15	Lack of demand	[5]
16	BIM is not a strategic priority	[1]
17	Existing information-sharing protocol	[6]

2 Stakeholders' Role in Innovation Diffusion

Stakeholders adopt innovations at different rates. Nevertheless, they are important to the adoption of innovation. In the grocery sector, a study by [21] explored the roles of stakeholders in the adoption of efficient customer response. Meanwhile, [10] observed that a challenge to BIM implementation is that stakeholders from large practices champion it. This suggests that stakeholders are essential to the implementation of BIM. Consequently, the right stakeholders are required for BIM implementation and diffusion. Research has also shown that various stakeholders drove BIM adoption in various countries. However, the type of stakeholder is country-dependent [16] as the contextual factors are a significant determinant. Stakeholders act as change agents, and provide leadership among others in achieving the diffusion of innovations; thus, they are very influential [30]. It is therefore important to research the crucial stakeholders required for BIM diffusion, especially in developing countries where BIM implementation is yet to achieve similar success as the developed countries [2].

The objectives of the study are, therefore, firstly to identify the critical constraints to macro-level BIM adoption in the South African construction industry. Secondly, the study identified the significant stakeholders necessary for macro-level BIM adoption in the South African construction industry. Achieving these objectives will aid the industry-wide BIM adoption, which has hitherto been observed to experience varying implementation patterns [11].

3 Method

The study adopted a quantitative approach to achieve the study objectives, as stated earlier. Data was collected through a well-structured questionnaire. Existing studies have similarly adopted this approach [6, 7, 9]. Responses were from construction industry professionals in the Gauteng province of South Africa. This province boasts of a large number of construction activities and professionals. A total of 183 responses were collected from industry professionals; they include Quantity surveyors, Architects, Project managers, and civil engineers, among others (appendix). The respondents have various years of experience – 20.8% have above 15 years of experience, 19.1% have between 6–10 years of experience, 17.3% has 11-15 years experience, 37% have 1–5 years of experience while 5.8% of the respondents have less than 12 months of experience respectively. The questionnaire was divided into three sections, the first section dwelling on respondents background, the second section focused on the constraints to BIM adoption and the third section was on the stakeholders necessary for BIM implementation in the South African construction industry. the questionnaire adopted a 5-point Likert scale. The reliability of the instrument was tested for both sections, and a Cronbach alpha of 0.939 and 0.911 were achieved, respectively. This is considered adequate, and the instrument is reliable as a minimum of 0.7 is recommended [29].

4 Results and Findings

The respondents were presented with nine constraints to achieving macro-level BIM implementation. It is observed that the top five identified constraints to macro level BIM implementation in the South African construction industry are economic constraints(mean = 3.79, SD = 1.132), technical constraints (mean = 3.66, SD = 1.1832), managerial constraints (mean = 3.64, SD = 1.104), organizational constraints(mean = 3.60, SD = 1.082) and quality constraints(Mean = 3.55, SD = 1.102). Table 2 outlines the ranking of the constraints.

Table 3 outlines the ranking of the stakeholders critical to BIM implementation in the South African construction industry. The study findings indicate the most critical constraints to BIM implementation in the South African construction industry are economically related. Some economic variables include currency fluctuation and taxation, among others [20], which have been established to affect the construction industry significantly. An economically conducive environment will aid the adoption of BIM in the industry. Stakeholders have been observed to be struggling with technological innovation adoption due to investment-related challenges[19]. In addition, the ability of the management of construction organisations to sense and seize technological innovation capabilities is vital to achieving competitive advantage [8], and by extension, widespread BIM implementation, including its benefits[1]. Achieving this will help overcome other organisational barriers, and most importantly, leadership is vital in the adoption of innovations [30].

Meanwhile, the study findings also observed that achieving industry-wide BIM implementation requires private stakeholders as the driver. This is contrary to the experience of most BIM leading countries, whereby BIM diffusion was driven by the government. Therefore, private sector stakeholders must not wait on the government to drive BIM diffusion in the South African construction industry. A bottom-up approach is identified as appropriate for BIM implementation in the South African construction industry. Project consultants, technology advocates, educational institutions, software developers and professional bodies are the top five most critical stakeholders.

Table 2 BIM implementation constraints

Constraints	Mean	Std. Deviation	Ranking
Economic constraints	3.79	1.132	1
Technical constraints	3.66	1.183	2
Managerial constraints	3.64	1.104	3
Organisational constraints	3.60	1.082	4
Quality constraints	3.55	1.102	5
Structural constraints	3.48	1.054	6
Procedural constraints	3.48	1.113	7
Regulatory constraints	3.34	1.213	8
Political constraints	3.00	1.334	9

Table 3 Critical stakeholders to BIM implementation

Stakeholders	Mean	Std. Deviation	Ranking
Consultants	4.02	1.045	1
Technology advocates	3.84	1.14	2
Educational institutions	3.79	1.149	3
Software developer	3.76	1.114	4
Professional bodies	3.71	1.125	5
Corporate clients	3.69	1.087	6
Software vendor	3.65	1.114	7
Individual clients	3.46	1.198	8
Contractors	3.39	1.184	9
Public clients	3.34	1.174	10
Government	3.14	1.3	11

5 Conclusion

This study concludes that to achieve widespread BIM diffusion in the South African construction industry; there is a need for an economically supporting environment, innovation savvy managers, provision of supporting infrastructure, and required technical training, among others. Also, to achieve widespread BIM diffusion in the construction industry in South Africa, private stakeholders must drive the process and not wait for the government to lead. Although the private stakeholders must drive the adoption of BIM, the government must provide an environment supporting business, required infrastructure and support for the construction industry. The study's findings provide guidance in decision making for the construction industry stakeholders to achieve widespread BIM diffusion by identifying the critical constraint and the key stakeholders. The study identified the most significant constraints and stakeholders, thus providing areas of focus for the stakeholders.

Appendix


Virtual construction manager
Supply chain management
Structural Engineer, Building Modeller,...
Structural Engineer
Sequencing Modeller and Detailing...
Sequencing Modeller and Detailing...
Quantity surveyor, Cost Modeler, Virtual...
Quantity surveyor, Construction manager
Quantity surveyor
Property developer
Project manager, Quantity surveyor,...
Project manager, Quantity surveyor,...
Project manager, Quantity surveyor, BIM...
Project manager, Quantity surveyor
Project manager, Building services engineer
Project manager, BIM Manager, BIM...
Project manager
Lecturer
Futurist
Environmental Scientist
Engineering Surveyor
Civil technician
Civil engineer, Structural Engineer, 3D...
Civil engineer, Structural Engineer
Civil engineer, Project manager,...
Civil engineer, Project manager, 3D...
Civil engineer, Project manager
Civil engineer, Modelling manager/...
Civil engineer, Digital project coordinator,...
Civil engineer, BIM Manager, 3D Modeler
Civil engineer, BIM champion, BIM leader,...
Civil engineer, BIM champion
Civil engineer
Building services engineer
Building Modeller
BIM Platform Resellers
BIM Manager, 3D Modeler
BIM coordinator, BIM leader
BIM coordinator
Asset Manager
Architectural Technologist
Architect, Project manager, Sustainability...
Architect, Project manager
Architect, Building Modeller, Virtual...
Architect, Building Modeller, 3D Modeler,...
Architect, BIM Manager, BIM champion,...
Architect, BIM Manager, 3D Modeler,...
Architect, 3D Modeler
Architect
3D Modeler, Modelling specialist,...
Axis Title
0
5
10
15
20
25
30
35
40
45
Axis Title
Frequency

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Ontology-Based Computerized Representation Method for BIM Model Quality Standards

Xinglei Xiang, Zhiliang Ma, Žiga Turk, and Robert Klinc

Abstract High-quality BIM model is the premise to ensure the effective application of BIM technology. Thus, many countries and organizations have developed standards to clarify the requirements of BIM model quality on data completeness, consistency, and correctness. However, due to the complexity of BIM model and the professionalism of standards, checking BIM model quality manually is challenging and time-consuming, so it is necessary to develop automatic check systems for BIM model quality. To develop the system, computerized representation of BIM model quality standards is the key and basic step. Towards the objective, this paper proposes an ontology-based computerized representation method for BIM model quality standards. In this method, OWL is applied to represent the concepts and relationships, and SWRL is used for representing BIM model quality rules in the standards. After representing the Chinese BIM model quality standard, a rule base composed of 41 SWRL rules is constructed and the effectiveness of the method is verified. This research contributes to the development of BIM model quality automatic checking system and the promotion of BIM technology.

Keywords Building Information Model (BIM) · Quality standards · Ontology · Computerized representation

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1 Introduction

The rapid development of Building Information Modelling (BIM) technology has a huge impact on the Architectural, Engineering and Construction (AEC) industry over the past decades. In the application of BIM technology, BIM model, as a unified information model, is the carrier of information transmission and sharing among BIM authoring software, and is also the data basis in various application scenarios [1]. For example, in the case of BIM-based automatic cost estimation, the input BIM model must contain complete and correct geometric and material attributes for all components, such as slabs and beams [2]. Apparently, to ensure the effective application of BIM technology, as a premise, BIM model should meet some requirements in terms of data completeness, consistency and correctness [3]. In this study, the performance of BIM models in terms of data completeness, correctness and consistency is collectively defined as BIM model quality. Through extensive surveys on the current status of BIM application, it is found that, in most cases, the quality of BIM models cannot meet the requirements of practical application, due to the operation errors of modelling and the data loss in the import and export process of BIM authoring software [3]. It greatly restricts the promotion of BIM technology.

In order to improve the quality of BIM models, many countries and institutions have formulated BIM model quality standards, such as Singapore BIM guide [4] and NBS BIM object standard [5]. In China, the "National standards for graphic expression of building information modelling JGJ/T 448-2018" formulated by the Ministry of Housing and Urban-Rural Development is one of them (hereinafter referred to as "the Chinese standard"), which stipulates the requirements on BIM model quality in the design and delivery process [6]. However, in practice, it is difficult to check and control BIM model quality according to such standards. Firstly, the BIM model of actual buildings usually contains a lot of components and is complex in structure. Besides, such standards contain a huge number of textual clauses and involves lots of professional knowledge. Considering the efficiency and cost, it is rather time-consuming to check BIM model quality manually. Worse still, there is no automatic check system for BIM model quality corresponding to the standards of any countries or institutions currently [7].

Accordingly, it is critical and urgent to establish a method for checking BIM model quality automatically and further develop an automated system. Apparently, to achieve this goal, the first step is to make computers understand and use BIM model quality standard. However, up to now, all the BIM model quality standards are written in natural language in the textual form. Professional BIM modelers can understand and master them easily, but computers cannot directly use them. Therefore, to realize the automatic check of BIM model quality according to the existing BIM model quality standards, it is necessary to establish an appropriate method for computerizing it.

This paper proposes a computerized representation method for BIM model quality standards based on ontology technology. The Chinese standard is used for introducing the process for implementing this method. Considering the consistency of the content of BIM model quality standards, the method can also be used for other standards.

2 Literature Review

Currently, no research has focused on the computerization of BIM model quality standards, so the scope of literature review is expanded to the computerization of any standard in AEC industry. In related researches, the computerized representation methods for the textual standard in AEC industry can be classified into three types, i.e., object-oriented representation, logical language representation and ontology-based representation [8]. In this section, the three representation methods are reviewed respectively.

Object-oriented representation is a method to abstract the concepts in the text of standards into classes and establish the inheritance relationship among the classes [9]. On this basis, these classes and their attributes are used for representing condition and conclusion clauses of rules. Finally, the rules are organized as tabular form, such as parameter table and decision table. In the 1990s, several studies introduced the object-oriented methods to the task of computerized representation of building standards. Garrett et al. [9] proposed the framework and overall process of using the object-oriented method to represent building design standards. Then, they proposed the building standards representation language SML (Standard Modeling Language) [10]. Also, Ward et al. [11] summarized the concepts in architectural design standards and represented them by using several classes (such as constraints, attributes and results), and then established the relationship between these classes. Furthermore, the object-oriented representation method has been used for the computerization of some various national building design standards. For example, Malsane [12] et al. established an object-oriented information model for the British residential fire safety standards based on the grammatical structure of natural language. However, object-oriented methods are difficult to support automatic reasoning [13].

Logical language representation methods apply the mathematical logic to represent knowledge and rules in building standards. Indeed, the rules written in natural language are converted into logical language representations [14]. The most commonly used logic languages are first-order predicate logic and deontic logic. Salama et al. [15, 16] employed the deontic logic to computerize the design standards of sewage control engineering. Xue et al. [17] proposed a semi-automatic generation method for using first-order predicate logic to computerize the tabular information in building standards. Besides, some researches tried to design and develop a new logic language representation method based on XML to represent building standards. Kerrigan et al. [18] firstly split the building design standards into a tree structure and represented it formally in XML language. Lee [19] designed a logic language for rules (KBimLogic) to represent standards based on XML language grammar and applied it to the computerized representation of Korean building design standards. The vocabulary of KBimLogic was derived from the summarization and induction of building design standards. The logical language representation of building standards is the closest to natural language and easy to understand for users. However, its representation ability is limited. The logic language can only represent deterministic rules. Besides, when using logic language representation method to represent large-scale knowledge and rules, a huge number of logic statements are needed, resulting in a tedious and inefficient reasoning process [14].

The ontology-based representation method is to use the ontology language for standardizing the representation of the concepts, relationships and rules in the standards. Ontology language uses triples to represent canonical text information, in which the classes and properties are the basic units of information representation. In recent years, the ontology-based methods have received more attention in the task of computerized representation for building standards in the phases of design, construction, and Operation & Maintenance (O&M). For the design phase, Ma et al. [20] applied ontology technology to the computerized representation of cost estimation standards, and further developed an automatic cost estimation system. For the construction phase, Zhong et al. [21] designed an ontology for the construction quality inspection for the projects. For the O&M phase, Zhong et al. [22] focused on the environmental monitoring, and developed four ontologies to represent building information, sensor information, and regulatory information based on national standards and design requirements, respectively. The above researches indicate that ontology-based representation method has advantages of the following two aspects:

(1) Powerful representation ability. In the above-mentioned studies, the standards are quite different, while ontology technology can realize the computerization of them.
(2) The great ability to integrate with other domain knowledge. Most of these ontologies used for representing standards that need to be integrated with other domain knowledge [23], which reveals that the ontology language has a good knowledge integration ability.

In this research, the BIM model quality standards generally contain a large number of clauses and will extend continuously with the improvement of requirements for BIM model quality, so the ontology-based approach is used for developing a method to computerize BIM model quality standards.

3 Methodology

The content of the Chinese standard consists of 5 chapters. Chapter 1 introduces the purpose of the standard and Chapter 2 lists the terms used in the standard. Then a series of requirements about BIM model quality are contained, including basic quality requirements for BIM model (Chapter 3), the detailed quality requirements for BIM model unit (Chapter 4) and other deliveries related with BIM model (Chapter 5), such as 2D drawings. Since this research focuses on the BIM model, thus, Chapter 3 and 4 are the main content to be computerized in this paper, which contain 15 clauses and 21clauses, respectively.

Studer et al. proposed a wide-accepted definition for ontology, i.e., ontology is the formalized representation of the explicit concepts in the domain and relationships among them [24]. The definition indicates that explicitness is the basic conditions to be represented by using ontology. According to the definition, most of the clauses in the Chinese standard can be represented by using ontology, while a few of them cannot. For example, regarding the clause *"the information of model units should be added and deleted according to application requirements (Clause 3.1.3 in the Chinese standard)* [6]*"*, it cannot be represented by using ontology language, because the term "application requirements" in the clause depends on the particular cases. On the contrary, *"Component-level model units of different materials should not overlap each other* [6] *(Clause 4.1.4 in the Chinese standard)"* is an explicit requirement and can be represent by using ontology. From this perspective, the clauses in Chapter 3 and 4 in the Chinese standard can be classified into clauses that can be represented ontologically and those that cannot. In this way, the clauses in the Chinese standard are checked one by one and a summary is shown in Table 1. This paper only focuses on the clauses that can be represented ontologically.

The general process for ontology-based representation for BIM model quality standard is shown in Fig. 1. Each step in the process is explained as follows.

Table 1 Summary of the two types of clauses in the Chinese standard

		Can be represented ontologically	Cannot be represented ontologically
Clauses	Section 3.1	3.1.1	3.1.2, 3.1.3, 3.1.4, 3.1.5
	Section 3.2	3.2.1, 3.2.2, 3.2.3, 3.2.4, 3.2.5	
	Section 3.3	3.3.1, 3.3.2, 3.3.3,3.3.5	3.3.4
	Section 4.1	4.1.2, 4.1.3, 4.1.4, 4.1.5, 4.1.7, 4.1.8	4.1.1, 4.1.6
	Section 4.2	4.2.2, 4.2.3, 4.2.4, 4.2.5	4.2.1, 4.2.6
	Section 4.3	4.3.2, 4.3.3, 4.3.4, 4.3.5, 4.3.6, 4.3.7	4.3.1
Total		26	10

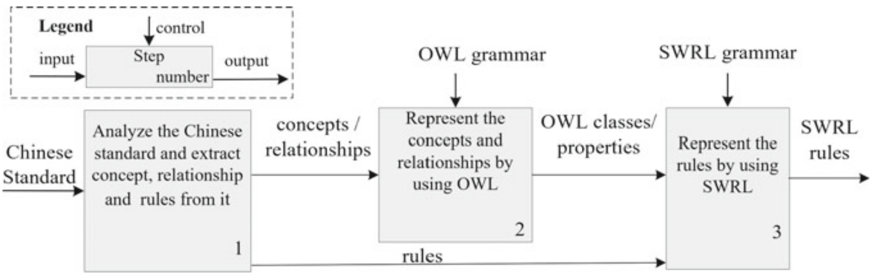

Fig. 1 General process for ontology-based representation for BIM model quality standard

Step 1: Analyze the Chinese standard and extract concepts, relationships and rules

To computerize the clauses in the Chinese standard by using ontology-based methods, extracting the concepts and relationships contained in the clauses is the prerequisites. Therefore, the first step in the general process is to analyze the standard and extract the concepts and relationships from it. For this purpose, the semantics of these clauses is analyzed one by one.

Step 2: Represent the concepts and relationships by using OWL

Then the extracted concepts, relationships and rules are represented by using ontology language to realize the computerization. For concepts and relationships, many ontology languages can be used for representing them, such as RDF (Resource Description Framework), OIL (Ontology Inference Layer), DAML (DARPA Agent Markup Language), OWL (Ontology Web Language). Among them, OWL is the most widely used and has obvious advantages in expressing semantic models and supporting automatic reasoning [25]. Thus, in this paper, OWL is used for computerizing the concepts and relationships in the Chinese standard. Specifically, OWL classes are used for representing concepts, and OWL properties are used for representing relationships [25]. For example, "OwlWall" is an OWL class defined to represent the concept "wall" in the textual standard, and "has_Material" is an OWL property to represent the relationship between building components (such as walls and beams) and material (such as concrete and steel).

Step 3: Represent the rules by using SWRL

SWRL is a rule language developed on the basis of OWL [26]. The rules expressed by using SWRL language can be combined with the concepts and relationships expressed by using OWL for automatic logical reasoning, so SWRL is used for computerizing the rules in this paper. Here, the Chinese standard is represented as a computer readable format.

The remainder of the paper is organized as follows. Section 4 presents the implementation of the Step 1 in Fig. 1. Section 5 and 6 introduce the Step 2 and Step 3 respectively. In Sect. 5, the concepts and relationships are represented by using OWL. In Sect. 6, the rules are represented by using SWRL. Section 7 draws the conclusion.

4 Analysis of the Chinese Standard

In this section, the clauses in the Chinese standard are analyzed and the concepts, relationships, and rules in the standard are extracted, as the basis of computerized representation.

4.1 Concepts in the Chinese Standard

By analyzing the semantics of these clauses in Chinese standard, it is found that each clause expresses one or more rules on the features of the objects in the BIM model or the relationship between the objects in the BIM models. For examples, the above-mentioned *Clause 4.1.4* declares a rule to restrict the spatial relationship *(not overlap)* between the objects *(component-level model units of different materials).* Based on this observation, the concept in the Chinese standard is generally divided into two types, i.e., object and feature. The object means the physical elements in the BIM model, such as walls and slabs. The feature means the characteristics of these objects, such as color. Object and feature are extracted as the top-level concepts.

In the Sect. 3.1 of the Chinese standard, the objects in BIM model are described as *"BIM model should be composed of model units, then the information is stored and expressed by the data of them. Model units are divided into project-level model unit (hereinafter referred to as project), functional-level model unit (hereinafter referred to as system), component-level model units (hereinafter referred to as component) and part-level model units (hereinafter referred to as part)* [6]*"*. The description indicates that the objects in BIM models are classified into two categories generally, i.e., model and model unit. Further, model unit can be divided into four sub categories, i.e., project, system, component and part. Each category can be further classified into more detailed concepts. Figure 2 gives some examples of the subtype of components, including wall, slab and so on.

Regarding the features, by reviewing the characteristics scattered in the clauses of Chinese standard, 51 features are extracted and summarized into four types of features, i.e., geometric features, spatial features, surface features and attribute features. Figure 2 provide several examples of geometry feature, including geometric shape and geometric accuracy. Finally, considering objects and features, 179 concepts are extracted and generalized from the Chinese standard.

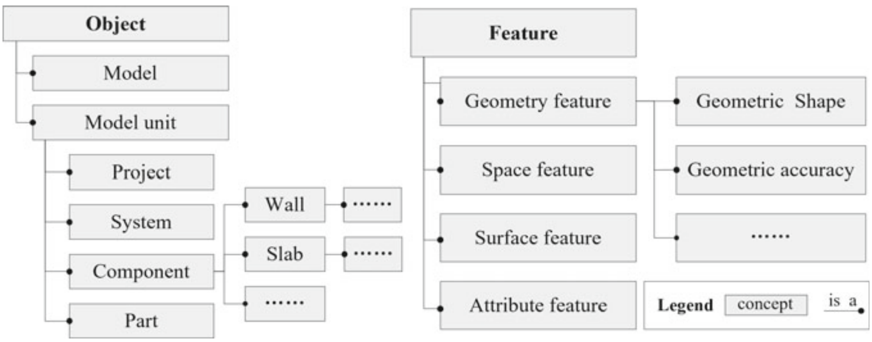

Fig. 2 Examples of the concepts within BIM model quality standard

Table 2 Relationships in BIM model quality standard and examples

No	Relationship	Related concepts	Examples
1	has a feature	between an object and a feature	the relationship between wall and concrete
2	connect with	between a component and the other component	the connection between the water pipe and the elbow
3	control	between a system and a component	the control relationship between water supply system and pump
4	belong to	between a part and a component	the dependency between reinforcement and beam
5	spatial topology	between a component and the other component	the spatial intersection between concrete beams and columns

4.2 Relationships in the Chinese Standard

Considering that there are only 2 top-level concepts, logically and obviously, three types of potential relationships can exist between the concepts in the Chinese standard, i.e., the relationship within features, the relationship within objects and the relationship between objects and features. Among the three types, the relationship between features, such as color and material, has no physical meaning in engineering, and it also does not exist in the Chinese standard. Apart from it, the latter two categories of relationships in these clauses are extracted and summarized in Table 2.

The first category is the relationship between object and feature, which is the Feature 1 in Table 2, i.e., "has a feature" relationship, such as the relationship between a wall and a type of material. The second category is the relationship between the objects, which includes the Features 2 to 5 in Table 2. In the Chinese standard, four relationships between objects are contained it, including "connect with", "control", "belong to" and "spatial topology".

4.3 Rules in the Chinese Standard

Based on the concept and relationship, rules for BIM model quality in the Chinese standard are extracted and decomposed. By analyzing the semantics of these clauses, it is found that the BIM model quality rules expressed by using these clauses have the similar composition and structure. Table 3 gives several clauses and their compositions as examples.

By disassembling the structure of these clauses, these rules can be decomposed into the following 4 parts, as shown in Table 3.

(1) Type of the object to be checked. For example, the type of the object in Rule 1 of Table 3 is "project".

Table 3 Example rules in the Chinese standard and the compositions of the rules

No	The rules in the clauses in the Chinese standard	Composition of rules			
		Type of object	Scoping conditions for object	The features/ relationship	Requirement
1	*Project should have a planar coordinate system associated with it*	project	none	planar coordinate system	should have
2	*The color of component should be consistent with that of its system*	component& system	none	color	should be consistent
3	*The color of component in fire protection system should be red*	component	in fire protection system	color	should be red

(2) Scoping conditions for the object to be checked (can be default). Some rules are only for part of a certain type of object. For example, Rule 3 in Table 3 only constrain the components of fire protection system. Thus, in these cases, the scoping conditions for the objects to be checked need to be declared in rules.
(3) The feature of the objects or the relationship between the objects to be checked. For example, in Rule 3 in Table 3, the feature to be checked is color.
(4) Requirement. The rule must indicate the explicit requirement on the completeness, consistency or correctness for the features of the object or the relationship between two objects. In completeness rules, the requirement is "should have", such as Rule 1 in Table 3. In the consistency rules, the requirement is "should be consistent", such as Rule 2 in Table 3. In the correctness rules, the requirement that object should satisfy is the specific value of "feature" or "relationship", such as Rule 3 in Table 3 (the required value of color is "red").

5 Representation of Concepts and Relationships by Using OWL

In this section, the extracted concepts and relationships are computerized by using OWL.

5.1 Representation for Concepts by Using OWL Classes

Here, each concept in BIM model quality standard is represented as an OWL class. Correspondingly, an individual can be defined for each class to represent specific data. Based on the 2 top-level categories of concepts in the BIM model quality standard,

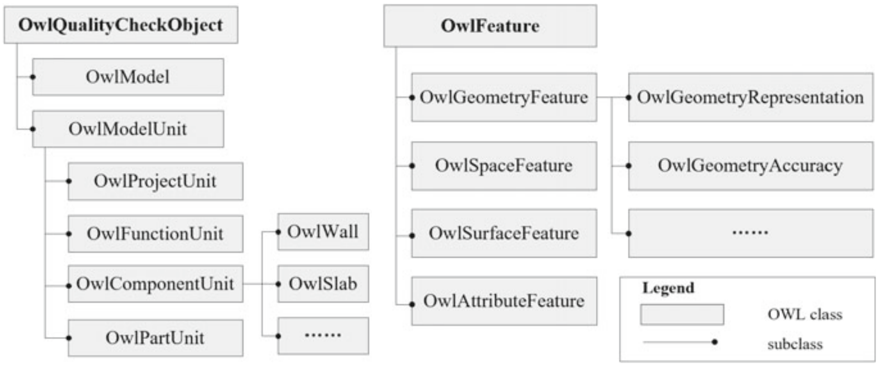

Fig. 3 OWL-based representation for concept in BIM model quality standard

this paper defines the corresponding base classes, i.e., class OwlQualityCheckObject for object and class OwlFeature for feature, as shown in Fig. 3. More detailed concepts are represented by subclasses. For example, four subclasses of OwlFeature are defined as OwlGeometryFeature, OwlSpaceFeature, OwlSurfaceFeature, and OwlAttributeFeature, to represent different types of features.

5.2 Representation for Relationships by Using OWL Properties

In OWL, relationships are represented by OWL properties. Each relationship in BIM model quality is represented as an OWL property in the ontology. Each property has a defined domain that indicates which class the property belongs to. Also, each property has a defined range to indicate which class or data type is used as value of it. In this paper, the five relationships in Table 2 are represented as five properties respectively, i.e., "has_feature", "connect_with", "control", "belong_to" and "spatial_topology". In addition, sub properties are defined via rdfs: subPropertyOf. Some sub properties are shown in Table 4. For example, the Property 1 in Table 4 (has_Color) is a sub property of has_feature, which is used for representing the color of a model unit.

Table 4 Examples of the definition of OWL properties

No	Property	Domain	Range	Explanation	subPropertyOf
1	has_Color	OMU	OwlColor	color of model unit	has_feature
2	has_Identifier	OMU	String	identifier of model unit	has_feature
3	Intersect With	OCU	OCU	Intersection between component	spatial_topology

Note: OCU refers to OwlComponentUnit, OMU refers to OwlModelUnit

6 Representation of Rules by Using SWRL

Normally, an SWRL rule is composed of two clauses, i.e., the conditions and the consequence [25]. Both the conditions and consequence consist of one or more atoms. An atom in SWRL is of one of the following four forms, i.e., Class (?x) (representing a certain class of individuals), Property (?x, ?y) (representing the relationship between an individual and another, or between an individual and a value of basic data type), sameAs(?x, ?y) (indicating that individuals of the same concept) or differentFrom(?x, ?y) (indicating that individuals of different concepts) [24]. Here, ?x and ?y are variables to represent the parameters, which can refer to a certain OWL class or any basic data type. Atoms for conditions are connected with "$\wedge$", and then "$\rightarrow$" means the action to get a consequence according to these conditions.

Based on the decomposition of BIM model quality rules and the grammar of SWRL language, this study proposes a SWRL-based representation method for BIM model quality rules. According to the analysis in Sect. 4.3, BIM model quality rules are composed of 4 parts, i.e., type of the object to be checked, scoping conditions for the object to be checked (can be default), the feature of the object or the relationship between the objects to be checked, and requirement. The proposed process represents these compositions sequentially by atoms and draws the conclusion, which consists of the following three steps, namely declare, judge and conclude. Among them, the steps of "declare" and "judge" construct the atoms of conditions in an SWRL rule. While the step of "conclude" derives the consequence of the rule. Figure 4 illustrates the implementation of each step and gives an example. In the example, the rule that needs to be computerized is *"The color of the component in fire protection system should be red"*.

In the step of "declare", three compositions of a BIM model quality rule are declared through a series of atoms, i.e., type of the object to be checked, scoping conditions for objects to be checked (can be default), the feature of the object or the relationship between the objects to be checked. Firstly, the type of the object to be checked is declared by an atom of Class (?x). In the example as shown in Fig. 4, the type of object is component and corresponding atom is *"OwlComponentUnit (?x)"*. Secondly, the declaration for scoping conditions for the object is completed by one or more atoms of Property (?x, ?y). The declaration for scoping conditions for objects consists of 2 parts, i.e., features or relationships used for defining the scope and their value. Therefore, each scope condition can generally be declared with 2 atoms. In the example in Fig. 4, the rule only applies to the component of fire protection system, thus the relationships used for defining the scope is "Control", so the atoms to declare the scoping conditions are *"Control (?y, ?x) ^OwlFireProtectionSystem (?y)"*. Thirdly, the feature or the relationship to be checked is declared by an atom of Property (?x, ?y). In the example in Fig. 4, the feature or the relationship to be checked is color, thus corresponding atom is *"has_Color (?x, ?z)"*.

After the step "declare", the next atom judges whether the feature or relationship of the objects to be checked satisfies the requirements in the rule. According to the analysis of Sect. 4.3, for the completeness rules, the requirement is "should

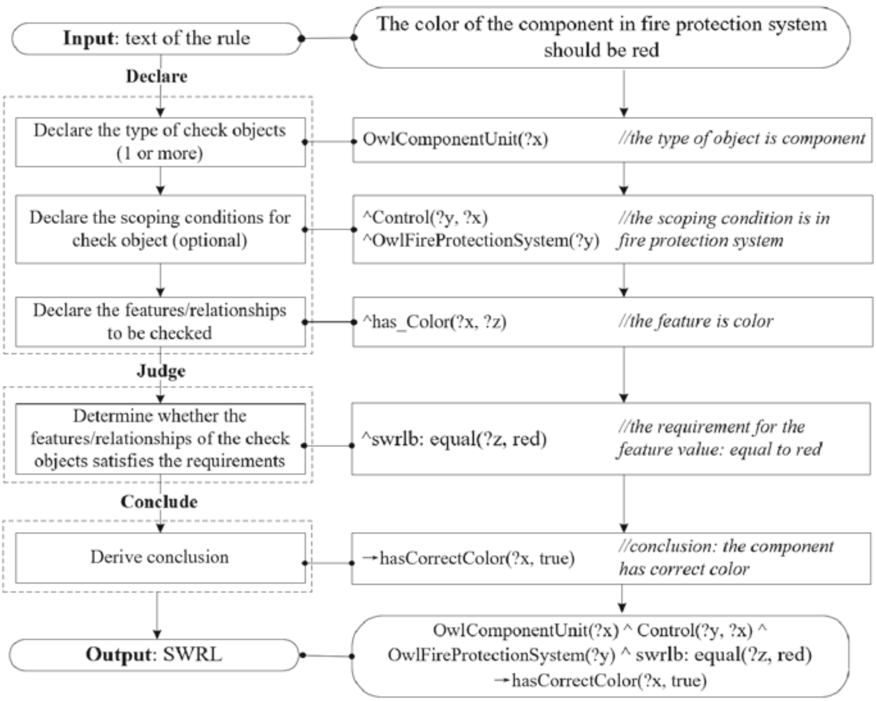

Fig. 4 The process to construct SWRL rules and an example

have", thus the corresponding atom for judgement is in the form of (Property > 0) (x, y), which means the value of the feature or the relationship is not empty. For consistency conditions, atom can be constructed by the property sameAs. For the correctness condition, it can be determined whether the value of the feature is equal with the value specified by the standard. The example as shown in Fig. 4 is a rule for correctness and the atom for judgement is "swrlb: equal (?z, red)".

Finally, the atom of the consequence is constructed to indicate whether the object satisfies the rule (true/false).

Applying the above process, the Chinese standard is represented into a computer readable format and a rule base composed of 41 SWRL rules is established. The rule base can be applied to the BIM model quality check task according to the framework shown in Fig. 5. The framework consists of 3 operators.

(1) Import model and extract data. The needed information is extracted from BIM model for quality check, such as geometric information.
(2) Perform reasoning. Based on SWRL rules, the extracted information is check by available inference engine (such as Jess or Jena).
(3) Export and visualization. BIM model check results are displayed to users through graphic reports and positioning marks.

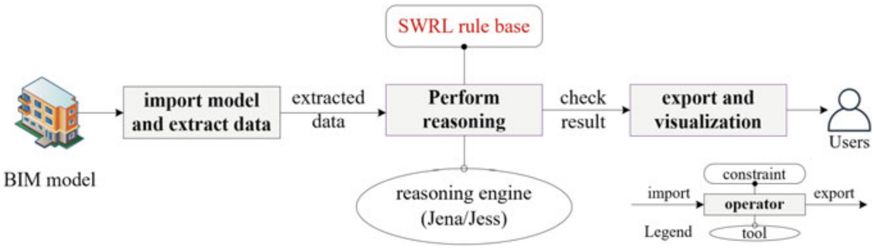

Fig. 5 The framework to apply SWRL rule base to check BIM model quality automatically

7 Conclusion

This paper proposes a method to apply ontology language to computerize the BIM model quality standards. In this method, OWL is applied to represent the concepts and relationships, and SWRL is used to represent BIM model quality rules in the standards. By representing Chinese BIM model quality standard as example, a rule base composed of 41 SWRL rules was constructed. This method not only can be applied for the computerization of other BIM model quality standards but also lays a foundation for the development of the automatic system for BIM model quality.

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An Approach for Fire and Smoke Compartmentation Using the IFC-Structure

Janna Walter and Joaquín Díaz

Abstract Fire is a major hazard for any building. Therefore, fire protection engineer can take various measures to prevent the spread of fire and smoke. One of the most effective fire safety measures is dividing a construction facility into separate fire and smoke compartmentation, which represents an essential part of integral fire protection planning. Fire compartmentation consists of a single room or a series of related rooms and have to be integrated directly into the construction structure. In this context Building Information Modeling (BIM) or more specifically the open-BIM standard Industry Foundation Classes (IFC), which can represent a digital building model with its structure by describing geometry, materials, and relationships between objects, can be used for the digital management of fire compartmentation. In this paper, we present an approach for representing fire compartmentation using the IFC data structure, which has been triggered by investigating current scope of standardization work pertaining to fire safety. By using the IFC data structure for the exchange of information, a reliable basis for the consideration of fire compartments is created, thus preventing expensive compensation measures as well as facilitating cooperation between different designers. Throughout the paper, we explore the possibilities, advantages and challenges of this approach.

Keywords Building Information Modeling (BIM) · Industry Foundation Classes (IFC) · Passive fire protection · Fire compartmentation · Spatial structure

1 Introduction

When designing an architecture like a building, many aspects must be considered. One of the most important is the space and its arrangement and construction by architectural elements. They are defined by vertical and horizontal elements and can

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include, for example, walls or floors. Architectural elements design spaces specifically according to their function and at the same time allow many different functions in the lifecycle of a building, as evident in many old buildings. Thus, spaces can be indoors or outdoors. A collection of spaces needs an overall organization, which can be divided into zones for further differentiation, for example, for thermal protection calculations.

A major consideration in fire protection planning in Germany are the spaces in a building and their arrangement for fire compartmentation, which can be done at an early stage of a project. The creation of fire compartments is a focus of national and many international building codes, such as the Canadian National Building Code. One of the greatest dangers in the event of a fire is the spread of smoke and toxic gases, as well as fire without a fire compartmentation, as was the case in the loss event at Düsseldorf Airport in 1996 [1]. A clear and correct delineation of the spatial extent of fire and smoke compartments must be considered in order to avoid the spread of fire and smoke as well as unintended consequences and costs for later interventions and additional plant engineering measures. Currently, the textual part of the fire protection concept is used to describe the fire compartments of a building project, which are represented in color in the fire protection plans by the architectural elements, such as a fire wall.

BIM is intended to ensure that the information stored in the digital building model is accessible to all parties involved in the design, construction, and operation of a construction. The methodology enables project participants to collaborate digitally in an integral way from the early design phase. Different requirements are set for the collaboration, which have to include the spatial zone assignment of fire protection. In addition to the spatial information from the digital model, the semantic information is important to enable a technical assignment and structuring of the spaces for fire protection planning.

The open BIM standard Industry Foundation Classes (IFC) [2], which can represent a digital building model with its structure by describing geometry, materials, and relationships between different objects, like a room, can be used for the digital mapping of fire compartments with modifications and extensions. With the introduction of IFC4-schema, the IfcSpatialZone entity was added to represent different space zone roles and flexible space objects in the building information model, and to realize a method of space reservation and space zone assignment [3]. For the exchange of information, the use of a spatial zone assignment in the IFC data model creates a reliable basis for the consideration of fire compartments, which decides on further necessary fire protection measures and prevents expensive compensation measures, as well as simplified cooperation between different planners.

In this research, the suggestion is that using the IFC data structure can be a feasible approach to representing fire and smoke compartmentations, which have been elicited by investigating current scope of standardization work pertaining to fire safety. However, while there is research on integrating fire protection into BIM and IFC, the focus is on semantic information [4–7]. Spatial information and its structure have been studied in only a few researches [8–11], although is one of the most important bases of fire safety planning, not only nationally but also internationally, since they all have the same goal of preventing the spread of fire and smoke. The research of Kitzlinger [8] already showed the importance of room and area structuring in fire protection planning. Likewise, Norén et al. [10] as well as the German Association for the Promotion of Engineering Methods in Fire Protection (VIB) [11] have published space-relevant parameters and information for digital exchange. Therefore, the aim of this research is to develop a BIM-driven approach to representing fire and smoke compartmentations in the 3D digital data environment. The paper is organized as follows: Sect. 2 and Sect. 3 set out the investigation, firstly identifying data elements required for fire and smoke compartmentation and secondly investigating suitable mechanisms in the BIM model with fire and smoke compartments. The IFC standard was chosen for this purpose because fire protection engineers receive the digital building model from the architect for further use and do not currently create their own models. Section 5 presents an implementation of a prototype BIM model with fire and smoke compartmentalization. From which the benefits and the challenges that hinder the use of fire compartmentation are highlighted. The paper concludes with a summary and with an outlook on potential future research directions.

2 Related Work

2.1 Fire and Smoke Compartmentation

According to the German building Code for fire protection, a building structure must be arranged, erected, altered, and maintained in such a way as to prevent the development of fire and the spread of fire and smoke and, in the event of fire, to enable the rescue of people and animals and effective fire-fighting operations. Structural fire protection is one measure of the fire protection system which aim is to plan a building before construction so that the consequences of a fire are kept to a minimum. For this, one of the elementary measures is fire compartmentation. This involves dividing buildings into different fire compartments and fire safety zones to limit the spread of fire and smoke in the event of an outbreak. Buildings may have one or more fire compartments that are bounded from other parts of the building by fire walls or fire-resistant slabs. In addition, fire compartments may in turn include several fire safety zones. Figure 1 shows an example arrangement of fire compartments with included fire safety zones. Openings in these fire compartments and zone walls or floors shall be of the same fire resistance class as these walls or floors. In addition to fire compartments, smoke compartments are required in buildings to prevent the spread of smoke in the building and to enable people to be rescued for a sufficiently long time (protection goal). This applies in particular to buildings with a high volume of people (e.g. hotels). They are divided by smoke protection closures (e.g. smoke protection doors), which are intended to prevent the passage of smoke for a certain period of time. A fire compartment usually contains of different smoke compartments as well as groups of spaces (e.g. apartments) and/or spaces (e.g. staircase or storeroom)

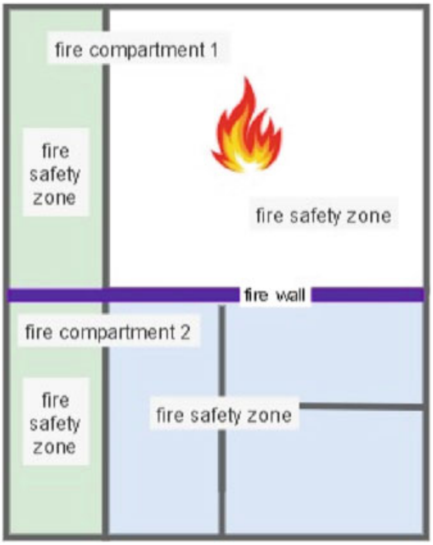

Fig. 1 Example of fire compartmentation

represented as a fire safety zone. For this reason, it is important to consider spaces and their arrangement.

The factors influencing a fire include the type and quantity of the fire load, the arrangement of room geometries, as well as the room geometry itself, openings and the construction of walls and ceilings. For fire protection design, engineers therefore need the basic geometry and topology of a building, information about the size and shape of rooms, openings, and hidden voids, and exits from a room, among other things, to divide the building into fire compartments and fire safety zones. In the early preliminary planning phase, architects usually collect mainly basic information on higher-level objects, such as room and spaces, which is later documented in a room program and submitted to the fire protection engineer for bidding. In this phase, fire protection planning information can already be developed as a rough concept [8].

In practice, the integration of fire protection planning into the BIM method often takes place first in the design planning phase, even though the essential foundations for fire protection planning are already laid in the preliminary planning phase [8]. In addition, the focus is currently placed on the required semantic information of the fire protection planning, although the spatial information is nevertheless important to represent a technical arrangement of the rooms and areas in the fire compartments and fire safety zones in the digital building model.

2.2 Spatial Arrangement

Managing information about areas represented by architectural components such as rooms is used and required in many areas of the construction industry. For example, rooms that contain or should contain the same properties are usually grouped into spatial zones. This type of spatial zone assignment is mostly used for electrical, heating, ventilation or sanitary analysis or calculations. For instance, a typical use case for spatial zone assignment is the BIM coordination between architectural and MEP models [3]. However, research and development in spatial zone assignment in BIM methodology is mainly done for plumbing, electrical and HVAC. Although, spatial zone assignment for various spatial roles such as lighting, security, and construction is a fundamental requirement for the collaborative design approach [3], and fire protection is one of them. The principles of fire compartmentation for digital cooperation are of national interest as well as international. Many building codes, such as Canada's, include fire compartmentation because they all share the same goal of preventing the spread of fire and smoke.

Kitzlinger [8] presents in his research that for the integration of fire protection planning in the digital planning process with BIM, a fire protection specialist model based on planned spaces is required. For this, he has provided approaches for implementation and defined some required information for spaces in BIM. In accordance with the IFC standard, Kitzlinger suggests that digital models with the class IfcZone and its PropertySet Pset_ZoneCommon be supplemented with information from the spaces. According to the IFC standard, IfcZone represents a group of spaces or zones [12]. For this reason, only components and areas that are modelled as a space or zone can be assigned to this class. Also, Norén et al. [10] and the VIB [11] have already defined required information or properties for a room level in the digital building model.

The mapping of the data elements onto the IFC standard for fire protection planning regarding the spatial assignment has not yet been investigated. With the IFC standard, it is possible to create rooms without building components and then assign them to zones. However, as already mentioned, no building components can be assigned to these zones. This is important for fire protection planning. The class IfcSpatialZone introduced with IFC 4 makes it possible, but there is no BIM authoring software yet that supports its use. Currently, documentation is being produced by buildingSMART international that includes a list of potential use cases of IfcSpatialZone and a guide to encourage software vendors to implement features that can facilitate the use of IfcSpatialZone in their BIM authoring tools [3].

3 Modelling Fire and Smoke Compartments in BIM

As part of the VDI (Association of German Engineers) committee's work, we modeled a sample building model to represent the relevant fire protection information for data exchange. In this context, two steps are considered to model fire and smoke compartments for the sample building in BIM in this research. First, the data elements associated with fire compartmentation were identified. In the second step, the identified data elements were mapped onto the IFC standard.

3.1 Data Elements of Fire and Smoke Compartments

There are two major data elements for fire compartmentation: attributes and spatial structure of fire and smoke compartments. In this study, we will focus on the structure and the relevant attributes for the structure itself. The general attributes could include, for example, the area of a fire compartment or the length of a smoke compartment and describe the properties of a compartment or a fire safety zone.

For fire compartmentation, it must be possible to model fire compartments and fire safety zones. As mentioned in Sect. 2.1, the fire compartments can contain various numbers of fire safety zones as well as individual rooms. The fire safety zones can also consist of individual rooms or groups of rooms. Some important areas that must be defined for fire protection planning include escape routes, units of use, and rooms with special danger. The fire compartmentation components also include walls and ceilings, as well as penetrations and doors. The focus of this study is on spaces. The other building components must be subjected to a separate investigation.

3.2 Mapping the Data Elements Onto the IFC Standard

The standard IFC spatial view is *IfcProject* > *IfcSite* > *IfcBuilding* > *IfcBuilding-Storey* > *IfcSpace* which corresponds to a spatial hierarchy [13]. However, a fire compartmentation cannot be presented to such a hierarchy. For example, there can be two different fire compartmentations in a building storey, each of which extends differently in height and length, and at the same time includes additional different fire safety zones. Therefore, spatial zoning needs to be non-hierarchical and allows for potentially overlapping subdivision of a building. Objects of the IFC schema can be assigned to a hierarchical spatial structure element (IfcSpatialStructureElement) and a non-hierarchical spatial zone (IfcSpatialZone). For this reason, the IFC entities IfcSpatialZone and IfcZone are suitable for mapping the data elements of fire compartmentation, as it was mentioned in Sect. 2.2. The definition of IfcSpatialZone is "*A spatial zone is a non-hierarchical and potentially overlapping decomposition of the project under some functional consideration. […] A spatial zone might have its independent placement and shape representation.*" [12], while IfcZone is a collection of IfcSpace objects and other IfcZone objects [12]. Both entities have fire compartment or rather fire safety as their type definition. As a proposal for fire protection planning, IfcZone would have to be extended with the function to group IfcSpatialZone in addition to IfcSpaces and IfcZones. This allows better management of the fire compartments with the included fire protection zones and provides a better overview. Furthermore, for the IfcSpatialZone entity, the space boundaries relationship should be added as in the IfcSpace entity, in order to take into account the change of zones. In addition to the "FIRESAFETY" typification of IfcSpatialZone, it is also recommended to define a property set with the properties for escape routes, unit of use and room with special danger, to manage the fire safety zones more efficiently.

4 Use-Case

A three-story building with underground parking was modeled as an example model to demonstrate the proposed BIM-driven approach to fire and smoke compartmentation. This example model was created to illustrate fire protection with associated use cases. On the one hand, the relevant required fire protection information will be presented, and on the other hand, the structure for a digital fire protection model will also be presented. As already mentioned, the building contains an underground parking as well as three additional building storeys with offices. It is approx. 50 m long and is therefore divided into three fire compartments by a fire wall and fire-resistance slab. The rooms on each building storey have been assigned to different fire safety zones. Figure 2 shows the sample building model with fire compartmentation and fire safety zones.

So far, there are only a few BIM authoring tools that have implemented the use of IfcSpatialZone. For this reason, the fire safety zones in Fig. 2, defined with the entity IfcSpatialZone, can only be drawn manually in color to represent them which is one of the challenges.

4.1 Benefits

The sample model can be used to demonstrate the benefits of fire compartmentation. Through the simple spaces, early information regarding fire protection can be passed on to the object planner to show which spatial structure is or would be required to achieve the necessary fire protection requirements. An early evaluation of fire safety is thereby possible to guarantee cost security, among other things.

Fire protection planners can use the "simple" fire protection model with the assignment as a rough concept and expand the model with further information from one performance phase to the next. In addition to fire protection planners, other specialist

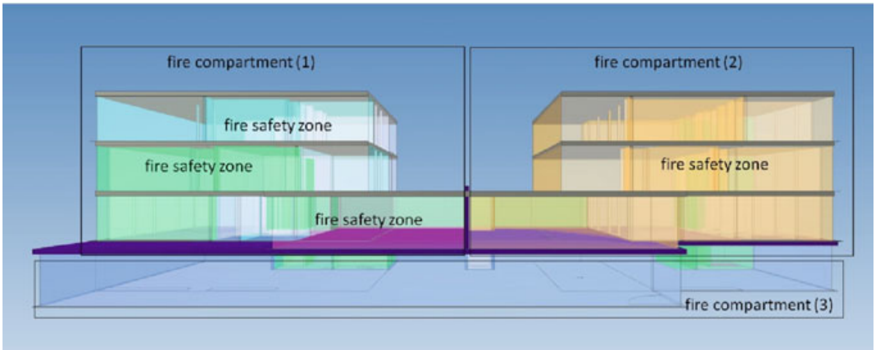

Fig. 2 Sample building model with fire compartmentation and fire safety zones

planners also benefit from the fire protection model, as they can plan fire stopping systems in their penetrations at an early stage and adapt their planning, e.g. cable routing, accordingly.

4.2 Challenges

As noted, there are few BIM software tools that have implemented the IfcSpatialZone feature, but buildingSMART international is working on an approach to encourage software manufacturers to implement it.

Currently, in practice, fire compartments are described in the text of a fire protection concept and represented in the plans by components that form fire zones. However, an area extending over several building storeys, for example, cannot be represented. Moreover, a well-defined BIM fire protection model is yet to be established. For these reasons, there is still no BIM software or software functionality that can be used for fire protection planning.

5 Conclusion and Future Work

Collaboration among AEC industry stakeholders, including fire protection, is necessary to achieve the building code's protection goals of fire protection. One of the important measures of fire protection planning is fire compartmentation. This paper has investigated the design of fire and smoke compartmentation in the open BIM standard IFC to show the need for and importance of compartmentation for fire safety in BIM. First, the background of fire compartmentation and related works with respect to BIM and fire protection were examined in more detail. Second, the necessary data elements for the fire compartment planning were analysed and mapped with the IFC standard. These were implemented in a sample model, from which benefits and challenges could be identified.

Furthermore, this work can be used to create the structure for a model view definition specifically for fire protection. Thus, the fire protection building model provides a reliable basis for decision making during the life cycle of a building.

Future work of the authors will include the analysis of the required properties for fire compartment presentation, for example, the area of a fire compartment or the length of a smoke compartment. Another aspect of this work will involve the creation of a fire protection model for BIM.

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Digital Twin Construction

Towards a Digital Twin System Design Based on a User-Centered Approach to Improve Quality Control on Construction Sites

Thibaut Delval, Mehdi Rezoug, Melanie Tual, Yasmin Fathy, and Romain Mege

Abstract The traditional quality control on construction site relies mostly on visual inspections and daily or weekly reports generated based on those inspections. This traditional practice relies heavily on the inspectors' personal judgement, detailed knowledge of the project, observation, and experience, resulting in a high probability of incomplete and inaccurate reports.

Over the past few years, the architecture, engineering, and construction industry (AEC) recognized the urgent need for fast and accurate control of construction quality to increase productivity and optimize construction costs by avoiding the rework of deficiencies. Digital tools, including the BIM model and the digital twin of the construction site, will improve productivity and should help to bring down the costs of non-quality. But they require detailed knowledge of digital practices and existing processes in construction, which is the mandatory condition for the construction industry to embrace new technologies through rationalizing its production processes. An "end user" approach needs to be led with on-site workers to understand the issues they face and how they currently work to understand better their needs regarding quality monitoring and how the digitalization of associated processes could help. This article focuses on the methodology used to conceive a digital twin for the construction site where construction companies (end users) were put at the heart of the approach. It also drives novel insights on quality control and discuss future directions to improve and automate quality control at construction sites.

Keywords Digital Twins (DT) · Automatic Quality Control (QC) · Construction Site · User-centered Approach · Building Information Model (BIM)

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1 Introduction

1.1 Defects Problems in the Construction Industry and Needs of Quality Control Digital System

In a construction process, quality defects often occur inevitably and repeatedly due to various causes (i.e., human, technical, logistics, environmental, etc.). Building or construction defect can be defined as “a fault, or deviation from the intended level of performance of a building or its parts” as per ISO 15686-1:2000(E) [1].

The defect is a physical phenomenon that must be corrected, and such an activity can be considered rework. The Construction Industry Institute (CII) defines rework as field activities that must be performed more than once in the field or activities that remove previously installed work from the project [2]. In other words, rework can be defined as unnecessary efforts to redo an activity or process that was incorrectly implemented the first time [3]. Considering the repair or rework measures that require these defects, they are seen as the leading causes of schedule and cost overruns, which seriously affect project performance and productivity [4, 5].

Several research works have been concluded mainly on the cause of defects and their impact on construction project costs. For example, Mills et al. [6] reported that defect costs accounted for 4% of the new residential construction contract value. Similarly, Love and Li [2] found that defect costs accounted for 3.15% and 2.40% of the contract value in residential and industrial buildings, respectively. The French Agency for the Quality in Construction publishes an annual report to evaluate the cost of construction insurance. In 2022, it is accounted for 4,2% of the contract value in residential buildings considering only insurance direct cost [7].

The main objective of construction quality control is to check and prevent defects as a part of project quality management. Therefore, it is a necessity for the construction industry to have a detection system that allows quick and easy identification of defects during the ongoing construction process.

1.2 Research Objectives

The quality control process for effective conformance checking in construction can be seen as part of the works carried out in the European project BIM2TWIN [8] dedicated to develop a digital building twin for optimal construction management. The main themes of this work include: (i) the conceptualization of the optimal Digital Twin (DT) enabled construction process; (ii) specifying and developing the overarching data structures of the DT, fundamental data processing chains, as well as the DT platform required to manage the data; Development of procedures and a software prototype for automating; (iii) Progress monitoring & quality control for volumetric building; (iv) Progress and quality monitoring of surface/textural work; (v) Occupational safety and health of workers; (vi) Equipment optimization.

The aim of our research work presented in this paper is to present a new system design for modeling the process of automatic tracking and quality control.

1.3 Structure of the Paper

The paper is structured as follows. Section 2 describes existing literature and methodologies for detecting quality issues in construction. In Sect. 3 will be formalized the technical compliance specifications and requirements for defining system design that includes a user-centric approach to determine the prioritization of quality control needs of site workers. A detailed analysis of European regulations was also carried out based on user requirements. Use cases were then selected, focusing on concrete works (problems of flatness, axis deviation) and mechanical plumbing and electrical works (correct equipment position regarding comfort and safety.). In Sect. 4, will be incorporated these user requirements for automating quality at construction sites and discussed our proposal digital process for automating quality analysis using emerging technologies, in particular, the role of Artificial Intelligence (AI) and Machine Learning (ML) for recognizing objects/equipment on the site. The functional modeling, with the BPMN (Business Process Model and Notation) format, including tasks and associated information exchange, has also been included in the same section. The conclusion of the paper and future directions will be shown in Sect. 5.

2 A User-Centric Approach to Define the Uses of Digital Technology on the Construction Site Applied to Quality Analysis

2.1 Total Quality Management (TQM)

Total Quality Management (TQM) method has been traditionally used in the construction industry to detect issues arising from complex processes, production flow and quality requirements within the construction progress cycle [9]. Moreover, the method can be used for detecting defects in the building. However, it requires a lot of effort from stakeholders in a context where in our experience, construction companies, especially middle and small sized, don't have the time and resources required to establish the correct environment and organizational culture.

Recent research studies on quality control tools and methodologies in construction focus on the contribution of TQM. Mohrman et al. [10], define TQM as an approach to managing organizations which emphasizes the continuous improvement of quality and customer satisfaction, entails the application of systematic tools and methods for managing organizational processes with these ends in mind, and involves the establishment of structures such as quality improvement teams and councils for maintaining focus on these ends and enacting organizational improvement processes. This management theory originated in Japan in the 1980s and has been growing in the manufacturing and service industries. Only in recent years has it been applied to the construction industry (which can be seen as a combination of manufacturing and services) to address clients' increasing demand for high-standard delivery for large and complex buildings as well as a strong need for securing the quality, cost and timing of such large projects.

To improve quality and eliminate defects, TQM bets on the human factor, helping managers to oversee all tasks and activities to maintain the required level of the quality. TQM assumes that stakeholders of quality control are get trained for developing new processes and teambuilding, and that "the employee's mindset shifts from one of just monitoring quality to continually looking for opportunities to make improvements" [11]. TQM provides organizations with statistical tools to get a grip on the reality of construction projects, these tools include histograms, control, cause-effect, and flow charts, but encourages as well to use Pareto Principle, checklists or scatter plots [12].

TQM will take time for those who have the resources to successfully adopt it because it entails a significant culture shift and requires phasing in these changes to reduce their impact [13]. Most companies will also need practical guidance and assistance in adopting and executing quality-improvement programs. Based on our experience within the BIM2TWIN project, such a method to control quality defects has been produced. However, it tends to be also abstract, top-down and thus not adapted to improve work on construction sites where most stakeholders have a very practical job and very little time and available resources. In conclusion, such an approach will be in most cases very difficult to implement in that sense, that it doesn't take into account the specificities of working conditions and specificities of people conducting quality control on construction sites as well as the large variety and interests of stakeholders taking part in the construction process.

2.2 Using Design Science Research to Better Control Quality Defects

The existing literature about stakeholders in the quality control of construction sites is scarce and limited. To this end one of the innovative aspects of the BIM2TWIN project is to involve end users in the design of a digital tool using Building Information Modelling (BIM) technology to improve the quality of work on the construction site. It is based on its design methodology on Design Science Research (DSR).

The Design Science Research (DSR) is defined as "a scientific methodology of problem-solving that was developed specifically for the Information Systems (IS) domain" [13]. DSR methodology is mainly a research methodology initially meant to develop information technology (IT) artifacts. It involves the creation of new knowledge through the design of new or innovative artifacts, analysis of use and performance of these artifacts to improve information systems [13]. DSR, or constructive research, in contrast to explanatory science research, has academic research objectives generally of a more pragmatic nature. Research in these disciplines can be seen as a quest for understanding and improving human performance. Moreover, DSR process was described "as being consistent with previous literature, providing a model and methodology to conduct the research, and providing a system for presenting and evaluating the research data". Although it didn't explicitly place the user at the heart of the design, our BIM2TWIN project emphasized associating users to the design of the digital twin. In order to do so, construction companies were involved in BIM2TWIN and in the first step of the project, users were asked about their difficulties and expectations, notably on quality control. To this end, an online questionnaire was shared with construction companies' employees and two workshops were organized with construction companies' representatives, focusing on their difficulties and their use of new technologies to control quality among other things. The limit of the way this methodology was used is that there was no work conducted to identify who would practically use the tool to be designed, in which conditions, to address which needs, to fulfill which motivations and so on…

As a result, questionnaires and workshops delivered interesting but yet very generic results, that could hardly be used by design teams. For example, some of the identified barriers to better quality control were linked to shortage of skilled workers, or lack of time and resources. Although interesting, these results could hardly be taken in account by design teams as such and the idea is that this was mainly due to incomplete user research where the identification of the different categories of end users was missed and a focus on people and their individual experiences, needs and daily habits.

2.3 End User Approach Used in Our Research

In BIM2TWIN project, users involved didn't represent the diversity of end users. For practical reasons, workers and worksite managers were not associated with a particular construction process because they were considered to be not familiar with interviews and online meetings techniques, as they don't work in offices but only on the construction site. Nonetheless, they are the ones who are in charge of the quality control in the first place. So, in this project, we decided to conduct further interviews with them to complete information on quality control gathered with users « from the offices». We conducted interviews based on a two-parts individual interview plan.

In the first part, we asked workers to describe how they would control quality on the construction sites, namely, which tools they would use, how they would report quality defects, to whom, etc. Surprisingly, workers rely on visual inspections and taking photos with their phones. However, the quality of captured images was a problem, interviewees stated that they could not always zoom enough to properly check from the plan was what expected. Quality control could be conducted by virtually anybody which diluted responsibility. In case of quality defects, they would take pictures with their phone. They also reported the fact that they were provided with « quality control template» to fill it out if a defect is detected. This template tended to be ineffective and subjective to inspectors. Moreover, pictures were seen as the most efficient tool and enhance a low-tech approach for quality control. However, it needs to be printed out and added to the quality control template, which was not always done. All participants working hands on the construction site expressed their lack of overview on the construction site, in the space and in the time as well as going into details.

This information gathered during these "extra interviews" did put in perspective information we got from other participants and helped us define priorities for the development of use cases.

The second big input of these interviews was to confront the results of a literature review conducted by scientists on quality defects with the onsite professionals during the second part of our interviews. Workers were asked to evaluate the severity and recurrence of defects identified in the literature according to their experience.

As shown in Fig. 1, inputs to the literature review helped scientists to have a more accurate view on quality issues faced by professionals on the construction site, as they could provide us with a clear view on what each type of defect meant for them in their experience. Our decision to widen the scope of interviewed people helped us get more practical, technical and precise information from end users that proved helpful to define a system for control quality.

3 Methodology to Define a System Design for Control Quality

3.1 Quality Defects and Technical Specifications

The end user approach has helped to define most important defects at a construction site to monitor through our system design for control quality. The next step was to make the relationship with the technical specifications allowing to characterize them (see Sect. 3.2.1), where we have classified these defects by categories according to their geometrical (physical) and spatial aspect based on the structuring adopted by the construction quality guidelines. For example, based on the structuring defined in the DTU (Unified Technical Documents) describing the design and the execution of building products, established by the French centre for building science and techniques (CSTB), particularly Normes-DTU (NF-EN) (European harmonized norms concerning the construction work); we could outline the following diagram (Fig. 2):

Defect/Deviation name	Frequency of occurrence			Severity			Technicality		
	Less Occurred	Occurred/ Slightly Occurred	Mostly Occurred	Important	Less Important		Easy	Middle	Hard
Offsetting - Offset element (mismatch)		X		X			X		
Partially represented element		X		X			X		
Axis deviation		X		X				X	
Verticality deviation		X		X			X		
Planeness deviation (Flatness)		X		X			X		
Surface honeycombing			X		X		X		
Surface Cracking			X		X		X		
Surface Pitting (Pinholes, bugholes, blowholes)			X		X		X		
Visible lift lines and/or Cold Joints			X		X		X		
Reinforcement cover thickness deviation	X			X				X	
Main rebar/ Stirrups binding is non-compliant	X			X					X
Incorrect rebar size/ quantity/ spacing/ No detail drawing	X			X					X
Finished concrete surface are non-compliant	X			X			X		
Expansion joint/ Movement joint is inadequately placed	X			X			X		
Debris are left on the concrete surface		X		X			X		
Mortar Thickness joint Deviation		X		X				X	
Mortar Joint Position Deviation		X		X				X	
Height of equipment not in compliance					X			X	
Minimum number of outlets not met					X			X	
Minimum distance between networks not respected				X				X	
Minimum depth of pipes not respected				X				X	
....									

Fig. 1 Result of Spada Construction workers's analysis on most common construction defects

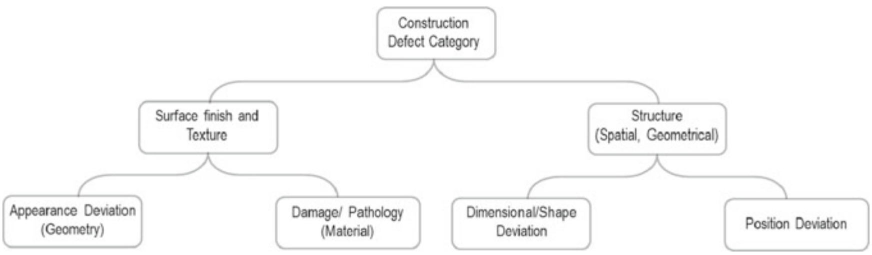


Fig. 2 Category of potential deviations and quality defects in construction site

Based on analysing our conducted interviews, construction quality guidelines and defects classification, we can categorize the quality defects into two main types:

1. Surface based defects (shown in Fig. 3): the defects that we can identify visually on the surface of the constructive element of which we can distinguish two subcategories:

   – Appearance deviations: these are errors committed during the installation or construction work, which leave a poor-quality appearance not conforming to the expected contractual requirements or the specifications required in the quality reference systems (e.g.: color or materials of the floor covering not compliant, wrong size of wall tiles, thickness of the brick joints not compliant, etc.).
   – Damage or surface pathology: these are physical defects impacting the visual and external aspect of the construction element (e.g., honeycombed surface, surface cracking, surface pitting, cold joints, surface holes, etc.)

2. Volume based defects (shown in Fig. 3): this is the category we will focus on. It contains two main sub-categories:

   – Dimensional/shape deviation: all the problems related to "3D Shape" issues of an element: errors in the thickness of a wall or a slab, errors in the section of column or beam, flatness or regularity errors.
   – Position deviation: all the problems related to XYZ position and orientation of the element – absolute or relative to other elements (e.g., horizontal deviation between load-bearing walls, vertical tilt of wall or columns) (Fig. 4).

In the rest of this section, we describe each type of the aforementioned defects with their technical specifications and relevant data in three main steps:

1. The first step of our process has been to analyse, for each family of elements all the relevant documents and guides highlighting the technical specifications in relation to European and world construction standards (see §3.2.1). During our analysis, we were able to select the relevant implementation rules and the recommended tolerance thresholds, which will serve as a reference base to qualify the construction elements and judge its compliance with the specified requirements.

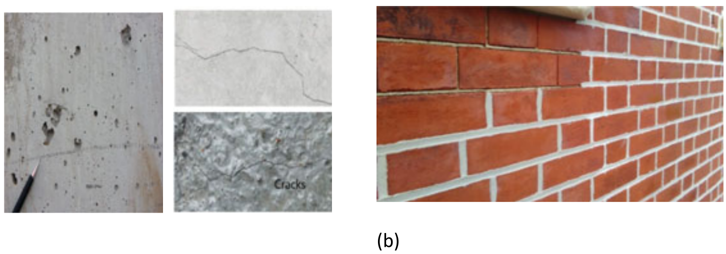


Fig. 3 Example on surface defects **a** Damage/surface pathology, **b** Appearance deviations

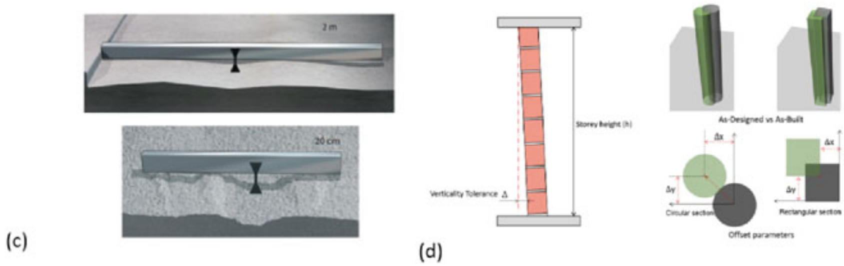


Fig. 4 Example on structural defects **c** Dimensional/shape deviation, **d** Position deviation

2. All the selected defects in the end user's approach have been analysed in a dynamic table using a multi-layer structure. The defects currently identified in this work, which are not exhaustive, mainly concerned 8 types of technical sets or disciplines, as follows:

   – Cast-in-place concrete structure
   – Masonry construction
   – Precast concrete structure
   – Electrical installation
   – Plumbing
   – Gas
   – HVAC
   – Thermal insulation

   Each defect is described by a set of attributes/properties, including its type (i.e., surface or structural), the construction elements concerned (e.g., wall, post, slab, window, staircase, etc.), the adapted control method, the corresponding control phase (e.g., before formwork), the frequency of occurrence of the defect on-site, its severity, the cause of the defect and the technicality (i.e., the complexity of carrying out the control of this type of defect on site) (see Fig. 1).
3. Each type of defect is referred to a dedicated data sheet. The latter contains all the required exchange information for the quality control system to be integrated into the digital twin platform. For example, the technical data sheet contains information about the defect thresholds (e.g., axis deviation for structural concrete elements is considered as a defect if > 15 mm), the detection method (e.g., as-built conditions to Standards limits Comparison), the required information in the as-built model and eventually the required information in the as-designed model (see Figs. 5 and 6).

Defect/Deviation name	Building component by Work Type				Defect category				Control Method			When should be performed ?		
					Surface		Structure							
	Cast-in-Place Structure Concrete	Structure (Precast- Concrete)	Masonry construction	Electrical, Plumbing, HVAC, Gas	Appearance Deviation	Damage/ or surface pathology	Dimensional/Shape Deviation	Position Deviation	As Built to As-Designed comparison	As-built to as-built comparison	As Built to specifications comparison	Before placing Formwork	After striking formwork	Before/After installation
Offsetting - Offset element (mismatch)	X	X	X					X	X			X		
Partially represented element	X	X	X					X	X			X		
Axis deviation	X	X	X				X			X	X	X	X	
Verticality deviation	X	X	X				X			X	X	X	X	
Planeness deviation (Flatness)	X	X	X				X				X	X	X	
Surface honeycombing	X					X			X				X	
Surface Cracking	X					X			X				X	
Surface Pitting (Pinholes, bugholes, blowholes)	X					X			X				X	
Visible lift lines and/or Cold Joints			X			X			X				X	
Reinforcement cover thickness deviation			X				X		X				X	
Main rebar/ Stirrups binding is non-compliant	X						X		X			X	X	
Incorrect rebar size/ quantity/ spacing/ No detail drawing	X							X	X			X	X	
Finished concrete surface are non-compliant	X	X			X				X				X	
Expansion joint/ Movement joint is inadequately placed	X				X						X		X	
Debris are left on the concrete surface	X				X						X		X	
Mortar Thickness joint Deviation			X		X						X			X
Mortar Joint Position Deviation			X		X						X			X
Height of equipment not in compliance				X				X			X			X
Minimum number of outlets not met				X				X			X			X
Minimum distance between networks not respected				X			X				X			X
Minimum depth of pipes not respected				X			X				X			X
....														

Fig. 5 Extract from the table summarizing the most common construction defects

3.2 Technical Requirements to Support Quality Control Process on Construction Site

In order to identify the main source of detected defects in the quality control process, it was first essential to analyse the various possible methods of comparison to detect any deviations (i.e., geometrical, spatial, surface or textural) between the elements built on site and their expected quality. According to our bibliographic research and field interviews with site operators, three methods of data comparison were identified according to the use case and the type of deviation/defect to be detected.

1. As-built to as-design comparisons (also called Scan-vs-BIM method); Specifications often require as-built to design comparisons. For example, the thickness of an existing cast-in-place concrete beam may need to be compared to its designed thickness. In these cases, design information needs to be extracted from the project model and serves as a baseline to which the as-built conditions are compared.
2. As-built to as-built comparisons; Some specifications may require the comparison of as-built information to other as-built information. For example, the height

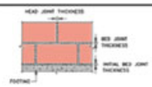
Evaluation indicator : Thickness Dimensions and Tolerances of Mortar Joint				
FEATURES		**DETAILS**		
Element category		Reinforced Masonry Construction		
Description		Generally, modifications in the thickness of mortar joints are the primary focus from aesthetic point of view but it could be the cause for bad performance of reinforced masonry structures. Masonry should be constructed within certain tolerances to ensure the strength and appearance of the masonry is not compromised.		
Standards limits (Construction specification)		**French Standards (DTU)**	**American Standards (ACI)**	**British standard**
		Mortar Joint thickness (t) according to the different reinforced masonry construction materials: • Aggregate concrete block: t =1cm -2 cm • Clay bricks: t = 1cm -2 cm • Autoclave cellular concrete block: t = 8 mm - 15 mm	Mortar Joint **thickness** with **Tolerances**: • Bed Joint thickness **BJ_t = 9.5 mm** (Δ = +/- 3.2 mm) • Head Joint thickness **HJ_t = 9.5 mm** (Δ =- 6.4 mm / +9.5mm) • Initial Bed Joint thickness **IBJ_t = 9.5 mm** (Δ =- 3.1 mm / +9.5mm)	The thickness of an individual bed joint **should** not vary from the average of any **eight successive joints** by more **than 5mm.**
Comparison Method		As-Built conditions to Standards limits Comparison		
Required informations for As-built model (Acquisition Information/Quality)		**Value**	**Format** (Texte, numérique, mixte)	**Unit** (M, Pa, L/Min)
Acquisition Properties	Acquisition devices	cameras/Laser scan	string	mm
	Acquisition locations	Scan side and position	string	mm
Acquisition Data Quality	Accuracy		float	
	Spatial resolution		float	N/A
	Other properties			N/A
Required Informations for As-Designed model (BIM/IFC Model)		**Value**	**Format** (Texte, numérique, mixte)	**Unit** (M, Pa, L/Min)
	Required building elements	Wall Type (masonry unit, mortar joint spacing), Wall Total Thickness, Wall Core Masonry Thickness, Wall Finish Face 1, Wall Finish Face 2, Block Type		
	Required LOD			
	IfcEntity	IfcWall		
	Requires non-geometric attributes	Materials specification, quality requirements (tolerances to mortar thickness)		
	Other properties	Images library		
Required informations from/to BIM2TWIN Platform		**Value**	**Format** (Texte, numérique, mixte)	**Unit** (M, Pa, L/Min)
Dimensions values from as-built model	Other dimensions (scale,....)		float	mm
Dimensions values from as-Designed model (Input)	Other dimensions		float	mm
Deviation value (Output)	Defect Type	Mortar Thickness	string	N/A
	Attributes	Delta BJ, Delta HJ (bed and head joint)	float	mm
		Affected Element	string	N/A

Fig. 6 Example of a data sheet with recommended requirements for assessing the quality of mortar joints on brick walls

of adjacent risers of built stairs may need to be compared, or the distance to already checked walls

3. Comparison of as-built conditions to specified limits; Specifications can require comparison of as-built information to specific values or limits, without comparing the as-built conditions to design. For example, the distances between rebars installed on a construction site may need to be compared to a specified minimum or maximum distance value rather than to a value obtained from the design. Specifications may refer to other specifications or specifications sets for example, construction specifications based on the ACI's "ACI 117 — Standard Specifications for Tolerances for Concrete Construction and Materials".

From this observation, we can deduce that the quality control process is mainly based on three types of data. The diagram below illustrates when these data are produced according to the construction phases (Fig. 7):

1. As-designed and as-planned data: they are considered as a reference of what should have been done and when during the construction process.
2. As-built data: they are acquired during the construction process, by different methods, in order to check the quality of built or already built element.
3. Specific data (or construction code data): they are generic "state of the art" rules coming from the construction codes and regulation. This data is not necessarily available in the as-designed or as-planned data.

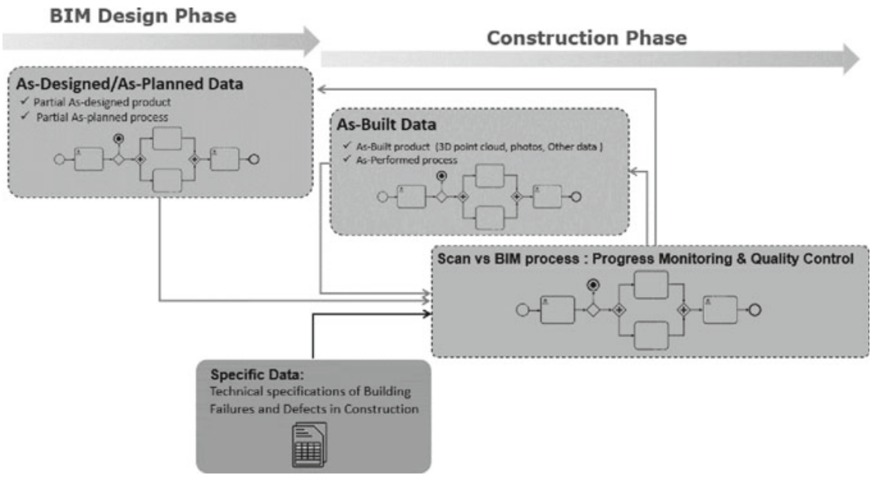


Fig. 7 The main data sources for the Control Quality process

3.2.1 As Built Data

The as-built data comprises all types of data and information acquired or reconstructed during the construction phase. Measurement data are obtained via automated or semi-automated acquisition techniques: (1) Image data (photos and video streams), (2) Point cloud data (via laser scanning or dense photogrammetry), as well as (3) Raw data from the embedded sensors (e.g., timestamped locations and poses of acquisition devices). Reconstructed data are obtained via conversion processes or inference from measurement data: (1) surfaces and volumes reconstructed from point clouds, and (2) semantic attributes inferred via machine learning methods applied to image and geometry data.

Depending on the type of building element and structural defect to be analysed, the assessment of progress and deviations will be based on certain types of analysis methods such as occupancy-based methods, appearance-based methods, inference of material as well as specific shape analysis methods. More specifically, occupancy-based methods infer progress for construction elements in a binary fashion, i.e., an element is observed or not. Appearance-based methods monitor progress by tracking visual changes, possibly by detecting image features and inferring materials from images. Shape analysis methods require converting the 3D point clouds and possibly image data into surfaces and volumes, before reasoning in terms of tolerancing metrology. This requires distinguishing between local and global geometric error metrics, while dealing with uncertainty such as noise or outliers, and missing data due to occlusions or incomplete measurements.

3.2.2 As-Designed Model/Data

Is the set of BIM data and models produced during the design phase, represented in the high-level process map by the collapsed sub-process [0] (See Sect. 4.2). The list below is a non-exhaustive list of graphical and non-graphical data that can be produced during this phase by the design team:

- Discipline-specific BIM Model: All discipline IFC models (Infrastructural, architectural, structural, electricity, plumbing, HVAC, …),
- 3D BIM model of the different interior/exterior building elements/equipment (e.g., MEP equipment's with the highest LOD),
- Element properties (Pset): Dataset with properties of a building element (e.g., material parameters of a concrete column, classification, …),
- Bill of Quantities (BoQ), also Specification: A tabular list of the individual work stages required to complete a particular construction task/service,
- As-planned schedule: construction process with element group/subset of model (e.g., model of the walls of a floor),
- 4D BIM Model: All 4D construction processes are linked to their associated elements, allowing for statements regarding the expected construction state at any given observation time. Furthermore, quality control of the building elements cannot be performed from geometric information exclusively. Consequently, properties such as material, discipline or position (interior/exterior) of single elements need to be evaluated during this process. These parameters are expressed by alphanumeric values which are assigned to the respective objects.

4 Digital Processes for an Automation of Quality Analysis on Construction Sites

4.1 State of the Art

To improve the manual process of quality control and defect inspection, it is necessary to have automatic control tools linked to an information system. The tool should allow inspectors and/or managers to perform their tasks as simply and efficiently as possible and detect any defects as early as possible.

Traditional methods make use of minor technical advancements like introducing email and tablet computers into the manual monitoring process. These methods still require manual work, but already contribute to the shift towards digitization [14]. More advanced methods try to track individual building components through radio frequency identification (RFID) tags or similar methods such as QR codes. Wang et al. [15] proposed a tele-inspection system based on augmented virtuality (AV) for defect detection and empirically compared with traditional photo-based methods. Dong et al. [16] presented a telematic digital workbench system for construction defect management, enabling to monitor collected site defect data through a mobile device and synchronize the location of visual information on the site with the 3D model as well.

Several BIM-based methods have also been developed in recent years [17]. Current state-of-the-art procedures apply vision-based methods for more reliable element identification. These methods either make direct use of photographs or videos taken on site as input for image recognition techniques or apply laser scanners or photogrammetric methods to create point clouds that hold point-based 3D information and additionally color information.

There are different types of quality defects, including geometric and surface defects. Research efforts have been put into describing the geometric properties of objects for detecting defects from point cloud data captured by laser scanners or photogrammetry [18, 19]. Several strategies have been put forth in the literature for object identification tasks. They are often divided into data-driven vs model-driven, local vs global descriptors, and other categories. Model-driven approaches require domain expertise to perform knowledge-based matching, but data-driven methods perform better for shape aspects of objects while statistically matching training data; they are unable to recognise objects with complicated geometry. Data-driven methods frequently fall short when applied to objects with primitive shapes (e.g., planar). This makes it difficult to distinguish objects that share characteristics, such as cabinets and doors [18]. On the other hand, a few studies, which blend scan-vs-BIM and scan-to-BIM, concentrate on the geometric updating of existing BIM objects throughout the construction and operation phases [20].

As discussed in the previous section about the recommended requirements for assessing the quality of some objects, including mortar joints on brick walls (shown in Fig. 6), it is expected that assessing the quality of each object requires the values from the design stage as well as tolerance requirements for each property. Overall, it is necessary to detect objects automatically from the captured point cloud and then extract geometric and surface descriptions that allow determining any quality issues or discrepancies between the built objects at the construction site and design specifications. In conclusion, in order to implement effective defect control and management, solutions to each problem must be integrated through a systems approach that considers the relationship between the defect information flow and the construction process. To this end, the following chapter will propose a framework for integrated defect management using state-of-the-art ICT to improve current defect management practices.

4.2 Technological Bricks and Processes

In the current state of the art, researchers and startup companies have taken a direct approach – identify a construction management problem, select one monitoring technology to provide data, and attempt to provide a valuable service. Yet this is severely limited, because the reliability of information inferred from a limited data stream is unreliable and inaccurate, and because the approach is not extensible nor scalable.

To address the challenges, a Digital Building Twin concept is proposed, targeting the development of a comprehensive, holistic solution for rapid and intelligent survey and assessment of construction quality and works progressing (Fig. 8).

As reported more in this document the Digital Twin concept is the subject of an EU research project named BIM2TWIN comprising seventeen professionals and academics partners specialized in the construction field. In the Building Digital Twin approach, various advanced remote sensing technologies are used to capture the state of a construction site rapidly and accurately in various digital formats (e.g., point cloud data, photo or video streams, QR Code, …).

The process is organised in two parts: design phase and construction phase. It consists of a logical chain of the collapsed sub-process which are individually expanded (see the following sections) with all the details concerning the tasks and activities as well as the corresponding data flow (i.e., input and output).

The first step takes place in the design phase and consists of producing all the design data (i.e., mainly as-designed product and as-planned process of the project) needed for the remaining tasks and sub-processes of the workflow. This process is to be carried out by the project design team. Selecting a target task (looped task): from the as-planned construction schedule, which list all construction task for all building elements with start and end date, the quality control process can be started by selecting a target task for which we want to perform the on-site inspection. This selection can be carried out, by the site quality manager (or the site defect manager), according to different criteria. For example, by following the control checklist provided by the construction company's inspection plan, or by simply targeting a construction task involving an important or sensitive building element for the rest of the construction works (e.g., foundation elements, load-bearing structural elements, …). This step allows to identify the list of building elements targeted by the quality control process as well as the other related elements. This affects the choice of the tool or technology to be used during inspection.

The second step (SUB-PROCESS [1]) generate the point cloud data representing the actual state of the construction project (i.e., as-built model corresponding to task Ti of the construction schedule at one particular observation time-point). Indeed, the quality control process of volumetric building elements is mainly based on volumetric point clouds obtained either directly through 3D scanning technologies or indirectly using photogrammetric techniques followed by a set of processing steps to generate a 3D point cloud from images/photos. The main output of this sub-process is the post-processed 3D point cloud representing the as-built model which will be compared with the corresponding as-deigned model.

The next step (SUB-PROCESS [2]) comprises a set of automatic and/or semi-automatic services that take as input data a post-processed point cloud as well as a 3D geometry of the as-designed model and generate as output a labelled point cloud.

The labelled point cloud is then (SUB-PROCESS [3] overlaid and compared with the corresponding state of the as-designed model to automatically find the list of discrepancies and deviations between the two models. Then the list of identified

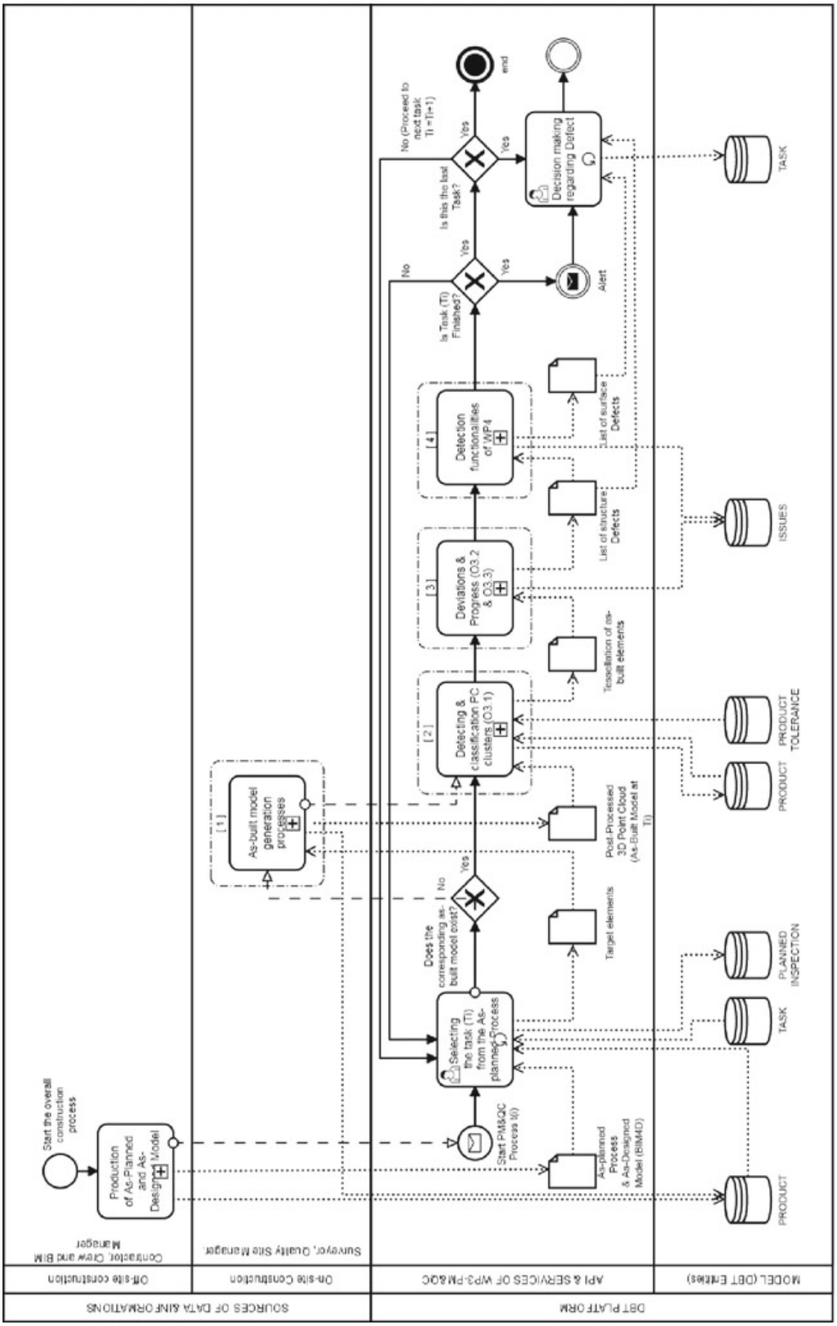


Fig. 8 High-level Process Map of the proposed Quality Control Process

deviations is used to perform further processing steps to evaluate the deviations and identify defects based on the actual quality requirements dictated by a construction project's specifications. If the found deviations violate any of the requirements stated in specifications, they constitute defects and hence need to be remedied.

The challenging part of this step is dealing with temporary works (e.g., formwork) and multi-layered objects (e.g., walls made of many material layers). Reasoning about the state of the object in these cases might not be enough using geometry data alone. For this reason, we aim to explore changes in visual textures as an additional step to ensure better performance. The sub-processes [1] to [4] are repeated in a loop until all the tasks of the project process are completed. The list of construction defects found at the end of each task is submitted to the involved decision makers. Depending on the severity of the defects, he will decide which actions should be undertaken to address the issue and update the planification accordingly.

The input data as well as the intermediate and final results of each sub-process are stored and archived in a project database specially designed for the quality control process and directly connected to the Central Digital Twin Platform.

5 Conclusions

Building element measurements as-built sometimes vary from those initially indicated in as-designed blueprints. To ensure the appropriate performance of objects and surface materials, all elements' dimensional tolerance and surface material should be examined across a multitude of historical digital twins' data during the quality control or assessment process. New doors are opening today with the storage of data resulting from the quality control process on the construction site thus digitized. Based on a deep understanding of users, of their needs and motivation, the digital twin can be optimized in data acquisition and analysis and proves to be very helpful especially in providing new proof of compliance, allowing the investigation of any performance defects observed after construction (particularly in the event of renovation) and the development of a new legal framework aimed at improving the monitoring of claims by insurers.

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Digital Twin-Based Automated Green Building Assessment Framework

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Abstract Accurate green building assessment (GBA) represents one of the best opportunities to understand the *holistic* sustainability strengths and weaknesses of *existing buildings* to inform their retrofitting decisions. However, the current process for GBA of existing buildings is very challenging, tedious, complex, time-consuming and costly, and suffers from lack of important data and information. Moreover, most GBA results are not leveraged to retrofit and improve the sustainability performance of existing buildings – they are mostly for just recognition and market edge. To address these limitations, this study aims to develop a framework for using Digital Twin (DT) technology to automate and improve GBA. Although unavailable *static* building data can be obtained from scan-to-building information modelling (BIM) process, real-time *dynamic* data cannot. Hence, real-time dynamic data from the internet of things (IoT) sensors and other data should be integrated into the BIM model to create the DT model of the building. A plug-in software can then be deployed to

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assess the sustainability performance level of the building within the DT environment automatically. The framework is based on the Building Environmental Assessment Method (BEAM) Plus, which is Hong Kong's leading GBA system. A *real* DT should feedback into the physical twin after receiving and processing data from it. Therefore, the automated GBA results should inform retrofitting decisions of the physical building. This study contributes to the understanding of how DT can be used to automate and improve GBA, and how the results can be used to improve retrofitting decision-making.

Keywords Digital Twin · Plug-in · Accurate Green Building Assessment · BEAM Plus · Existing Buildings · Retrofitting

1 Introduction

The world is in a *climate emergency*. Buildings are major consumers of energy accountable for nearly 40% of total global energy-related carbon emissions [45]. 75% of these are operational emissions resulting from energy use in the day-to-day running of *existing buildings*, while the rest remains embodied emissions associated with the materials, components, and processes used in new construction (World Green Building Council (WorldGBC), 2019). Decarbonizing (existing) buildings is thus one of the best ways to achieve sustainability. Moreover, buildings negatively impact people's health, wellbeing, and quality of life in countless ways. They cause air and water pollution, the biggest challenge for human health. The World Health Organization (WHO) has warned that 99% of world's population lives in areas with air pollution levels exceeding WHO thresholds [54]. In addition, materials and natural resources use, and waste generation in the whole building lifecycle are significant. For example, buildings are responsible for 50% of total global materials use [53]. To mitigate these impacts, various green building assessment (GBA) systems (BREEAM, LEED, etc.) have emerged worldwide as an important tool to assess, rate, and improve the sustainability performance of buildings.

However, GBA processes are very challenging, tedious, complex, time-consuming and costly [32]. Significant time and effort is required in collecting the massive amounts of data needed for the assessments. Many studies have also indicated that the computations, analyses, and interpretations of GBA results are ambiguous and sometimes even inaccurate [18, 47]. The current GBA processes for both new and existing buildings still rely on the conventional manual collection and documentation of *static* building data, which can be time-consuming, inefficient, inaccurate and thus unreliable. Another challenge specifically for the GBA of existing buildings is that its success depends on availability of accurate and required data enabling reliable modelling and assessment of the building [31]. There are almost always differences between *as-designed*, *as-built*, and *as-is* assets, but in most cases, these differences are largely overlooked [11], affecting the accuracy of the GBA. Appropriate and innovative methods are required to capture geometric data, and semantic and spectral data of materials for accurately modelling and assessing existing buildings. Furthermore, assessing and rating the sustainability performance of an existing building based on its historical performance data collected within a certain time period (usually one year) can be unreliable. Decisions made based on such GBA may be unrealistic in the context of *big* building data. *Dynamic* building data, for example, real-time measurements of energy consumption, indoor air temperature, humidity, luminance, CO_2, TVOC, $PM_{2.5}$, PM_{10}, occupancy, barometric pressure, HCHO/O_3, and other data, should be collected, analyzed, and used for GBA. This is because building performance is dynamic, changing constantly over time. The rating based on the previous year's (historical) data may not accurately reflect the performance of the building in the current and future years. As existing GBA systems are not equipped with dynamic and real-time configurations to fulfil this requirement, the current process suffers from lack of important data and information.

Previous studies have proposed frameworks to automate and improve the efficiency and accuracy of GBA processes through integration with building information modelling (BIM) leveraged to facilitate the assessment processes [16, 32, 51]. This scholarship has been comprehensively reviewed in [4]. However, they focused on the GBA for new buildings and ignored existing buildings, although the latter contribute to sustainability problems to a much greater extent. A key reason is that BIM provides designers with detailed information to compare the impacts of different sustainable solutions and to assess the sustainability of new buildings from the early design stage. But it is often difficult to use BIM in existing buildings because of major obstacles such as: (1) lack of BIM model, and (2) difficulties in obtaining real-time and accurate data of building operations and performance, and in extracting and assimilating semantic data [48]. Consequently, the static configuration of existing BIM-based automated GBA tools falls short of detecting and considering dynamic changes in building operational performance [43]. This limitation has led to the recent idea of shifting from the static to an automated, dynamic, real-time approach to assessing the sustainability of existing buildings [43]. However, this idea has not been sufficiently explored and generic frameworks are still very limited.

To address above limitations, this paper aims to provide a generic framework for Digital Twin (DT)-based automated, dynamic, real-time GBA of existing buildings. DT can empower a building model by integrating both static and dynamic data to create a *realistic* virtual representation of the physical existing building and provide rich configurations for automated GBA of the building. The framework is based on the Hong Kong Building Environmental Assessment Method (BEAM) Plus Existing buildings (EB) GBA system. The paper is organized as follows: BIM configurations for GBA are discussed, followed by scan-to-BIM process for as-is BIM model creation, real-time dynamic data collection via the internet of things (IoT) technology, DT applications in the buildings sector, and the proposed DT-based framework that integrates BEAM Plus to automate and improve GBA accuracy and efficiency.

2 BIM Configurations for GBA

BIM is the foundation of digital transformation in the buildings sector. It provides a centralized database for the automated GBA of a building [16]. But the data contained in a BIM model is *static* and does not benefit from *real-time* capability. GBA based on BIM-based building performance simulation results requires accurate and reliable data of the building. Usually, 2D drawings or data are used for creating the BIM model. However, for existing buildings with inaccurate, missing, or out-of-date data due to, for example, retrofitting or lack of BIM model, another method of obtaining building data is required. 3D laser scanning, photogrammetry, and geographic information systems (GIS) have been widely used to capture accurate geometric and materials spectral data and create as-is BIM models [26, 49]. Despite their usefulness, their application to improve GBA processes is still very lacking.

BIM-based GBA depends on effective data management, and interoperability between BIM software (e.g., Autodesk Revit) and building performance simulation tools [42]. Plug-in of a simulation engine into BIM software and the conversion of data through an open-source file format are widely used data conversion techniques enabling successful BIM implementation for GBA [26]. The use of open-source file formats, such as Industry Foundation Classes (IFC) and Green Building eXtensible Markup Language (gbXML), to transfer building data from BIM to a simulation tool was reported [15, 17]. Al Ka'bi [1] compared 10 of the most common building performance simulation tools suitable for GBA: Design Builder, IDA-ICE, IES-VE, EnergyPlus, TRNSYS, eQUEST, Autodesk Green Building Studio (GBS), Ecotect (discontinued in 2015, replaced by GBS), RIUSKA, and VIP-Energy. BIM-based thermal performance analysis required for GBA was explored by Liu et al. [27], while computational fluid dynamics simulations were used to evaluate wind velocity and pressure in sustainability assessment standards based on BIM-based geometries [55].

These building performance simulations are designed for specific purposes, with limited potential for customization. Moreover, a BIM model does not contain all the data required for *complete* GBA. Such data (geospatial, management, asset attributes, and real-time asset performance and utilization data) should be integrated from other sources. For seamless data integration, management and analysis for BIM-based automated GBA, researchers have developed programs within the Revit API using programming languages, such as C# [7]. Dynamo and Grasshopper are two commonly used visual programming APIs with BIM [22].

Although current BIM configurations, such as modeling, simulating and analyzing, enhance the efficiency and quality of GBA at the design stage of new buildings based on static data, they are limited when it comes to existing buildings in operation stage. First, existing buildings may change in their design and conditions when retrofitting works are performed and the as-designed and as-built BIM models become less useful for the GBA. Second, most existing buildings do not have BIM model. Third, the performance of existing buildings changes over time and current BIM-based automated GBA frameworks/systems are limited in their inability to monitor and understand such performance for better GBA. Scan-to-BIM and IoT technologies provide an effective solution for monitoring and understanding the static and dynamic building performance – a necessity for accurate and effective GBA of existing buildings.

3 Scan-To-BIM

For accurate and effective automated GBA of existing buildings, it is necessary to have accurate as-is (not as-designed or as-built) BIM models of the buildings. The as-is BIM modeled by scan-to-BIM process has been widely used in many applications in the buildings sector [49], but with scarce application in GBA specifically. Feeding data of the existing building captured by an accurate method is the basic principle of as-is BIM [48]. The as-is BIM model should act as an accurate 3D virtual representation of the existing building, containing geometric and semantic data of building elements. Although photogrammetry and GIS are more affordable, 3D laser scanning is the most accurate and fastest method for geometric data acquisition [26]. Digital cameras and laser scanners can collect 3D point cloud data (3D-PCD), the most popular type of 3D data used to model as-is BIM. However, integrating laser scanning and photogrammetry is recommended to generate complete and accurate geometrically and semantically rich as-is BIM model [50]. While data acquisition by conventional RGB camera is quick, the quality of the color is affected by the image-capturing environment. Data captured by hyperspectral imaging method on each pixel can therefore be used in a detailed analysis to attain accurate identification of objects and materials against various environmental exposures [3].

Regardless of the acquisition method, 3D-PCD and images should be preprocessed prior to the as-is BIM modeling. Preprocessing includes data cleaning and registration [46]. Upon images and 3D-PCD integration, semantic segmentation and object recognition is conducted to create semantically rich BIM objects and their interconnections. These BIM objects can be verified against data obtained from facilities management (FM). The as-is BIM model created from the scan-to-BIM process forms the foundation for the DT used for the automated and improved GBA.

4 IoT

IoT is an emerging technology where many devices are linked via the internet to share data. Its architecture is capable of sensing the environment, automatic collection of real-time data and transmitting that data to back-end server to derive analytics [25]. Hence, a BIM model containing only static data can be modernized with dynamic data collected via IoT sensors [44]. This dynamic data collection can also be visualized in the BIM model in relation to sensor locations in the physical building to obtain real-time *status* of the building [2]. Accordingly, there are various applications of BIM-IoT integration in building energy management, such as real-time visualization of energy use [24], and representing measured energy use data in BIM using color-coding [12].

BIM-IoT-based monitoring framework for providing a comprehensive view of the status of buildings [21] and human-activity simulator to evaluate activity-recognition methods for indoor environments [56] are examples of BIM-IoT integration for monitoring building indoor environment. Monitoring air comfort ensures that airborne contaminants do not give rise to unacceptable levels of indoor air pollution in normally occupied spaces. To reduce health and safety hazards, [35] developed a prototype that collects real-time temperature and oxygen data using BIM-IoT. Furthermore, [8] and [34] developed frameworks to achieve colorful visualization of indoor temperature, humidity, and thermal comfort in BIM models, with real-time sensor data. BIM-IoT integration has been used for many applications in the buildings sector. But its use for providing dynamic configurations for GBA is rare.

The applications of BIM-IoT denotes its capability of delivering a comprehensive view of the building status by collecting and analyzing big building data. However, this integration does not provide, for example, geospatial data necessary to assess site location-related credits, for example, in GBA. Predictive models can be developed using big data analysis techniques such as machine learning and data mining to shorten GBA time [33]. Implementing these technologies in a collaborative environment with various interdependencies among stakeholders can lead to security concerns [29]. Furthermore, the success of GBA for existing buildings rests on maintaining real-time connection between physical assets to inform their retrofitting decisions by identifying the building's strengths and weaknesses. A higher level of digital technology – DT – which is equipped with more data and allows for higher connectivity and security is therefore introduced for automated, dynamic, real-time configuration of GBA.

5 DT

A DT is a *realistic dynamic* virtual model of a physical object, system, environment, or process (physical twin). It responds and behaves like its physical twin. The concept was first born in aerospace field for NASA's Apollo program. Generally, the term is linked to smart manufacturing and industry 4.0 [40]. But quite recently, DT has received significant attention in the buildings sector. A key challenge for DT application in this sector however is that the meaning and benefits of DT itself are not well understood. Many researchers and practitioners naively and simply equate DT to mere static BIM models produced in design and construction [36]. Others perceive DT as the mere integration of BIM models (containing only geometric and semantic data of materials) with IoT sensor data to generate insights by analysis and simulation. According to the "Data Leadership Guidance Note – Digital Twin" powered by the Smart Cities Council Australia New Zealand, as a minimum, a DT model must ingest geometric and graphical data, geospatial reference data, asset attributes (natural, physical, social, economic), management data, and real-time asset performance and utilization data (Smart Cities Council Australia New [39]. Moreover, DT must provide the following five capabilities: (1) maintaining two-way live *connection* between the virtual and physical building; (2) *integrating data* from various sources via various digital technologies to derive meaningful information for users; (3) *visualizing* the real-time data across the whole project and asset operation lifecycle; (4) *analyzing* (and or processing, modelling and simulating) the "federated data" sets to fulfill business objectives; and (5) *securing* the data and information by applying relevant technical security and privacy standards. A summary of some relevant previous studies applying DT in the buildings sector is provided in Table 1.

Clearly, studies that explore the potential and application of DT in GBA of existing buildings are few. This paper presents a framework for applying DT to automate and

Table 1 DT applications in the buildings sector

Studies	Application	Project Description
[30]	DT-based simulation method for designing thermal system that can be integrated in lightweight roof structures	High resolution analysis was used for initial product development. Complex geometry model takes actual roof geometry and uses scripting to automate interaction with the thermal systems. A reduced resolution method was used to add characteristics of the system to an industry standard whole building simulation model. Operational sensor data was utilized later in the product lifecycle
[23]	DT-based building life cycle management framework for building facade and building interior	A wireless sensor network (WSN) was installed on the building facade of an office building to collect real-time data. Collected sensor data were integrated with BIM data to create DT
[43]	DT-based building sustainability assessment	BIM model was developed based upon project information model created in the design stage. IoT sensors measured indoor air quality and outdoor environmental conditions. Feedback about perceived comfort were collected from building users. Total energy provided by charging station was constantly monitored by a smart meter. Real-time data fed DT of the building, which can be used to estimate current sustainability level
[38]	DT-based lighting energy saving strategies assessment for university buildings	DT was created by integrating data from the physical building and database defining occupants, operation scenarios, and field measurement data. Energy consumption patterns were analyzed, with energy saving strategies proposed

Note: studies that were based on BIM models (e.g., [19, 20] but (naively) claiming to be based on DT are excluded improve GBA accuracy and efficiency, discussing the match-up between GBA and the functionalities provided by DT.

6 BEAM Plus

BEAM Plus is Hong Kong's leading GBA system [13]. It offers a comprehensive set of performance criteria for a wide range of sustainability parameters across the whole lifecycle of buildings. It includes the six types, BEAM Plus New Buildings (NB), BEAM Plus New Data Centres (NDC), BEAM Plus Existing Buildings (EB), BEAM Plus Existing Data Centres (EDC), BEAM Plus Interiors (BI), and BEAM Plus Neighborhood (ND) [14]. The proposed DT-based automated GBA framework is based on the BEAM Plus EB, which assesses the sustainability performance of the management, operation, and maintenance of existing buildings. Moreover, BEAM Plus EB assesses all ages and types of existing buildings, including commercial buildings, residential buildings, industrial buildings, etc. [13]. Building assessment is made under the seven performance categories of Management (MAN); Site Aspects (SA); Materials and Waste Aspects (MWA); Energy Use (EU); Water Use (WU); Indoor Environmental Quality (IEQ); and Innovations and Additions (IA). Each category contains sustainability performance criteria which the building being assessed must fulfil to achieve applicable and bonus credits. Based on the number of credits achieved, the building may be certified as Platinum (75 + credits achieved), Gold (65–74), Silver (55–64) or Bronze (40–54), to reflect the overall sustainability performance.

There are over 42,000 existing buildings in Hong Kong, most of which are over 30 years old [28]. In the private sector alone, there are over 9,000 buildings aged over 50 years old (Development [10]. It is important to encourage building owners, especially those in the private sector, to retrofit buildings and adopt green building management, operation, and maintenance, which can help achieve *Net Zero* targets by 2050, creating more sustainable built environments for people. Thus, providing a more accurate, efficient, effective, and technology- and data-driven GBA for existing buildings is critical.

7 Proposed DT-Based Automated GBA Framework

As illustrated in Fig. 1, the proposed DT-based automated GBA framework is implemented in four main steps, including (1) as-is BIM model creation, (2) dynamic building data collection, (3) DT model creation, and (4) BEAM Plus EB assessment using DT. In the following subsections, the four steps and their relationships are described to give an overview of the methods and tools to automate and improve the accuracy and efficiency of GBA of existing buildings using DT technology.

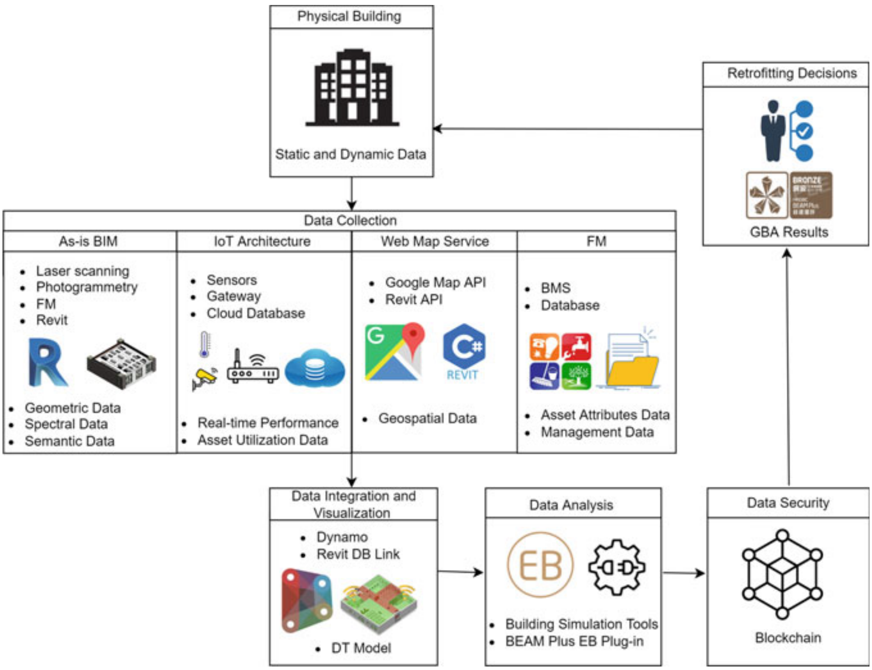

Fig. 1 DT-based automated, dynamic, real-time GBA framework

7.1 As-Is BIM Model Creation

First, an *accurate* as-is BIM model of the building must be created. Figure 2 illustrates the as-is BIM model creation process. We propose the use of an integrated laser scanning-photogrammetry approach for more accurate geometric data acquisition. However, GBA requires detailed modeling with materials properties (semantic information of materials). The required semantic information could be obtained from pre-existing (specifications and building materials) information about the building. Such information may be obtained from the FM office (Case-I) and/or by processing image data from independent imaging systems (Case-II). Hence, more accurate hyperspectral image data captured concurrently with laser scanning can be integrated into 3D-PCD where no pre-existing information from FM office is available. Specifically, Case-II is recommended where the building has missing (pre-existing) information, which may be the case for many (older) existing buildings.

It is significant to convert geometric and semantic data to information to create *objects*. Geometric data captured from laser scanning can be converted to geometric information by data cleaning and registration process. In Case-I scenario, geometric information can be integrated with specifications and building materials information obtained from FM office to create objects. In Case-II, geometric information integrates with semantic information obtained from cleaning and registering image data

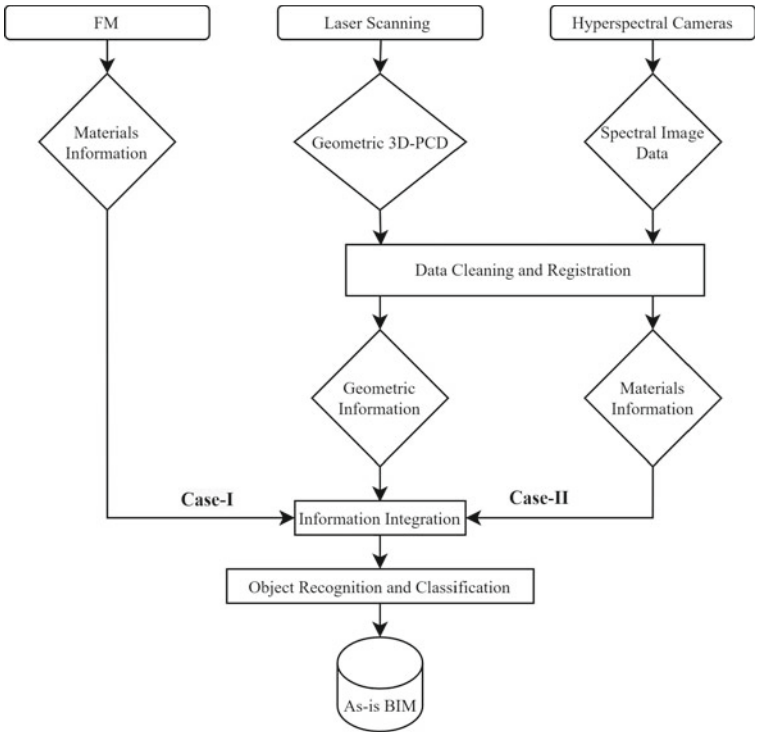

Fig. 2 As-is BIM model creation process

to create objects. 3D representations can be created in BIM upon *recognizing* and *classifying* objects to create a precise and complete as-is BIM model of the building. In our exploration of the scan-to-BIM approach for creating as-is BIM model (Fig. 3), we used the FARO Focus Premium Laser Scanner to scan a classroom building at The Hong Kong Polytechnic University. Focus Premium is the newest, most accurate, fastest, and most data-sharing-enabled scanner on the market today, featuring entirely new components with a proven design [12]. The resulting 3D-PCD was processed in both Autodesk Revit and ReCap and used to create accurate as-is BIM model of the building in Revit.

7.2 Dynamic Building Data Collection

Time-series and/or real-time data can be collected by IoT sensors installed in the physical building to measure all required parameters (environmental, energy, etc.). Microcontrollers and gateways are middle-tier components that primarily collect data from the sensors. These components can be deployed not only for data collection

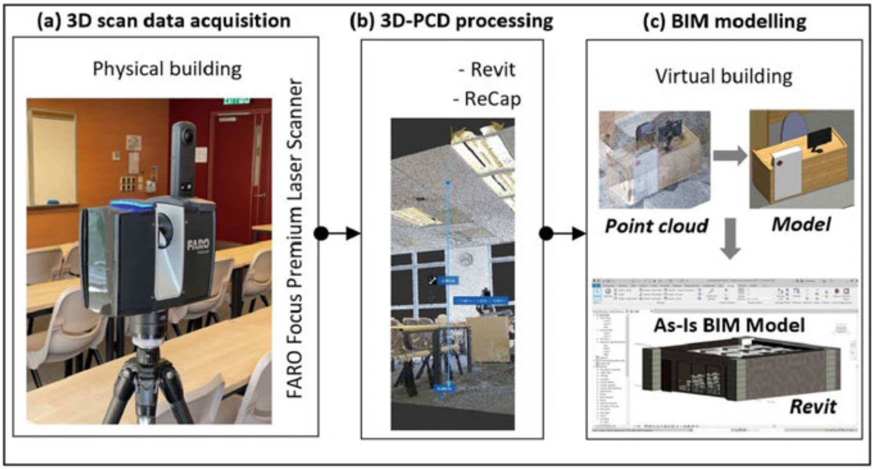

Fig. 3 As-is BIM model creation process of a university classroom building

and transmission to cloud database, but also for data aggregation and summarization. The cloud database serves as a repository for data sent from the microcontrollers and gateways. Choosing between network connectivity options for IoT deployment depends on the requirements/goal of the project. Among various network options, such as LoRa, Wi-Fi, Zigbee, and BLE, LoRa is recommended for meeting low power and long range communication requirements.

The locations of the IoT devices in the physical building should be indicated in the BIM model. [37] created a unique family for sensors in the as-is BIM model, which are described with alphanumeric IDs and green building properties corresponding to the locations of the sensors in the physical building. In exploring the IoT deployment for dynamic environmental data collection for automated GBA of the classroom building, we used three Milesight AM307 LoRaWAN Sensors and Milesight UG65 LoRaWAN Gateway (Fig. 4). AM307 is an integrated "7-Sensors-in-1" sensor measuring temperature, humidity, CO_2, PIR, light, TVOC, and barometric pressure. Smart meters and smart portable sockets, such as Milesight Smart WS52x LoRaWAN Portable Socket, can also be used to collect energy consumption data. We then developed dashboards using ThingsBoard IoT platform to visualize the sensor data.

7.3 DT Model Creation

The next step is to integrate all data required to create the DT model of the building: (1) as-is BIM model (Sect. 7.1); (2) IoT sensor data (7.2); (3) geospatial data; (4)

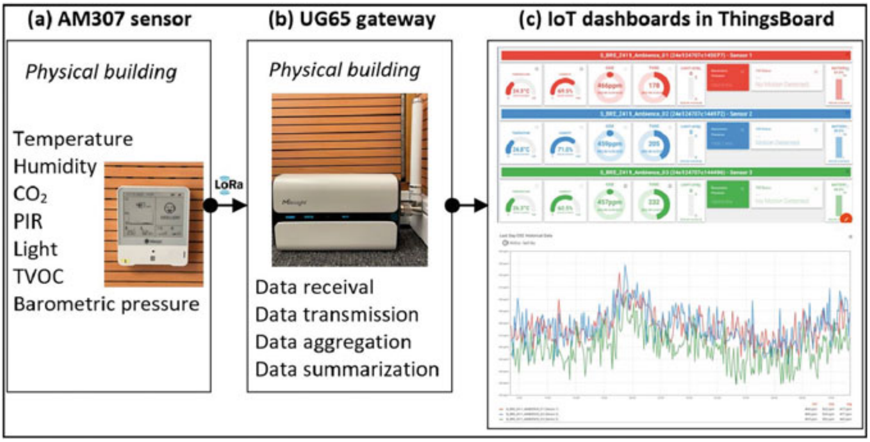

Fig. 4 Dynamic environmental data collection of a university classroom building

asset attributes data; and (5) management data of the building. [44] reviewed BIM-IoT integration and highlighted the lack of cloud-based approaches. Autodesk Forge helps to fill this gap by providing a cloud-based platform for BIM-IoT data integration [6]. The Forge viewer is equipped with IoT toolkit that can remotely integrate with any number of sensors and report any captured data in real-time in the viewer, where the data is displayed in BIM model. However, there are limited number of building performance simulations that can be run within Forge, and the feasibility of developing a specialized plug-in to automate GBA within Forge has yet to be explored. Hence, Dynamo is recommended for integrating the IoT sensor data into the as-is BIM model [8]. Any other performance-related data of the building, such as energy data from Building Management System, can also be integrated into the model using Autodesk Revit DB Link [5]. As mentioned earlier, geospatial reference data is essential for both DT and GBA. Therefore, Google Maps API can be integrated with Revit API using C# [9]. Integrating all the necessary data input leads to the DT model of the building.

This DT model is an integration of cutting-edge digital technologies, such as BIM, IoT and GIS, and involves big data for processing AI and machine learning functions. The fusion of all these technologies and the live connection with the physical twin and its stakeholders create significant security threats [41]. Blockchain (BC) technology can be integrated to guarantee "data security" of the DT. [33] proposed the use of BC capabilities such as traceability and efficiency to verify the certificates issued for Green Star – New Zealand. By integrating BC, the DT-based automated GBA information can be shared/stored in a traceable manner for making green building certification and retrofitting decisions on the physical building.

7.4 BEAM Plus EB Assessment Using DT

To achieve the automated, dynamic, real-time approach to GBA, the knowledge in the seven performance categories of BEAM Plus EB (see Sect. 6) should be embedded into the DT model. Then, a sustainability assessing plug-in software can be deployed to assess the BEAM Plus EB credits of the building within the DT environment automatically. GBA plug-in software can be developed using C# [16]. This plug-in should be equipped with toolkit for linking building performance simulation and analysis tools required for the GBA. The materials-related information and quantities required for MWA credits can be calculated using the materials takeoff function in the DT model. Various building performance simulation tools, such as GBS and IESVE, can be used to assess the data required for EU and WU credits. The entire process of data exchange between these building performance analysis tools and the DT model can be automated using the developed plug-in software. The real-time sensor data and geospatial data visualized in the DT can be linked to the plug-in software to assess IEQ and SA credits. Furthermore, FM data required for MAN credits can be easily extracted from the DT. In addition, information on green technology, practice, and their benefits required for IA credits can also be delivered by the DT. A user interface (UI) for the plug-in software can be developed using the same C#. This UI not only automatically reports the overall BEAM Plus EB sustainability performance level of the building: Platinum, Gold, Silver, or Bronze. It also automatically generates the assessment reports and measures to retrofit and improve the performance of the building to achieve the desired or highest level of sustainability performance or BEAM Plus rating.

8 Conclusions and Recommendations

This study developed a framework for using DT technology to automate and improve GBA accuracy and efficiency in existing buildings. The framework consists of four main steps: as-is BIM model creation, dynamic building data collection, DT model creation, and BEAM Plus EB assessment using the created DT model. In this paper, the four steps and their relationships were described. The study contributes to the understanding of how DT can be used to automate and improve GBA, and how the results can be used to improve retrofitting decision-making. If the DT-based automated GBA results are satisfactory, then the building may directly pursue the green building rating. Otherwise, the GBA results should inform retrofitting/improvement decisions/needs of the building. The study would be useful to building owners, occupiers, facility managers, green building councils, and other key stakeholders, such as governments, pursuing and promoting GBA and rating.

Despite the contributions, some limitations exist. First, the framework was only partially implemented and demonstrated. Further research focuses on full implementation and demonstration. Moreover, the framework is based on BEAM Plus, which may be different from other GBA systems. Further studies can tailor it to other GBA systems. Merging the potentials of big data analytics and DT would improve the GBA process while reducing human effort requirement and process expenses. Future studies could develop a process flow for big data analytics within DT for GBA.

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Automatically Quantifying Movement of Prefabricated Building Components on Site for a Location-Based Management System: An Ecosystem for Digital Twin Construction

Fabiano Correa, Alex Maciel Roda, and Sergio Scheer

Abstract With the increasing availability of equipment to automatically monitor on-site construction, construction management should change considerably in the future. A data-driven construction management should be a system which receives periodically data from the field, reasons over construction information present on BIM models, and has a representation of the possible outcomes based on input data / information. Such scenario is one of the uses of Digital Twins for Construction. Instead of instrumenting the construction site, one option is to create "smart building components", by attaching to each one of them an IoT device which will report their own state over time. Analyzing patterns on data from IMU and RSSI, as well as GPS when on open field, it is possible to identify and quantify movement and waiting times, as well as the precise moment in which a component installation happened – a micro-management more akin to Lean Construction. Although simplistically, this representation could be a prototype for a Discrete Event Simulation (DES). Construction progress monitoring thus become an automatic and remote process that could send signals and drive a representation of the process itself. Employing Location-Based Management System and Building Information Modeling, we create an ecosystem that takes advantage of the IoT solution to register and inform the decision makers over construction progress, allowing management of resources to remain on time and on budget with the advance of construction. In this paper experiments in real environments are presented with the automatic progress report of framing installation in the façade of a building.

Keywords Digital twin · BIM · IoT · Lean construction

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1 Introduction

With the increasing availability of equipment to automatically monitor on-site construction, construction management should change considerably in the future, even when compared to state-of-the-art management done based on Building Information Modeling (BIM) practices.

Common BIM software tools and current processes were not developed to deal with automatic and frequent data acquisition / insertion, or more specifically with the *amount of data in volume, velocity and variety* which could come from IoT (*Internet of Things*) systems and are incompatible for unassisted human processing – although previous research explored this possibility [1]. Instead of envisioning how BIM practices and tools could evolve in the near future to cope with and encompass data-driven approaches, one could more promptly rely on the technology of Digital Twins (DTs) [2].

A data-driven construction management system would receive periodically data from the field, reasons over construction information present on BIM models and had a representation of the possible outcomes based on input data / information. Such scenario is one of the uses of DTs for Construction, to deal not with the product itself (mimicking the behavior of the building), but with production processes – the different production activities happening simultaneously and continually to construct the built environment.

Many challenges do exist in implementing DTs of a construction site, such as: 1) Automatic monitoring system; 2) Digital Twin representation or model; 3) "Running" or simulating the Digital Twin for a specific task, such as production management, to name a few [3]. Besides that, one should consider the scale of such computational representation, as potentially each production activity would demand a different implementation (for monitoring, representing, and simulating or evaluating), and as such, there would be additional integration problems to solve with subsequent combination of DTs in some hierarchical architecture [4].

Regardless of the availability of equipment and sensors to monitor production activities, it is hardly the case that one solution would fit all kind of activities: cameras should be the more general choice to multiple tasks, although they would demand more computational resources. Also, the scale of the construction site and of the quantity of teams of workers should not be underestimated, because some solutions scale with the size of the space being monitored, because of sensor's range of "view", or with quantities monitored – be it a unit for tracking, or because of communication channels.

Among alternatives in implementing automatic monitoring, instead of instrumenting the construction site, one option is to create "smart building components", by attaching to each one of them one IoT device which will report their own state over time. Such smart component could add value to product lifecycle management, reporting when it was fabricated, stored, transported to construction site, and so on – and indirectly it could also report construction site progress, depending on the sensors available to it.

In the context of a Federal Government initiative in Brazil to promote competitivity in the Construction Sector, a prototype of the Digital Twin with smart building components was developed and tested in real scenarios. In the following sections, a brief review of state-of-the-art research on Digital Twins on Construction will be presented, along with details of Digital Twin experiment with an IoT- and BIM-based smart buildings components.

2 Digital Twinning Construction Sites

Digital Twins are digital representations or models of physical assets. With such general definition, especially considering the importance and increasing adoption of Building Information Modeling (BIM) processes in Architecture, Engineering, Construction and Operation (AECO) sector, one has the impression that both could be the same.

Although there is not consensus in the scientific community around what, exactly, should be a digital twin in the Construction sector, and what are the differences between it and BIM models, one definition is of particular importance for emphasizing the role simulation can have in DTs, and main benefits of employing such technology: "The digital twin concept, however, is strongly related to IoT and combines the digital representations with intelligent connections such as algorithms and simulations to consolidate the enormous amount of information and data from different sub-systems and to make dynamic and real-time decisions" [5].

Digital Twins were first conceived in the Manufacturing sector, and they could be employed during: 1) *Design phase*, where simulation with CAE systems helps teams evaluate and chose alternatives based on performance; 2) *Production phase*, mirroring production lines and eventually robotic cells simulated faithfully; 3) *Operation phase*, where the product itself could send data from embedded or attached sensors to provide more accurately the situation of real objects in real environments.

Beyond differences in DT implementations based on what is being twinned, there is also differences in the complexity of the use or the type of simulation which it is capable of running. Table 1 illustrates nine different configurations or possibilities for DT implementation, where one configuration is clearly the most adequate for twinning construction sites.

As construction sites are very dynamic, with many layout changes as buildings are erected, and also with the majority of activities being conducted by teams of construction workers instead of machines and robots, right now the more relevant configuration for construction sector would be a *Lighweight digital twins*. In that scenario, IoT systems (for automatic monitoring of actitivities) become the most important part of the Digital Twin as their results could compose a dashboard of production metrics or provide data from further analysis and facilitate decision-making processes.

Table 1 Classification of Digital Twins, adapted from [5]

	Complexity		
Applications	*Lightweight digital twins*	*Multi-physics, multi-scale simulation systems*	*Autonomous systems*
Simulation in the development			
Operation of products and systems	X		
Product life-cycle management			

The information generated from automatic monitoring systems should be due processed and employed in decision-making system to be of value for construction management [5]. In this regard, it is essential to employ a compatible management system to take advantage of the data-driven opportunity leveraged by the IoT / DT implementation previously discussed. Koskela [6] was a pioneer in adapting and studying how Lean Production, developed on Toyota for automobiles, could be applied to Construction.

For the development of one IoT system for monitoring, inside a Digital Twin Ecosystem, one important point is how to consider tasks and activities on the field, as represented in Fig. 1. In the lean approach, different stages, such as "Moving" and "Waiting" are characterized and included in control and management systems, stages which could be identified in the data history of sensors.

Many years of development brought LBMS (Location-based Management Systems) [7] with software support to plan and control on site construction for repetitive activities, trying to balance activities flow.

The direct inspiration for Digital Twinning Construction Sites is DTs of factories, which already has many implementations. For that matter, such implementation aims to provide a planning tool to evaluate changes in layout, or exchange machines and robots, and simulating production without stopping the plant, and avoiding minimal disruption of activities, until all details are decided.

Most of the benefits of a Digital Twin for construction sites should come with the capability to simulate its "dynamics" – its changes through time and progression of fronts of work. It could be as simple as a mapping of sequential activities in a

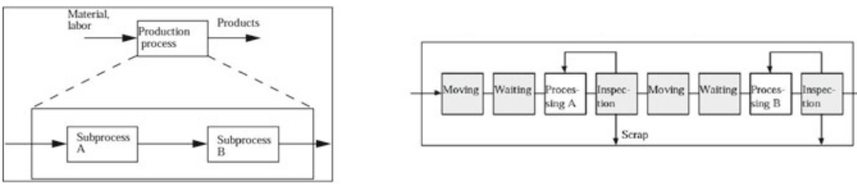


Fig. 1 Comparison between traditional and lean view of construction activities (Adapted from [6])

diagram such as BPMN with historic productivity rates indicating mean transition times, or more advanced such as discrete event simulation or agent-based simulation considering space restrictions on a BIM model of the field. The tradeoff between benefits and implementation and operation costs of such approach for a construction site are still to be properly analyzed.

With a lightweight DT in mind, one possibility would be the monitoring system continually providing data that should be aggregated based on 4D BIM models elaborated with software tools implementing Location-based system (LBS) features, such as Vico Office. LBS seems to be totally relevant in this context where, for instance, one is tracking a repetitive task – in that case, installation of frames in the facades of the entire building, and each façade is a different location for the system, with such locations being identified automatically from the IoT system. So, sensors that could provide location on construction sites and / or inside buildings would be a necessity.

Among applications found in the literature, there are examples for construction site twinning, creating digital twins for bulk silos by means of Decision Support System (DSS) [5], evaluating the role of LoD in 4D/5D BIM models of construction sites [8], integrating VR in BIM models on sites [9], and conceiving digital twin for safety management [10–13], among others in the most recent research on the subject.

3 Framework for Digital Twin Construction

When opportunity arose to demonstrate how IoT technology could be integrated with BIM models in real environments for control and management on construction sites, for a *Brazilian Federal Government* initiative, an entirely new approach needed to be developed, and a deployment strategy was planned and negotiated with construction companies in a small-time frame.

The experiments were planned to evaluate only the IoT system in real conditions, on construction sites, with minimal local resources (only one point for electricity and another for wired internet for the gateway on the engineer's room). To work with LoRa (*Long Range*) communication technology was appealing for the scale of the construction site. Commercial IoT devices where tested, and a schedule to track frame installation for the façade of a specific building, agreed. With a reduced team responsible for development, the conceived framework should consider minimal code and more configuration of available web services.

Also, as plans and development were done in parallel with negotiations with construction companies, and minimal input, involvement, and learning of the inner workings of the proposed system by engineers and worker on the sites, such context minimized the potential innovation in the actual management process.

In the Fig. 2, the conception and implementation of the solution is divided in different modules. The proposed framework consists of IoT systems, smart building components itself, and a management system that re-plan construction activities

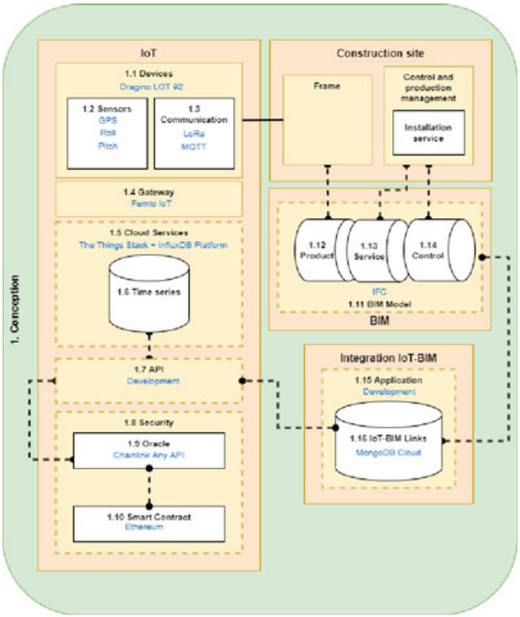


Fig. 2 Framework for monitoring system with IoT technology

based on current performance. This article would detail only the IoT system, and the blockchain module will be briefly mentioned.

What should distinguish the proposed framework from most found in the recent literature is the approach to, instead of instrumenting construction sites, instrument prefabricated building components, making them smart. The installed device and its sensors should be able to characterize waiting and movement times, and the moment when building components are installed, and the service is finished, and prepared for quality inspection. The main disadvantage is that it scales linearly with the amount of building components needed to track – although in the future, one hopes that costs of devices will continue to fall, and the technology do develop so devices shrink and consumes less energy per data sent.

3.1 Smart Building Components and IoT Systems

The main idea behind the developed IoT system was that it would be possible to analyze patterns on data from different sensors and correlate it to different stages or states of the building component throughout the process of it arriving at the construction site and it being installed in the building. Some sensors, like IMU (*Inertial Measurement Unit*), or signals, like RSSI (*Received Signal Strength Indication*), as well as GPS (*Global Positioning System*) data when on open field, allows in principle the identification and quantification of movement and waiting times, as well as the precise moment in which a component installation happened.

This is an approach that will obtain more data about progress of construction activities on the field, and automatically. Such approach could be likened to a micro-management more akin to Lean Construction. Micro-management approach is the first important aspect to plan and implement in the IoT System, because the amount of data sent to the cloud should be compatible with both the velocity of the (indirectly) monitored activities but also with management decision making processes. Gathering more data than needed could make applications more expensive (paid cloud services is based on data amount and flow rate, for example), or overloading engineers – for this experiment, only one activity is being monitored, but there are dozens occurring simultaneously, and hundreds or thousands throughout building construction.

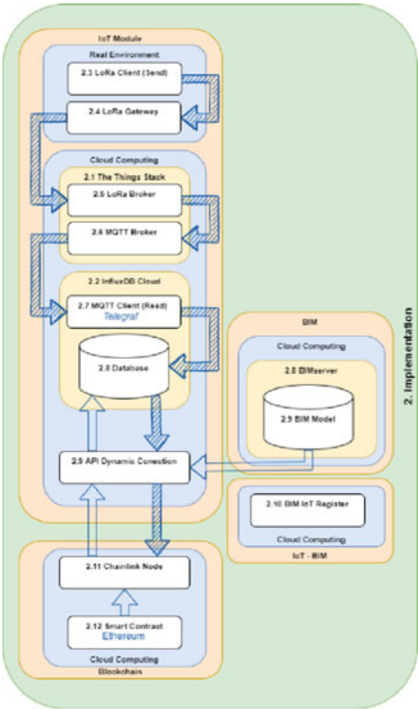
The implementation of the IoT Systems, and the data flow between the device and cloud computing services and applications are illustrated in Fig. 3. Frames receive, upon entering the construction site, each a GPS tracking device which communicates via LoRa (Long Range). A LoRa server (*The Things Stack*) is used to receive data on the cloud from the components and transfers it internally to a MQTT (*Message Queuing Telemetry Transport*) Broker. Further communications are done through the MQTT Broker and clients – a client (*Telegraf*) from a time series database (*InfluxDB*) is used to read data from the cloud and to store it in a database for further processing. An API is queried over the hard-coded pattern that identifies current state of each frame on site.

Although for the activities dealt in the experiments the signal pattern was easy to grasp visually, for different building components and for different processes of storage and installation, the number of different sensors / signals should make patterns recognition a challenge. However, data from construction process tasks could also be used in Machine Learning algorithms to find more complex or non-obvious patterns – and makes pattern identification more robust and less prone to misidentification or errors.

Designing the construction process as a sequence of timed events, the transitions between states of the process could then be directed by the IoT system. Although simplistically, this representation could be a prototype for a Discrete Event Simulation (DES). Further exploring how Schedule and Tasks represented in IFC schema could be used to automatically create BPMNs, and how BPMNs could be a template for Discrete Event Simulation, could in effect deliver a real Digital Twin for Construction.

In resume, by devising such system, the "smart building component" sends periodically data packets that are interpreted and associated with different tasks in the construction site, such as: stored, in-transportation, and installed. Construction progress monitoring thus become an automatic and remotely process that could send signals and drive a representation of the process itself. Employing Location-Based Management System and Building Information Modeling, we create an ecosystem that takes advantage of the IoT solution to register and inform the decision makers over construction progress, allowing management of resources, to remain on time and on budget with the advance of construction. In this paper, experiments in real

Fig. 3 IoT System



environments are presented with the automatic progress report of framing installation in the façade of a building.

4 Experiments and Results

The effective use of the system, integrated with production management systems would require a larger horizon of time and more cooperation with construction companies and contractors.

Experiments were conducted in two different construction sites in 2021. Most of the experiments were done in the first construction site over 3–4 months periods with around 3 visits to the location during development phase; the other location was used for operation trial with the monitoring system already debugged and working for data collection.

The primary communication is based on LoRa technology, and the first tests were conducted to check the signal strength and the range of communication between devices and the gateway. The construction activity that was monitored occurred on the third floor, where window frames were modified by the addition of a small device, a GPS tracker. In the first experiment, the gateway was located at the second

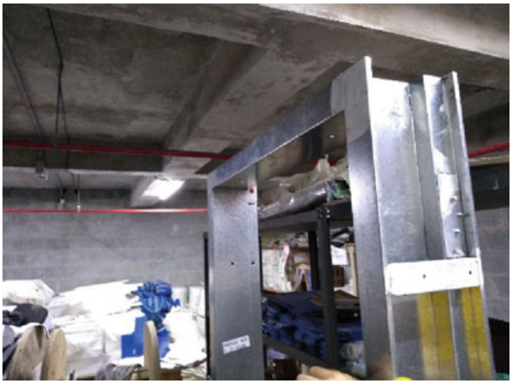


Fig. 4 Preliminary test with fire door frames

underground floor, and devices communicated successfully in the third, fourth, and fifth floor – locations which were available to visit at the moment.

Preliminary tests were made to evaluate the device and communications issues relating to construction environment. Figure 4 illustrates a first test with the installation of fire door frames, trying to capture and characterize movement and installation instant from data – one reason for that test was because the routine of the device is based on two cycles, with indefinite amount of time: firstly, it tries, for a configured amount of time, to achieve GPS signals; after success, or failure, it sends a message and then sleeps for 1 h, or awakes as soon as its IMU detects movement (with a small amount of time configured between each possible message). In the case of the IMU and a few other types of sensors based on position and measurement references, the pattern could be more informative by a wise positioning of the device on the building component, making specific pattern identification easier.

Even for activities of a short period of time, if it takes at least 2–5 min, such device could be used. If it continually finds GPS signal, the behavior is more predictable, and the system could send data in periods of 1 min, if needed.

Although RSSI could not be easily employed to identify storey location, or height of the devices, as it depends on the layout between gateway and devices, a systematic mapping of the signal characteristics in different time frames could be used to help in the inference process. Figure 5 demonstrates the values of RSSI during movement from gateway location to third floor, when walking carrying all devices (each color is one device) through a stair in the building – in this case, the reduced strength of the signal as one is climbing the stairs and then movement on the same level could be used for such identification.

4.1 IoT Devices

The IoT system, in the experiments, was comprised of one gateway with 8 channels for listening simultaneously devices, and 18 devices (*Dragino LGT92*). Each message

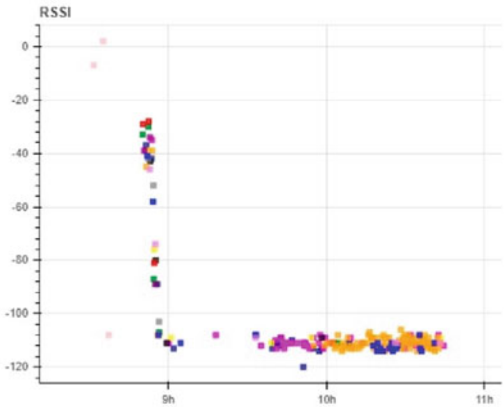


Fig. 5 Evaluation of RSSI to detect in which storey are happening the monitored activities

Table 2 Bytes per message

Size (bytes)	4	4	2	1	2	2	1	2
Value	Latitude	Longitude	Alarm and Battery level	FLAG	Roll	Yaw	HDOP	Height

of the device sends 18 bytes in the current configuration, as viewed from Table 2. Although the device could be reprogrammed due to be open source, the software allows some configuration changes, and in this case, the 11 bytes standard message (shown in the table below in the white cells) was completed with information from the IMU, which is the data that characterizes the stages of the monitored activity.

The device was conceived as a tracker based on LoRa communication, but GPS is unreliable inside a building.

4.2 Configuration of the IoT System

For the LoRa communication, each device has keys which should be configured in the gateway and on the LoRa Server on the cloud. For the experiments, the LoRa Server was *The Things Network* and *The Things Stack* (as the service itself was upgraded during development and final tests). It also provided one implementation of a MQTT Broker, for getting data for processing and storage.

Other configuration process was done with the use of *InfluxDB* on the cloud, and the *Telegraf* of the same platform, as MQTT client. So with zero code, and minimal configuration, data from the field was already available in the cloud, and stored for further processing.

4.3 Installation of the Monitoring System

The monitoring system is comprised of 1 gateway and at most 18 devices. Only the gateway needs resources from the construction site, such as electricity and internet connection. The model in use, *Femto IoT*, could listen simultaneously over 8 different channels, i.e., it could deal with 8 devices sending their data at the same time. Normally, the gateway is installed in the Engineering Room or Office at the construction site (see Fig. 6).

After the installation of the monitoring system, each device should be attached to a frame, which are stored in this case at each storey where they will be later installed (Fig. 7) – each frame could be there, waiting and storaged for months in the worst scenario, due to delays from other activities.

The registration of each device to each frame is done at this moment, where a device key (that is unique and immutable) is associated with a code particular to the supplier of the frames and could be associated with a BIM object by its GUID (**Fig. 8**). Because it is impossible with such system to know exactly in the façade a particular frame is installed, the link to the BIM object is useless for exact identification purposes. A simple web service was developed with Javascript to arrange that information on a *MongoDB* database, which later will be accessed by other applications. In the occasion where it is necessary to monitor more frames than the amount of devices available in one day, it was possible to detach the devices, and register

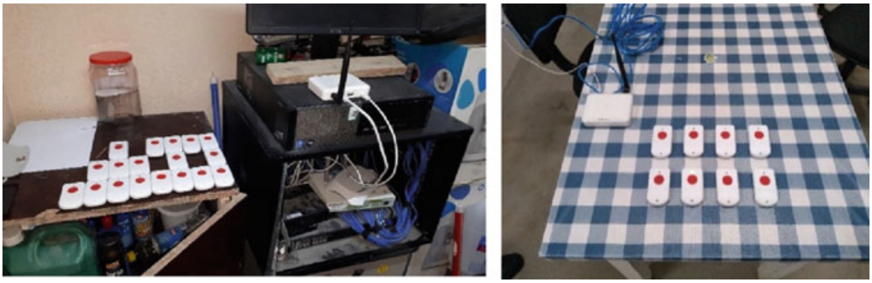


Fig. 6 Gateway installed in the Engineering Room (at two different construction sites), and devices for initial "hand-shake"

Fig. 7 Frames stacked and stored on each building storey

Fig. 8 Registration of the IoT-BIM link

them again to another frame, as management could be done based on timestamps of each relationship / link.

In the initial tests, the device was installed in the inner lateral of the frame (Fig. 9), the part that in the end would be inside the building – so the device could be dettached after use. For that particular activity and the way frames are stored and afterwards installed, positioning the device on the foot of the frame was decided to be better, as the IMU could easily capture the moment in which the frame is erected to be installed, only considering the Roll variable from the IMU unit (Fig. 10). Future expectation is that such devices could come from factory and could provide interesting data for the entire lifecycle of the component.

For the BIM module, IFC models (only for demonstration, a model of the building with only the frames to be installed used for illustration, see Fig. 12) were stored in a local *BIMserver* instance, and data needed were downloaded and extracted using *IfcOpenShell* library (Python module). Schedules (and time series from sensors) were written programmatically inside IFC just for evaluation.

The activity of frame installation was discretized following the BPMN diagram from Fig. 11. Each state or state transition should be identifiable from the data pattern from sensors. Part of the pattern could be configured on the IoT devices through cycles that make the device "sleeps" to save battery, communicating in periods of one hour, when without movement detected by the IMU. So, the interval of communication, or data points, are important to characterize the pattern.

One welcomed feature of cloud storage services are applications which could be easily used to monitor data. For the particular case of InfluxDB, one could create one dashboard with different graphs, updated in real time, by just selecting variables

Fig. 9 Installed device on the internal side of the frame

Fig. 10 Transporting and installing frame

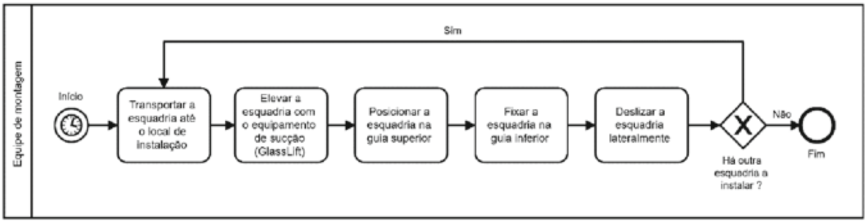
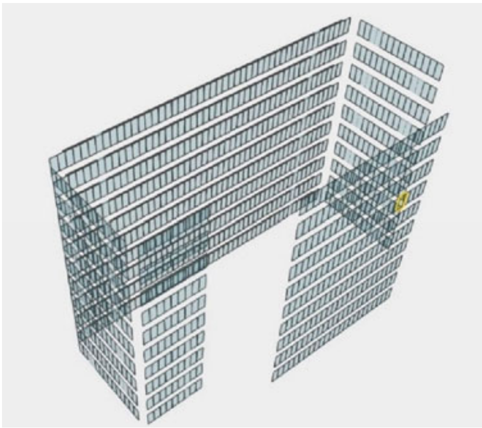


Fig. 11 BPMN of the process of installation of frames on the facade

Fig. 12 Frames in building's facade

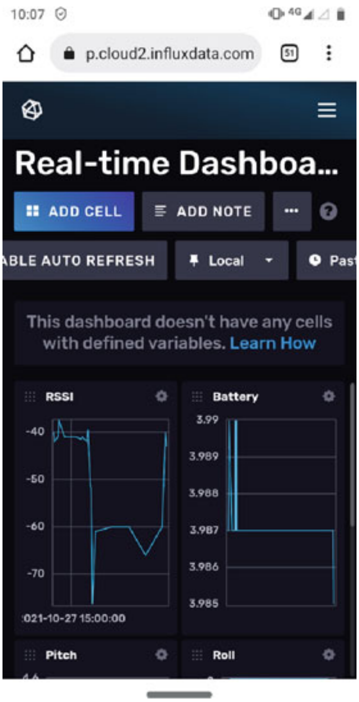


already stored and configuring minimal options for better visualization (Fig. 13). There is also the possibility to access it from mobile web browser (Fig. 14).

With the system entirely developed and sent to another construction site, with slight changes in the process, it could be verified successfully that the system allowed

Fig. 13 Dashboard for online monitoring

Fig. 14 Mobile interface to dashboard



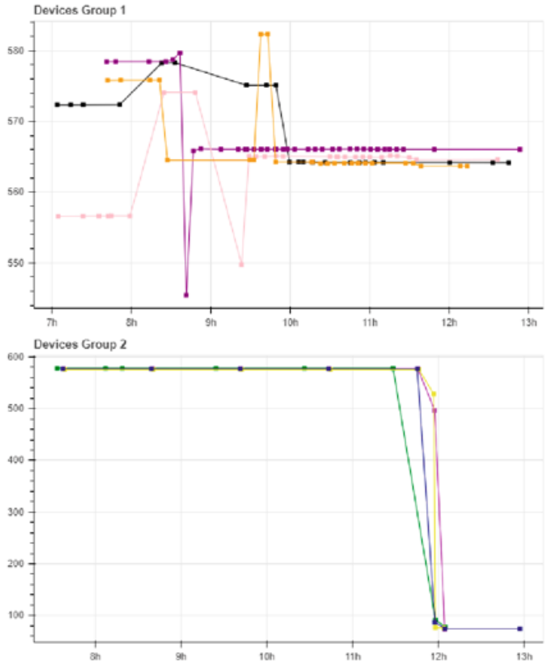


Fig. 15 Patterns seen during operation

the remote monitoring of activities on site, and in real time. Figure 15 presents signals from two groups of frames, transported by different means, and installed in distinct hours of a day, and the same pattern appears in the data, indicating among other things, when installation occurred.

Some experimentation with blockchain technology in the implementation of smart contracts based on data from IoT devices were tested afterwards, based on time-series storage in the database, but due to the amount of detail needed to explain it, it will be left out of this manuscript. The implementation and operation are cumbersome, and it would only be advised to use such technology associating it to automatic payment of the installation services to contractors and sub-contractors.

Future development of the Digital Twin Ecosystem would translate historic data measurements for each type of activity (different activities that involve movement and waiting stages for prefabricated building components) in probabilistic distributions to implement transition times in a Discrete Event Simulation (DES) as demonstrated in [14].

5 Conclusions

A monitoring system, based on IoT technology, for construction activities progress on site was proposed and tested on real conditions. It is only a part of a larger framework, which could be interpreted as one future instance of Digital Twin Construction.

The system was tested on two different construction sites and its behavior was solid. The LoRa communication was found to be very adequate to construction sites, with range of communication achieving more than 2 km of radius, through all doors, slabs, walls and other construction work in between devices and gateway.

A very positive point is that for the IoT system to monitoring, there was few coding needed as the approach could take advantage of services and solutions available and compatible with the devices. The interaction of the user about BIM and IoT links were most demanding.

GPS could not be reliable to identify precise position of façade elements, when movement occurs inside the building – even with open façade, errors were 10 times higher than 2-4 m expected. RSSI should be further investigated as it could provide a better way to pinpoint in the space the location of components, although it would need several mappings of strength of signal over layout changes on construction sites, and a probabilistic inference type of location should be implemented.

Although such system could be used today to give automatic data for production management, the entire process of Plan-Do-Check-Act should be changed to take advantage of the new system – a data-driven approach should be used with Location-based Management Systems. Authors would like to acknowledge support for this research through Brazilian Federal Government program “Construa Brasil”, associated to the Ministry of Economy and RECEPETi, and Construction companies MPD and Grupo Kallas.

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Automatic Parametric Generation of Simulation Models from Project Information in Digital Twin Construction

Timson Yeung, Jhonattan Martinez, Li-Or Sharoni, Jorge Leao, and Rafael Sacks

Abstract In construction, simulation can provide production planners with forward-looking or predictive situational awareness of the potential impact of proposed changes before implementation. Planners can experiment extensively with various alternative production plans and systems without suffering real-world consequences of failure. Addressing the need to have proper control of the jobsite, DTC is a model for managing production in construction that leverages data streaming from different monitoring technologies and artificially intelligent functions. Overall, DTC offers accurate project status information (PSI) and proactive analysis and optimization of ongoing design, planning, and production processes. The integration of automated monitoring and information integration algorithms contemplated within the DTC framework may be able to provide the kind of information needed for practical simulation at short intervals, thus offering construction planners a powerful tool to optimize the decision-making process regarding any necessary changes to designs or plans, by automatically generating accurate and reliable simulation models based on the current jobsite progress, resource information, and safety conditions. This paper describes an automated system for parametric generation of simulation models for this purpose from project intent and status information stored in a DTC database. This is one aspect of broader research that involves design, development and testing of a DTC simulation and optimization system. A construction case study is provided to demonstrate the technical feasibility of automatically and parametrically producing simulation models based on data from a digital twin.

Keywords Building Construction · Simulation · Digital Twin · Production Planning and Control

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1 Introduction

Digital Twin Construction (DTC) is a proposed data-centric mode of construction management in which information and monitoring technologies are used in a lean closed-loop planning and control system [1]. In this paper, we focus on the need for DTC systems to provide accurate Project Status Information (PSI) and to support functions that can proactively analyze and optimize ongoing production planning and control decisions. Predictive simulation of potential outcomes from the current production status at any point in time is an essential component of DTC systems, embodying the two-way nature of digital twins – not only monitoring conditions in the physical twin, but also driving decisions about their operation, and potentially controlling the operations directly. This harnessing of computing power enables production planners to evaluate the potential consequences of any changes they contemplate to the production system using the digital twin, and thus to apply changes wisely to the real system.

At the production planning level, current project status includes the actual progress, work quality, workers' recent locations, equipment and materials, and safety conditions, the design intent models, and the status of the production system itself (types and number of crews, number of workers per crew, equipment assignments, material flow policies and status, information flows, etc.). In the DTC paradigm, the simulation can be considered a bridge between big data and computing power with complex human goal-seeking, thus supporting global optimization of the project. To fulfil this goal, the simulations are expected to capture the full complexity of modern construction projects and project the production systems' future behavior based on real-time streams of project information [2].

Furthermore, production decisions of this kind must be taken at short time intervals to be effective. The cycle-time from monitoring to data interpretation to simulation to prediction and optimization must be short enough for any production changes that are selected to be effective. For most building construction projects in practice, this requires a 'plan-do-check-act' (PDCA) cycle time of a day or two at most. Given the long cycle times (often measured in weeks) for traditional monitoring and reporting cycles in construction, this is the key requirement driving the need for parametric generation of simulation models.

This paper presents an automated parametric model generation system designed to demonstrate feasibility of the predictive aspect of the emerging DTC production planning paradigm. The system uses a structured, ontology-based generation method to set up the simulation with up-to-date project information. The simulation is implemented using agent-based modeling based on the principles of generalization and modularity. The proposed framework is demonstrated through a real-world residential project case study. Here, we automatically generate a simulation model using information from a digital twin graph database and then predict the performances of alternative production plans. The resulting ability to compile, run and interpret simulations in automated fashion in cycle times short enough to support production control is the key contribution of this work.

2 Predicting System Behaviour in Digital Twin Construction

Figure 1 below describes the full cycle of functions of a DTC system as contemplated in the EU BIM2TWIN project [3]. We are primarily concerned here with the 'Predict Performance' function shown at the left of the 'Digital Twin' box. This function draws input from a) the Project Intent Information (PII), which includes the design BIM models and the construction plan defined in the previous cycle of the PDCA loop, b) the product and status knowledge that reflects the current status of the project, and c) from the two forms of archival knowledge – product and process standards (analytical models), and empirical data from archived digital twins of completed projects (data-centric models).

In this chapter, we provide the background to the technologies selected for these key components of the DTC prototype: the graph database and its ontology, parametric agent-based simulation, and the role of knowledge that can be expressed as generic, parametric templates of agent behaviours supported with learning from data describing real-world patterns.

2.1 Digital Twin Graph Repository

Construction projects are known to have a "one-off" nature [4]. Each project is unique not only due to unique building designs but also to the physical conditions of the site and the temporary organization set up for the project. Moreover, each project's

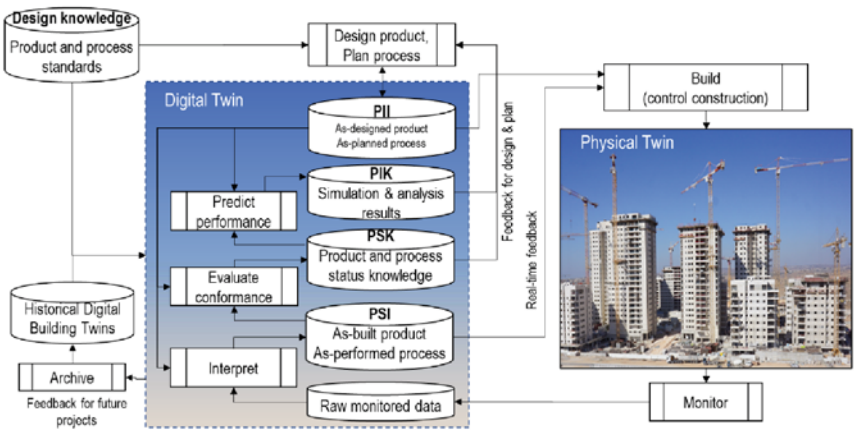


Fig. 1 BIM2TWIN Digital Twin Construction System Architecture [1]. *(PII – Project Intent Information; PSI – Project Status Information; PIK – Project Intent Knowledge; PSK – Project Status Knowledge)*

production system tends to evolve through time within the project to accommodate unforeseen disruptions. These differences within and between projects have been a major barrier hampering simulation's adoption by the industry [5]. For simulation to function as a practical decision-support tool, there must be an automated mechanism to ensure its reusability within and across projects.

To this end, we propose integrating simulation with a digital twin graph repository. The digital twin graph repository uses state-of-the-art semantic web technologies (SWT) to define and maintain a controlled vocabulary of processes, roles, objects, and interactions. We adopted the BIM2TWIN (B2T) ontology [6], a new process-oriented construction phase model that provides an improved basis for advanced process evaluation in the digital twin environment. The B2T ontology encompasses status and intent information, linking the as-designed and as-built products with the as-planned and as-performed processes. This ontology comprehensively captures the fundamental elements of the production system (process, resources, locations, and products).

Using the B2T ontology as the backbone data schema, we used the Thing'in graph platform to host the project data. Thing'in [7] is a research platform that stores and maintains linked data in graph format in the cloud with connectivity to Internet of Things (IoT) platforms. This combination of SWT and IoT makes Thing'in a suitable platform for digital twin applications, where bilateral information processing between the physical and digital twins is essential. The Thing'in platform offers information retrieval functions through Application Programming Interfaces (APIs). In our prototype, the simulation model generation algorithm uses these APIs to retrieve the relevant project information from the Thing'in platform.

2.2 Agent-Based Simulation

Simulation is the discipline of building and experimenting with computer-based representations of systems to model their primary behavior. Simulation applications in construction range from earthmoving to high-rise construction [8]. According to AbouRizk [9], computer simulation techniques are particularly effective in the construction domain at offering the tools needed to design and analyze construction processes regardless of their complexity or dimension.

Production systems in construction are complex systems made up of numerous interacting social and technical sub-components. Construction simulation researchers have often conceptualized these systems with a transformation view and modeled systems as sets of processes that transform inputs to outputs. However, the lean construction view is that effective simulation of construction systems requires utilizing the transformation-flow-value (TFV) view [10–12]. The TFV view proposes that, in addition to the transformation view, construction systems should be viewed through production flows [13] and value streams [14]. The transformation view describes the physical changes that occur to make products from raw materials, while flow and value views comprehensively incorporate the details of resource applications (materials, human resources, equipment and information) through time, including non-value adding as well as value-adding consumptions. Accurately representing this view of construction requires modeling these four flows explicitly as agents in their own right, with independent behaviors – modeling of production events (activities) as would be done in the transformation view (e.g. using critical path method modeling with discrete event simulation, for example), is insufficient [15].

Agent-based modeling and simulation is a proven paradigm which has previously been used for effective computational modeling of complex systems in various domains [16]. Agent-based Simulation (ABS) models a system as a collection of autonomous agents interacting with other agents and the environment [17]. Nonlinear interactions of these components or agents give rise to emergent behavior observable at the global scale [16]. ABS takes a bottom-up actor-oriented modeling approach that aims to reproduce the behaviors of individual elements in a system. An accurately modeled system is expected to exhibit higher-level emergent behaviors as observed or designed. This bottom-up approach inherently relies less on abstractions of system structure and models system behaviors more on a one-to-one scale.

2.3 Historical Project Database

As construction sites adopt digital monitoring systems, the data on past projects accumulate. This data raises the possibility for quantitative analysis of performance and for acquiring valuable knowledge from it. For example, we can derive the frequency and severity distributions of disruptions in the construction site, such as quality issues, safety incidents, and weather disruptions. We can characterize certain contractors or suppliers' reliability and productivity. Through data mining, we can extract crew and management's decision patterns [18].

Aligning with the data-centric principle of DTC, we propose integrating simulation with a historical project database that contains project status and intent information from past construction projects. This database allows us to calibrate the simulation models quantitatively. During the modeling process, we can use information from the historical database to populate and run the simulation, then compare the result against the as-performed status records. In this comparison, we are not checking whether the overall progress prediction is numerically correct - we are checking whether the emergent behaviors of the system components are as expected.

The historical database also greatly improves the simulation's usability at project initiation. Statistical distributions extracted from past projects can provide a good reference point for calibrating simulation parameters, especially at the start of a project. During the initial phase, we have little to no project status information to indicate how the production system may perform. The database helps resolve this situation by providing a grounded "first guess" of simulation parameters that are based on empirical data from real projects.

3 BIM2TWIN Parametric Construction Simulation System

This study aims to demonstrate the feasibility of a data-centric, proactive production planning workflow in the DTC paradigm that can leverage project information to achieve global production system optimization. To this end, we propose a system framework called the BIM2TWIN Parametric Construction Simulation System (PCSS). The PCSS's purpose is to faithfully reproduce the current state of the project and construction site for predictive simulation in an automated, reusable, and scalable manner.

We adopted a parametric modeling process to meet the requirement for automated, reusable, and scalable compilation of simulation models. A parametric process "takes a minimal set of input to drive global changes to a master template and, ultimately, to the end product" [19]. In the agent-based modeling context, a parametric process takes a minimal set of inputs to instantiate and characterize all specified agents through predefined agent classes (i.e., templates). Collectively, these instantiated agents constitute the agent-based model (i.e., the product) for the given inputs.

In the PCSS framework (Fig. 2), the Generation Algorithm component handles the parametric process discussed above. This algorithm receives input from the Digital Twin Repository, the Historical Project Database, and the users [20] to populate and initiate simulation runs parametrically according to predefined agent templates. Collectively, these simulation runs predict the range of likely outcomes of a given production plan. The simulation results can be fed back into the Digital Twin Repository as forward-looking project intent knowledge or compared against records in the historical database for further parameter calibration.

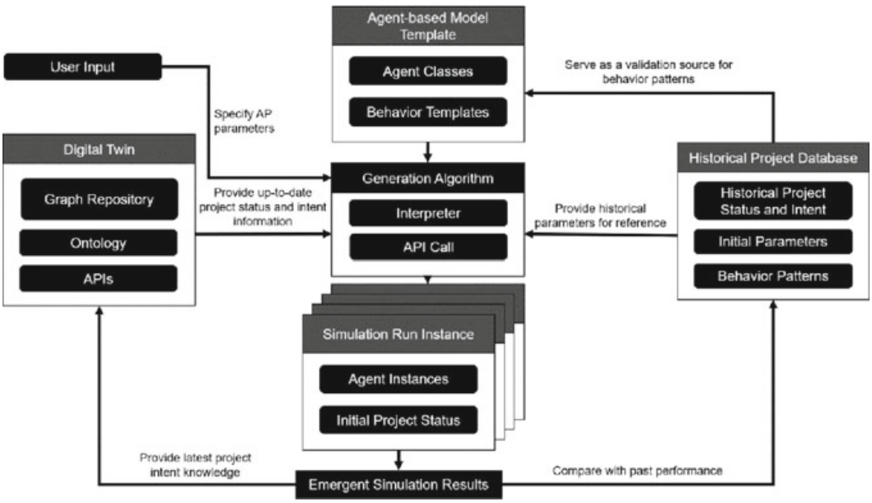


Fig. 2 Proposed system framework for the PCSS

Section 3.1 details the process through which we derived the agent templates, and Sect. 3.2 explains the model generation algorithm.

3.1 Parameterizing the Construction System: Agents and Agent Behaviours

To support the parametric model generation process, we conducted a three-step process to define a set of agent templates.

First, through semi-structured interviews and workshops with practitioners, we mapped out the work breakdown structure (WBS) of a typical building construction project from the structural phase to the finishing phase, as illustrated in Fig. 3. We identified the common technical dependencies between the processes in this WBS. While this process breakdown may be a trivial exercise for practitioners, it is a crucial step toward identifying the relevant agents for the simulation.

Second, taking the WBS as the basis, we identified the production system elements relevant to the processes. For each activity, we listed all relevant active agents (e.g., crews, suppliers, supervisor) and passive agents (e.g., material, equipment, location, product) specific to that activity. In other words, we identified for each activity specifically who is involved in performing the work and making decisions, what resources are used, what product is produced, and what other physical elements may affect the process. As an example, Fig. 4 shows the relevant agents for the drywall construction activity.

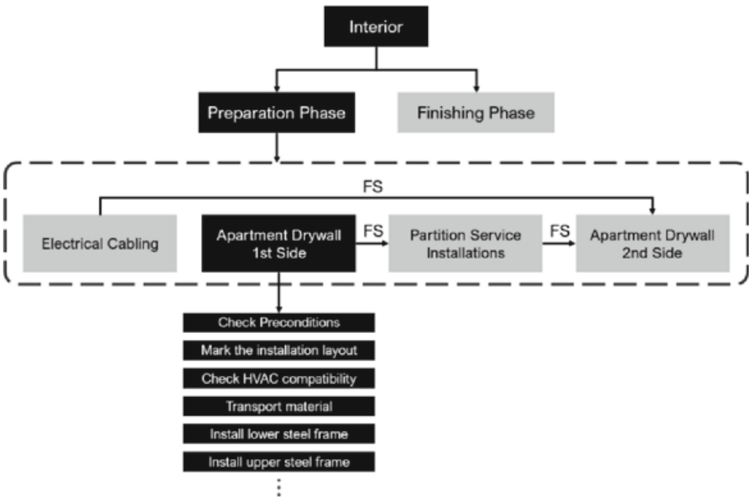


Fig. 3 Illustration of the work breakdown process

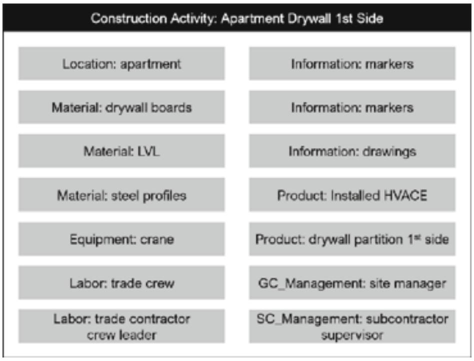


Fig. 4 Relevant agents for the drywall construction activity

Once we identified all the agents for the WBS, we reviewed these specific agent instances from each activity to identify patterns for agent classification. We arrived at five active and five passive agent classes that adequately represent the TFV view of the construction system. These classes are described in Table 1, which presents the fundamental elements of our agent-based simulation model.

The third and final step of constructing the agent templates is to define their parameters and behaviors. Parameters describe an agent's properties, while behaviors describe how an agent instance interacts with other agents, the environment, and other instances of itself. The behaviours of autonomous agents, and specifically human agents, are divided into actions, decisions, and motivations. These are described through a mixed mapping method of both state machine [21] and decision tree [22]. We chose this method because it is intuitive to understand and use for practitioners, and the resulting behavior maps can be easily translated into any programming language.

Finally, we arrived at the set of agent classes listed in Table 1. Each agent class contains a set of parameters, perception variables, and behavior templates. Behavior templates are behavior maps that define how an agent exists within the environment and how it interacts with other agents. A single agent class can have multiple behavior templates defined. These different templates represent the different behavior patterns that a class of agents may exhibit depending on their characteristics, such as skills, contract type, and control policy. In other words, there can be different agent types within an agent class, which may act very differently. We program these patterns of behaviors into separate behavior trees that can be activated for each agent instance based on characteristics defined in the input data.

Figure 5. depicts the process of agent instantiation and activation. Here, the agent class "WorkCrew" has three different behavior templates representing three crew types in finishing works. When the generation algorithm populates the model with crews specified by the input data from the DT, these templates are applied according to each crew's work type. The two plastering crews are instantiated as "Application Crews", while the HVAC crew has its own template activated. As an example, the difference between templates may be that Application Crews prioritize going to

Table 1 Fundamental elements of the agent-based simulation model

Element Type	Name	Description
Active agent	Labor	Labor produces products according to instructions from GC and SC management. It occupies locations, consumes material, and uses equipment to perform work
Active agent	General Contractor Management	GC management interacts/ manages all other active agents. It assigns tasks to labor, sends material orders to suppliers, requests design information from an engineering firm, and coordinates with SC management. It also updates its perception of project status through interaction with other agents
Active agent	Sub-Contractor Management	SC management manages the labor and equipment that belongs to it
Active agent	Logistics/Supplier	Supplier receives, prepares, and delivers material orders
Active agent	Engineering/Design Firm	Engineering firm provides design information for construction tasks to the GC management for further distribution
Passive agent	Material	Material is consumed by labor to produce products. Missing or defective material can cause disruption
Passive agent	Equipment	Equipment represents the necessary tool or machinery to perform tasks or transport materials
Passive agent	Location	Locations are the spaces in which all active and passive agents reside. Location can serve as storage, work zone, or both
Passive agent	Information	Information is the medium for all communication between agents. Task assignments, material orders, and progress reports are all examples of information
Passive agent	Product	Product is the output of a construction task
Other	Technical Dependencies	Technical dependencies describe the technical constraints between different tasks. Dependencies include prerequisite tasks, material conditions, and location conditions, among others
Other	External Conditions	External conditions are conditions external to the production system that can affect production, such as weather and holidays

apartments that have the largest work quantity, while the HVAC Crews prioritize finishing installation for the entire floor before moving on.

Figure 6 shows a screen capture of the AnyLogic® simulation software's visual modeling interface displaying the components of the Crew (labor) behavior. On the right-hand side is the behavior tree. The yellow-colored boxes are the different states, or activities, that the crew can engage in, such as waiting for instructions, working, and inspecting conditions. Between these states are decision points and

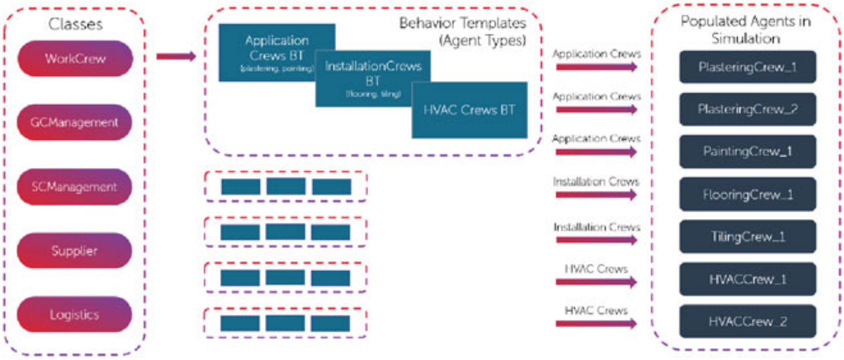


Fig. 5 The automated agent instantiation process

conditions that dictate the flow from one state to another. In the bottom left of the figure are the three other components. The input data define the agent parameters, and they characterize the agent instance. In this model, a crew is characterized by its crew id, type, size, work specialty, and productivity. Below these parameters are the perception variables, which store information needed for the crew's decisions and activities.

Lastly, we have behavior functions. These functions are programs placed inside states and decision points that contain the logic for work and decisions. In this proof-of-concept model, we modeled the different behavior patterns (behavior templates) as separate functions that can be called interchangeably depending on the crew's characteristics. For example, the "*choose_new_task_logic_prefer_quantity*" and "*choose_*

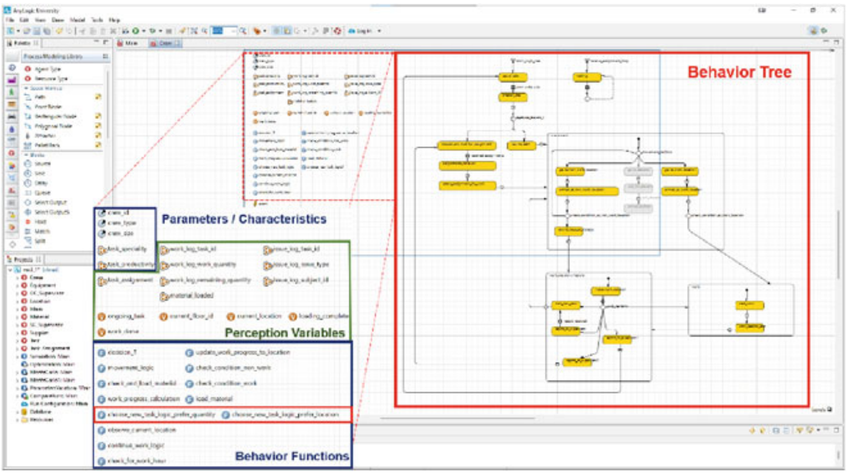


Fig. 6 The AnyLogic® simulation software's visual modeling interface showing components of the Crew (labor) behavior

new_task_logic_prefer_location" functions represent two different types of task prioritization behaviors. The former chooses tasks with the largest work quantity regardless of location, while the latter prioritizes completing tasks at the current location first.

3.2 Model Generation Algorithm

The generation algorithm interprets the incoming project information to populate the model with agent instances and set up parameters for each simulation run. The algorithm also contains API calls to the DT graph repository to retrieve project information. Thanks to the ontology-based approach adopted for the DT graph repository, the algorithm does not need a complex mechanism to ensure input data quality. This task is performed by the graph and its API functions, which are better suited to the task. This tight integration between input data source, data format, and modeling method means that the model generation process reduces to reading rows and columns in a table to instantiate agents and set their properties. This simplicity contributes to better automation and leads to efficiency in the generation process, shortening simulation cycle time, a key requirement for the use of simulation in practice [5].

4 PCSS Prototype Implementation

To illustrate the concept and the system, we implemented a propotype PCSS using AnyLogic® as the core simulation software [23]. The project status information (PSI) and the project intent information (PII) are provided from a graph database implemented in the Thing'in platform [7] according to the schema defined in the BIM2TWIN ontology [6]. A set of Thing'In API calls are applied to extract the information needed for the simulation generation algorithm. The extracted information is stored as Excel tables. At this stage, users define resource constraints and propose policy changes, creating a distinct set of project data for each alternative production plan they would like to test.

Once the user initiates a simulation cycle, the generation algorithm reads the tables, instantiates all agents using AnyLogic®'s Java APIs, and then starts the simulation run. Figure 7 illustrates the procedure.

5 System Testing

We applied the PCSS for the case of a residential project constructed in Finland. We focused on the construction work of one of the four buildings. This building (Fig. 8) has eight floors with 46 apartment units. The construction company that provided

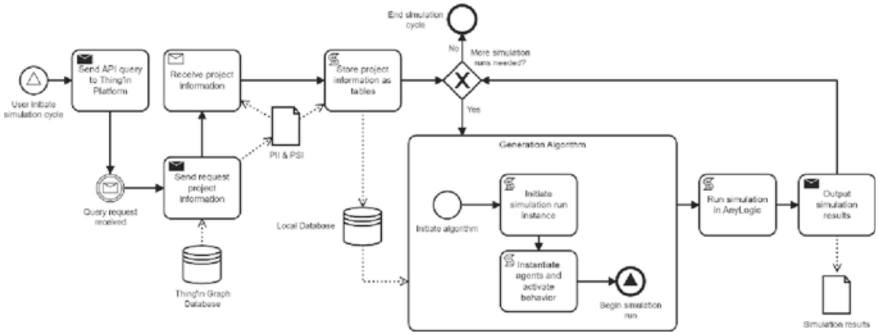
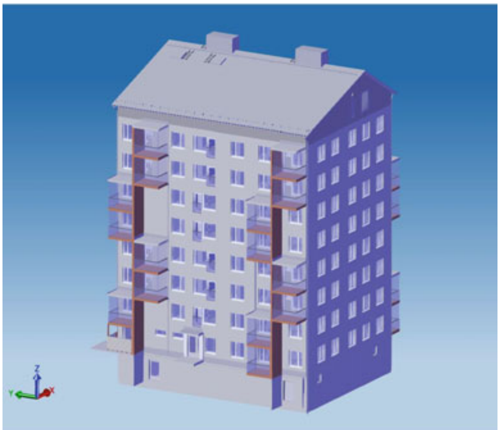


Fig. 7 BPMN diagram of a simulation cycle in the implemented system

Fig. 8 3D view of the building in the case study residential construction project



the data performed the interior phase of the project. Data collected from this project inlcuded:

1. LOD 400 BIM models
2. As-planned work quantities per apartment for each construction activity
3. Location-based as-planned and as-performed construction progress that is recorded through a centralized management system
4. Technical dependencies between construction activities
5. As-planned material consumption for each construction activity
6. Expected crew production rates for each construction activity

We consolidated the collected data into a coherent dataset that conforms to the data schema of the B2T ontology. This dataset, including the BIM models, was injected into the Thing'in platform.

The goals for the test were fivefold:

a) To demonstrate the ability of the PCSS to read a project's status data from the graph database at any given point in time;
b) To obtain input from production planners concerning the range of changes to the production system parameters that they would like to test;
c) To generate a valid simulation instance model for every required set of production parameters, where each set represents an alternate construction plan;
d) To illustrate the way in which the system could be used by running the simulations and providing predictive information for planners at different points in time.
e) To minimally validate the simulations by checking that the actual outcome at any of the points in time falls within the range of outcomes predicted by the system for the case of no change to the current production plan.

To demonstrate goal (a), we ran API calls to query information from the project dataset. Figure 9 shows three pieces of information in the JSON format as an example. The first object is a "bathroom drywall," object of type 'Activity' with id 827. The second object represents the as-planned material "drywall boards" and has parameters of quantity and cost. The drywall activity is linked to the material object through a relational object, "Requires Resources," the third object in the figure. In this object, the "source" field contains the unique identifier of the activity, while the "target" field contains the identifier of the material.

In practical application for compiling simulations, the API functions deliver the data in structured tables. Five tables are needed to instantiate agents: location, task, material, equipment, and crew. These tables describe the characteristics of individual agent instances and the relationships between agents. The algorithm also requires

Fig. 9 Examples of information retrieved from the graph database


```
{
  "_uuid": "b8a162b3-4e04-5668-ba1f-8eaad2e162d2",
  "_iri": "http://bim2twin.eu/suvela_test/activity827",
  "_classes": [
   "https://www.bim2twin.eu/ontology/Core#Activity"
  ],
  "_last_updated": 1660141720406,
  "_creationDate": 1660141720406,
  "https://www.bim2twin.eu/ontology/Core#plannedEnd": "0001-01-01T00:00:00",
  "https://www.bim2twin.eu/ontology/Core#id": 827,
  "https://www.bim2twin.eu/ontology/Core#plannedStart": "0001-01-01T00:00:00",
  "http://iot.linkeddata.es/def/wot#name": "bathroom drywall",
 },
{
  "_uuid": "8d48905e-1aa0-5fa6-9925-42d2e56dd63b",
  "_iri": "http://bim2twin.eu/suvela_test/asplannedmaterial487",
  "_classes": [
   "https://www.bim2twin.eu/ontology/Core#AsPlannedMaterial"
  ],
  "_last_updated": 1660141643598,
  "_creationDate": 1660141643598,
  "https://www.bim2twin.eu/ontology/Core#quantity": 25,
  "https://www.bim2twin.eu/ontology/Core#id": 487,
  "http://iot.linkeddata.es/def/wot#name": "drywall boards",
  "https://www.bim2twin.eu/ontology/Core#resourceCost": 1040
 },
{
  "source": "b8a162b3-4e04-5668-ba1f-8eaad2e162d2",
  "target": "dc1f7f73-ce3f-5bd7-9d6f-f66b9d2e6e29",
  "value": "https://www.bim2twin.eu/ontology/Core#requiresResource",
  "id": "dac486f2-ebf6-4713-a79c-20ef2d1e264a",
  "properties": {
   "source": "6a36ff8e-5dc5-4eb0-a1e0-774b95ab5193",
   "creationDate": 1660141729913
  }
 }
```

input defining the GC_Management's control policies of labor and logistics, such as push or pull control.

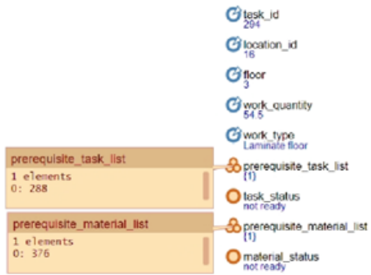
As described in Sect. 3.2 above, the generation algorithm reads the tables and populates the model for a simulation by generating agent instances for each item in the tables. The three figures below show examples of these agent instances. Figure 10 shows an instance of a laminated flooring crew that has received task assignments from GC Management and is currently performing a task as indicated by the "*ongoing_task*" variable. Figure 11 shows the status of the laminated flooring task before it was assigned to the crew. Figure 12 shows the location agent containing the laminated flooring crew. These three figures demonstrate how the system compiles and populates the simulation according to the given input data while respecting the linkage between different agents, and then correctly runs the simulation with these data.

As described below, the system was tested at three different status times. Multiple alternate plan parameters were entered for each status time, and the system compiled valid simulation instance models for each alternate plan at each status time. The validity of the instance models means that they could be run by the AnyLogic® simulation engine with no errors. This fulfilled goal (c).

The fourth goal was to demonstrate the PCSS's operation and its mode of use by demonstrating its ability to initiate simulation runs starting at different points in the project while reflecting the project status information provided by the digital twin repository. Using the actual project status as a reference, we ran simulations at three

Fig. 10 Agent instance of a crew generated from input data

Fig. 11 Agent instance of a task generated from input data



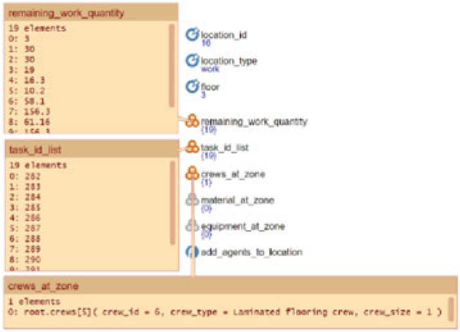
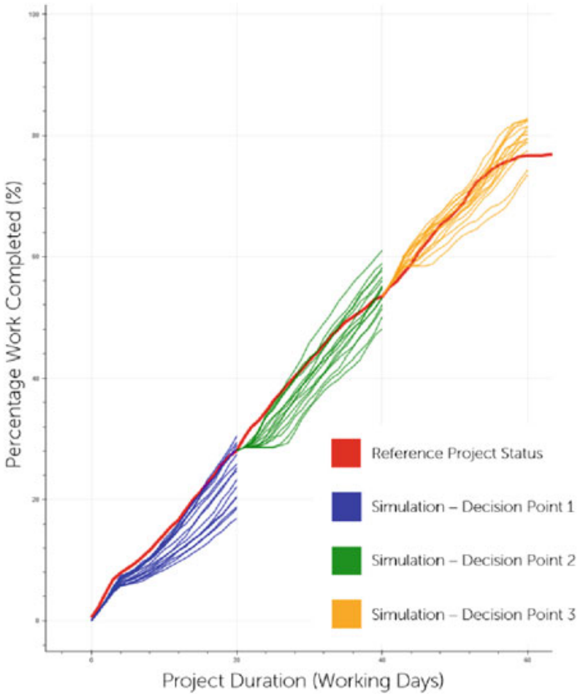


Fig. 12 Agent instance of a location generated from input data

different decision points in the project, and the results are presented in Fig. 13. These decision points are four weeks apart, which is a typical cycle time for medium-term look ahead planning. In the figure, the single red line represents the reference project status in the percentage of total work completed against project time. Since our current model does not account for all construction activities stated in our collected dataset, the reference status here is an estimate based only on the modeled activities. Meanwhile, the lines in blue, green, and orange represent individual simulation runs initiated at the three decision points (Day 0, Day 20, and Day 40). These simulation runs demonstrate goal (d).

Figure 14 is an enlarged view of simulation runs at the second decision point in the project (Day 40). Note that whereas each these runs started at the same date and same progress status, their progress at the end of the decision cycle is different. These differences are due to the inherent variances modeled within the simulation and the different ways in which agents react to these variances. Figure 14 also illustrates a scenario where an alternative production plan is compared against the baseline plan through simulation at each decision point. In this scenario, the production planner wants to understand the effect of doubling the drywall crew's size. This change in the production system forms an alternative plan. The alternative plan is simulated against the baseline of no action, and their results are shown in purple and orange, respectively. Although the AP tends to exhibit high production rates initially, due to the increased drywall productivity, the crews are soon starved of work. The end result is that the system's production rate over the entire month did not improve. We can observe that the AP runs are characterized by high productivity initially, followed by several plateaus later in the project. Meanwhile, the baseline runs have steady, near-linear productivity throughout the month. Therefore, while the alternative plan led to increased work progress in the middle of the month, most of the simulation runs of the alternative plan resulted in the same progress at the end of the month. From this phenomenon, we, and the production planners, can deduce that the productivity of the drywall crew is not the bottleneck of the production system, and the proposed action is unlikely to result in significant improvement. This simple scenario illustrates how the PCSS can support short cycle time PDCA loops within a DTC workflow.

Fig. 13 Parametric simulation run starting at different points in the project. The vertical axis represents the percentage of work completed. The horizontal axis represents project time in units of working days



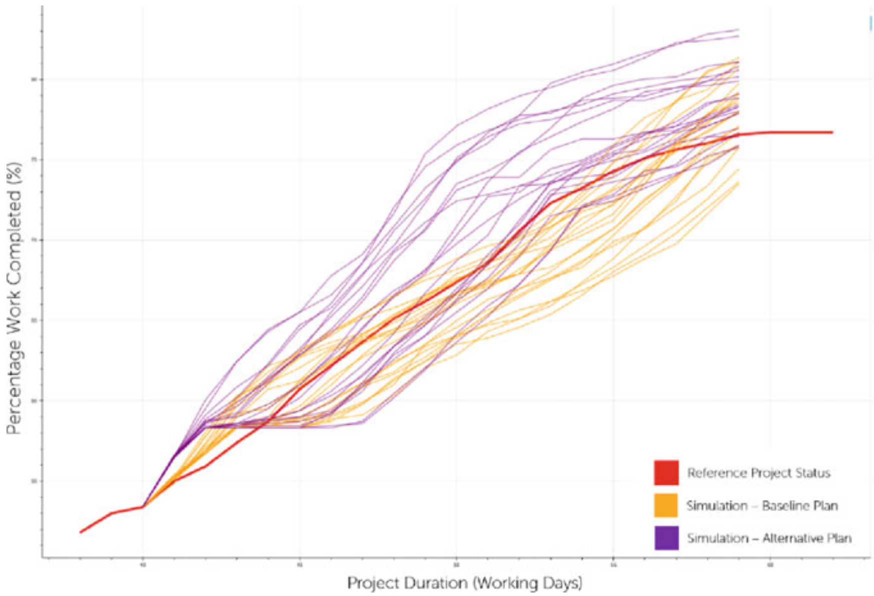


Fig. 14 Enlarged view of simulation runs of the baseline plan and the alternative plan at the third decision point in the project

Lastly, we consider Goal (e). This has not yet been achieved, considering the limitations of our current implementation. This will require further work to refine the agent behaviours, incorporate uncertainty values for the basic production parameters, and other refinements to the system as a whole.

6 Conclusion and Future Directions

This paper presents a novel automated system framework, the BIM2TWIN PCSS, to parametrically generate an agent-based simulation model according to project intent and status information stored in a digital twin graph repository. In line with the DTC system concept, we use the DT graph data to provide the construction projects' status and intent information. Similarly, we integrate historical project records for data-driven calibration of behaviour patterns. We conducted a proof of concept case study using data from a real-world residential project in Finland. We compiled a functioning prototype of the simulation model generation module and demonstrated its ability to take project information from a digital twin repository to instantiate agents and run simulations starting at different points in the project's life. In ongoing work in the BIM2TWIN project, we are building a prototype prediction, recommendation and optimization system that uses this simulation framework to provide production planners with forward-looking situational awareness.

The goal of the aspects of the research presented in this paper was to demonstrate the feasibility of automatic parametric generation of simulation models from the project status and intent information contained in a digital twin graph database. This has been achieved through implementation of a prototype model generation algorithm and testing its performance in the context of a Finnish residential building. While this study has demonstrated initial feasibility of our framework, further validation against multiple projects is needed.

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AEC Digital Twin Data - Why Structure Matters

André Borrmann, Jonas Schlenger, Nicolas Bus, and Rafael Sacks

Abstract With the increasing adoption of the Digital Twin concept in the construction industry in the operations and maintenance phase, researchers and practitioners are increasingly seeking suitable technological solutions for the design and construction phases. While it is widely accepted that the required platforms hosting the digital twin must be cloud-based to fulfill the requirements of ubiquitous accessibility and centralized consistency, questions regarding the need for data schema remain. Some academics argue that a structure-free organization of data is suitable for realizing digital twins and the data streams from and to the respective platform. Hands-on experience in the BIM2TWIN project supports a counter argument, i.e., that structure-free data is insufficient for most use cases around AEC Digital Twins. The sheer information complexity of construction projects requires well-defined data structures enabling unambiguous and error-less interpretation. This becomes apparent when reflecting on the well-established concept of the data-information-knowledge pyramid describing that raw data must be processed into understandable and meaningful high-level information for human decision makers, subsequently providing the basis for cross-project domain knowledge. Based on this observation, we highlight that object-oriented modeling is a widely recognized information modeling technique that facilitates the structuring of complex domain information. We compare it with ontology-based model concepts that provide a similar, yet more abstract means for information modeling.

Keywords Digital Twin · Data Model · Information Model · Ontology · Object-oriented Modeling

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1 Introduction

The term Digital Twin gains more and more popularity in the AEC sector. Originally coined in the manufacturing industry [22, 26], it describes a continuously updated digital representation of a real-world entity. In the AEC sector, the physical entity being twinned is usually a built facility, ranging from buildings over industrial facilities to bridges and tunnels [14, 33, 43].

While many different interpretations of the quite generic term "Digital Twin" exist, most have in common that a) some kind of sensor(s) is applied to capture the current condition of the physical entity and update its digital replica correspondingly, and b) the digital twin is used to test the expected outcomes of possible control interventions, which can then be applied directly to the physical twin.

Disagreement exists, however, when it comes to the data structures used to represent digital twins. While some researchers believe that un-structured or low-structured data is sufficient for representing digital twins of built facilities [8], Aragao & El-Diraby 2020, [21], this paper provides an argumentation that a digital twin is a natural evolution of a digital model and as such should be based on the well-established principles of object-oriented data modeling.

To support our argument, we refer to the ongoing research project BIM2TWIN which aims to provide comprehensive DT representation of constructions projects combining the process and the product view [44]. We show how a well-structured data model helps to reduce complexity and allows to perform the high-level analysis tasks required for decision making.

2 The BIM2TWIN Project

The BIM2TWIN project,[1] funded by the European Commission in the framework of the Horizon programme, aims at developing concepts and technologies for creating and maintaining digital twins of construction projects. As such it focuses on providing a digital representation of both, the constructed facility as well as the processes that are required to erect it. To separate design intent from actual realization, we distinguish as-designed from as-built in terms of the product description, and as-planned from as-performed in terms of the process description [43].

For the as-designed/as-planned process representation we make use of the well-established 4D BIM technology, combining sophisticated semantic-geometric models with construction schedules on component level. For the as-built and as-performed information, we compile a parallel object schema with abstractions that can accommodate information derived from monitoring technologies, ranging from laser-scan point clouds to mobile construction applications. Both aspects are incorporated in the BIM2TWIN digital twin platform.

[1] https://bim2twin.eu/.

In order to allow for a continuous update of the digital twin regarding the as-built facility and the as-performed processes, data is captured from the site by means of a multitude of sensors, including temperature, laser scanners, photo cameras, thermal cameras etc. The low-level data is subsequently processed into higher-level information, such as geometric deviations, surface qualities, task durations, safety hazards, etc., which are finally aggregated into knowledge presented to human decision makers as key performance indicators (KPI), related to quality control, schedule delays, safety issues etc. More background for the underlying philosophy is provided in Sect. 3.

The B2T platform is a core element of the BIM2TWIN project. It is designed to hold all the as-designed/as-planned as well as the as-built/as-performed information and provides coherent access to both end-users as well as services to the Digital Twin (functions as a single source of truth of the Digital Twin). The B2T platform is built upon the Thing'In platform provided by project partner Orange.[2] Thing'In itself is based on ArangoDB[3] - a multi-model database system supporting three data models (property graphs, JSON documents, key/value) with a unified query language AQL. By being schema-free, the database itself provides a maximum of flexibility, However, for BIM2TWIN, a properly defined data structure (information model) has been specified to achieve reliable interoperability.

In this paper, we discuss the information model that has been designed for the B2T platform and implemented using the property graph mechanism. We use it as example to illustrate our argumentation for well-defined data structures being required for properly handling digital twin representations and enabling decision making.

3 Data – Information – Knowledge

The differentiation of data, information and knowledge is a well-established concept in computer science [41]. Ackoff (1989) introduced the DIKW pyramid that consist of different layers of abstraction, namely *data, information, knowledge* and *wisdom* (Fig. 1). In this work, we focus on the three abstractions of data, information and knowledge because these are expressed in the B2T platform.

For these layers we provide the following definitions in the B2T context:

Data Layer. With "Data" we refer to raw data produced by sensors. Typical examples in the context of BIM2TWIN include images, measurement time-series, point-clouds etc.

Information Layer. "Information" has a direct meaning for the end user. Information can either be produced by processing data or manually entered by a human

[2] https://hellofuture.orange.com/en/thingin-the-things-graph-platform/.

[3] https://www.arangodb.com/.

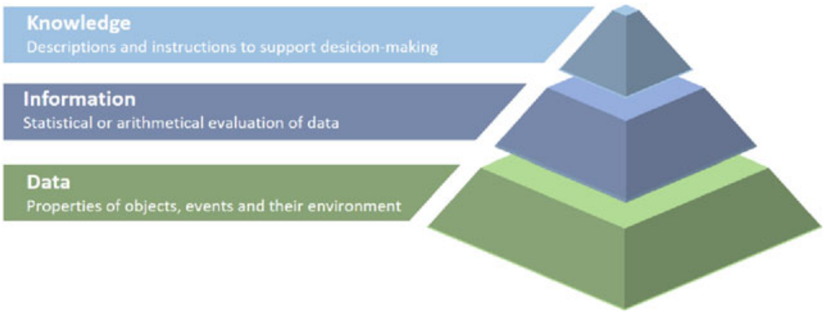


Fig. 1 The data-information-knowledge pyramid

user. A typical example in the context of BIM2TWIN is the completion status of a dedicated building element.

Knowledge Layer. The knowledge layer provides a higher layer of abstraction by aggregating and transforming information. It provides the basis for decision making. In the context of BIM2TWIN, this layer allows representation and tracking of Key Performance Indicators (KPI) of the construction project like cycle time, equipment utilization rate, and accident frequency.

4 Data Structures and Information Modeling – A Brief History

There is a long history of information modeling in computer science. The developments were dominated by the database sector for a long time; early approaches included the hierarchical model and the network model, however both are limited in terms of expressive power. This changed in 1970 with Codd's seminal work on the application of formal relational theory onto databases [19], which laid the ground for relational databases, which are still the most widespread type of database in use today. A key feature of relational data models is the possibility to connect data records in different relations (tables) through primary and foreign keys, which allows one to model complex information networks with minimal redundancy. A key aspect in this regard is the notion of normalization, which describes a set of rules which, when obeyed, result in a clean, redundancy-free database design.

Although powerful and generic, the relational approach to information modeling has limitations [20, 40]. For example, complex data types and relationships do not exist as such in the relational model, but have to be mimicked by a combination of relations (tables) linked through primary and foreign keys. Especially, when the data to be queried is distributed across multiple tables, a large number of join operations is needed, and the statements in the query language SQL become long and complex, slowing down the response time significantly. In addition, the important concept of class inheritance can hardly be mapped onto the relational schemata. These limitations became apparent when another very successful paradigm of information modeling became popular in the 1990ies: Object-oriented modeling (OOM) [28].

In its core, OOM is based on the concepts of classes that act as templates for concrete instances or objects. Classes have attributes and methods and relations to other classes. An important concept is inheritance, where a subclass inherits all the attributes of its superclass, thus emphasizing modularity and reusability. OO programs essentially instantiate objects of predefined classes, fill their attributes with values and let them interact. Thanks to many features that come along with OO paradigm, such as encapsulation and reusability, OOP has been extremely popular and is implemented in almost all major programming languages, including C++ , Java, and Python. Based on these developments, the concept of model-driven architectures for distributed systems was established [34].

While first employed for programming, the OO paradigm has also soon been adopted for more general analysis and design (OOAD) tasks, including the definition of data models for data exchange and persistent storage. In this context, the Unified Modeling Language (UML) was developed for visual definition of object-oriented data models. For the computer-processable form, a number of textual data modeling languages have been developed. These include EXPRESS, which has been employed across the large product modeling standard STEP (ISO 10,303) as well as the AEC-focused data model Industry Foundation Classes (IFC) (ISO 16739). Later, XML and XML schema were introduced. Although they evolved from a different background (SGML, HTML), they ended up with very similar features regarding object-oriented data modeling. In consequence, many data models have been encoded in XML schemata, including IFC (denoted ifcXML), but also the GML data models produced by the Open Geospatial Consortium (OGC) [39], and many, many more.

A more recent development is the JavaScript Object Notation (JSON) format originally used to serialize JavaScript objects, but increasingly adopted across a wide range of languages and applications in the context of web development [38]. In comparison with XML, it provides a leaner syntax (improving readability for humans and reducing data footprint) and has the advantage of direct support by programming languages such as Python without the need for sophisticated parsers. The schema language for JSON is JSON schema [3]. Again, a number of data models have been encoded into JSON schema, including the IFC data model [4]. However, limitations exist, particularly when diverting from a pure tree-like structure and using references to existing objects. This however, is very relevant for more complex graph-like information structures such as building models.

In the early 2000s, semantic web technologies were established with ontologies being the chosen approach towards information modeling. Ontological modeling adopts many concepts of object-oriented design while providing an even richer expressive power allowing a more fine-grained description of real-world entities [10]. Here, the Ontology Web Language (OWL) is used for describing the schema level (T Box), while instances are represented by RDF graphs (A Box). SPARQL provides the query language for retrieving information from both class and instance graphs. Semantic web technologies have seen increasing popularity over the last decade, particularly in the context of the Linked Data (LD) philosophy that respects the heterogeneity of the information model landscape while allowing one to flexibly connect corresponding entities across different data models [13]. In the AEC context, a number of ontologies have been developed and standardized by W3C [37]. Typically, the semantic extent remains narrower than in conventionally defined data models [36], but also a mapping of the full IFC model onto OWL exists [11, 35]. It is also worth mentioning that the linked data approach has recently been brought together with the transport format JSON resulting in JSON-LD and providing significant synergies [12].

Graph databases are a more recent innovation. While some graph databases implement the Semantic Web approach, maintaining RDF graphs with so-called SPARQL endpoints as their interface [18], others implement the concept of Property Graphs that allow assignment of attributes directly to individual nodes [29]. More recently, semantic-web databases also provide this feature through the RDF-star extension [24]. Graph databases often provide a large degree of flexibility when implementing a schema-free approach where instance graphs can be populated with literally any data. This flexibility, however, comes at a cost, namely the potential risk of incompatibility with applications relying on specific data structures. In consequence, many graph databases now implement a “meta-model” that clearly defines the type of nodes their attributes and the potential connections between nodes, thus mirroring the concept of a schema.

In the field of data science and machine learning, a contrary trend is visible: Instead of using highly structured data following the principles of OOM, simpler formats are often preferred, such as comma-separated-values (CSV) for representing tabular data. The background lies in the fact that most neural network architectures are based on manipulating and transforming matrix and tensor-like structures. Based on these observations, some companies[4] promote the conversion of object-oriented BIM data into these flat data structures for further processing using standard tools of Machine Learning, Big Data Analytics and Business Intelligence. It must be noted, however, that the required de-normalization typically either creates many redundancies or destroys relationships between data records.

Such approaches might be suitable for special, rather simple use cases. In the remainder of the paper, however, we will show that for the management of Digital Twin information of complex construction projects, well-structured and clearly defined data structures are required.

[4] E.g. https://opendatabim.io/.

5 Information Modeling for AEC Digital Twins

For the discussion, we clearly distinguish between information models (sometimes also referred to as data models) and file formats. When done properly, the information model is defined independently of any concrete file or transport formats using modeling languages such as UML. OGC, for example, uses the notion of "conceptual models" for information models that are defined in an implementation-independent manner on the one hand, and provides concrete encodings using different data formats such as XML on the other hand.

5.1 Requirements of Digital Twin Data Management

In this paper we focus on application of digital twins for construction management. The digital twin in this sense is a replica of the construction project including the as-performed processes as well as the as-built physical objects.

The requirements for the DT data management are derived from this purpose and include the following aspects:

- A product breakdown structure – a hierarchy of objects describing the facility under construction at various levels of granularity
  - differentiation between as-designed and as-built building information
- A work breakdown structure – a hierarchy of objects with interdependencies describing the construction processes to be performed at various levels of granularity
  - differentiation between as-planned and as-performed construction processes
  - notion of quality of the performed processes
- A resource breakdown structure -a hierarchy of objects representing construction resources (equipment, workers, and materials) that serve as input flows for the processes
- A location breakdown structure - a hierarchy of working zone objects that describe the locations where the processes are executed.
- linkages among these four breakdown structures that express the way in which the project is designed and built and how the processes are planned and executed, all at various levels of granularity

From this description, it follows that a graph structure is most suited to modeling the data because any given building model and digital twin is an inherently complex network of objects from each of the four structures and the relationships between them. Relationships may occur between objects of different levels of granularity, and ad-hoc aggregations are needed. The information structure must allow easy access and navigation in the complex network of connected entities by both human end-users and machines and algorithms. Most importantly, the information structure must support computation of the Key Performance Indicators that provide the basis for high-level decision making in the construction project (aka the knowledge layer, see Sect. 3).

5.2 Monolithic Models: Industry Foundation Classes

A more traditional approach towards data modeling is the concept of "monolithic data models" which implies the goal of developing an all-encompassing information model covering all aspects of a domain. One example is the IFC data model, which is described in more detail below. The advantage of this approach is the semantic rigidness and the "inner compatibility" that can only be achieved with one data model. The disadvantage, however, lies in the big size and high complexity of such data models.

The Industry Foundation Classes (IFC) developed and maintained by buildingSMART International (2021) is a well-known and internationally used standard for data exchange of construction-related information. The IFC data model implements the paradigm of object-oriented modeling, however with a number of particularities, such as the usage of objectified relationships, the usage of proxy elements and the inclusion of dynamically definable properties. Originally, the IFC schema was directly encoded using EXPRESS, while property set templates were kept outside of the schema and defined by separated XML documents.

Recently, bSI changed the development process and now relies on UML for defining the information model. It supports multiple serializations, with the most common one being the EXPRESS format for the definition of the IFC schema and STEP physical files for instantiation. However, mappings from EXPRESS to XML-Schema (ifcXML), to OWL [35] as well as to JSON [4] have been developed, thus opening the richness of the IFC data model to these specific technological worlds.

The IFC data model aims at covering the full range of the built environment, including buildings but also infrastructure assets such as road and railways, while considering all relevant domains, including architecture, HVAC, electrical etc. This naturally results in very big data model with more than 900 classes in the most recent version 4.3.

While very powerful and comprehensive, the IFC data model is regularly criticized for its extent and complexity [1]. Specific problems arise from the original use of EXPRESS as primary modeling language, which has found only little widespread adoption in the open-source developers community.

Although being a common misunderstanding, the IFC data model is not bound to the usage of files for exchanging information. Instead, the underlying STEP standard foresees the data model being used in databases etc. Parts 23, 24, 27 define bindings for the programming languages C, C++ and Java, respectively.

However, when it comes to concrete solutions for web-based data management of IFC models, there are a few options that natively support the EXPRESS format, among them the Open BIM server and Jotne EDMserver. However, as these are rather bespoke implementations they suffer from limited support and use by the wider community. Mapping to relational databases is possible, but is plagued by the well-known object-relational impedance mismatch [27].

Graph databases on the other hand seem to be a natural option for storing and managing networks of objects as an IFC instance model. Indeed, a commonly proposed option is to use "SPARQL endpoints" to manage and query RDF instance graphs following the ifcOWL ontology [23, 32, 45].

Another option is the usage of property graph databases. The conversion of the IFC model into graph meta-models for management of IFC instances in graph databases is hindered by the particularities mentioned above, in particular the notion of objectified relationships [16]. Future versions of IFC will aim to overcome these deficiencies [15].

5.3 Linked Data Approach

An approach contrary to the IFC approach of a monolithic data model is taken by the Linked Data Community following the concepts of the Semantic Web and Ontology modeling. Here, typically, much smaller data models are defined that focus on specific aspects of the built environment. In this context, the Building Topology Ontology, Building Product Ontology and the BRICK ontology have been published [37]. A key aspect of this approach is the re-usage of existing ontologies.

In the context of digital twins for construction management, some relevant ontologies are Damage Topology Ontology, Digital Construction Ontologies, Building Element Ontology [12]] but also the ifcOWL.

As discussed before, RDF data is stored in RDF databases which essentially are databases specialized on RDF data, accessible by means of SPARQL endpoints, providing standardized access to the data through the web.

The linked data approach is very relevant for the concept of digital twins as indeed many different aspects have to be covered, which are not available in one comprehensive monolithic data model, but in various ontologies with smaller scopes. A major challenge however lies in the correct linking of the individual ontologies and their objects. Nevertheless, thanks to its expressive power the linked data approach provides both flexibility but also rigidness when it comes to the specification of well-defined data structures.

On the data hosting side, ontologies are increasingly supported not only by dedicated RDF databases, but also by other graph databases. Although conceptual differences exist [6], a mapping from RDF graphs onto Property Graphs is possible [7]. A key aspect, however, is not to use the flexibility of graph databases in terms of node-specific extensions and particularities, but stick to the concept of schemas (here:

ontologies or graph meta-models) as this provides the necessary reliability in terms of agreed content for any application accessing the database.

5.4 Flat Data Approaches for Digital Twins

A few researchers have proposed a flat data approach for digital twins [21, 30]. In this case the data is represented in a mere tabular structure consisting of a large number of data records. Typically, this kind of bulk data is stored and exchanged using the CSV format. The notion of objects does not exist, neither the concept of a data schema describing the meaning of the columns, their data types and units. This allows a high degree of flexibility, however at the cost of interoperability, as the correct interpretation of the received data is the responsibility of the human programmer. Given the vagueness and imprecision involved, this easily leads to misinterpretation.

The flat data approach is appropriate for the data layer of the digital twin, where bulk data is (temporally) stored, processed and analyzed to feed the higher information levels of the DIKW pyramid. Typical examples are time series of temperature and humidity, location protocols of equipment and workers, object detection results of images or even raw point clouds (see Fig. 2).

However, flat data approaches are not suitable for representing complex information of entire construction projects. The simple concept of a data record cannot replace the notion of an object having properties and associations with other objects. If an information requires a non-basic data type (float, integer, Boolean), a multitude of columns is necessary, thus increasing complexity. Unlike the relational model, the flat data approach typically does not address normalization, leading to frequent redundancies and thus inconsistencies.

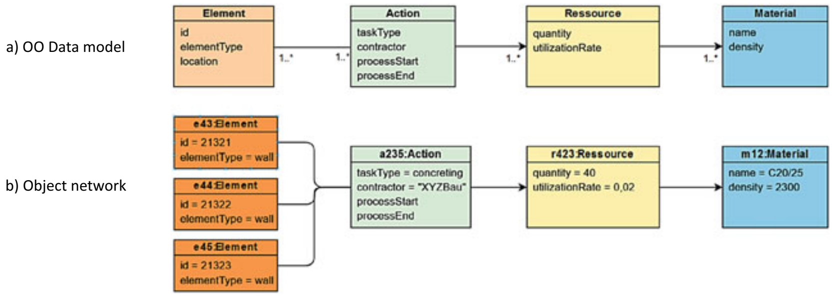
This is illustrated by the example shown Fig. 3 where (a) a simplified class diagram for representing the as-performed processes is depicted along with (b) an UML instance diagram showing the resulting object network when employing OO or graph databases, and (c) the corresponding flat data CSV representation. The lack of higher-level concepts in flat data, in particular object associations, results in excessive repetition of data that remains unchanged. In the shown example, this refers to action, resource and material data that must be repeated for every wall instance. This redundancy results in a massive increase in storage footprint and creates the risk of inconsistencies.

In relational database design, this effect is well known and can be overcome by *database normalization*, resulting in separate tables for *Elements*, *Actions*, *Resources*, and *Materials* in the shown example, to avoid duplication and redundancy [31]. The authors point out that this example is only a small section of a real DT data model, which typically has much more classes and associations (see next Section), rendering the flat data approach even less suitable.

Indeed, the complex interlinked nature of the information representing a digital twin of construction projects can hardly be reflected by flat tables, but deserves a navigable graph structure. It has been shown that graphs, as well as hierarchical

time	temp	dwpt	rhum	prcp	snow	wdir	wspd	wpgt	pres	tsun	coco
2022-02-11 00:00:00	6,4	2,1	74	0	0	200	4,7	11	1023,2	0	4
2022-02-11 01:00:00	6,4	1,5	71	0	0	200	6,5	13	1022,6	0	4
2022-02-11 02:00:00	5,9	2,2	77	0,1	0	200	6,8	14	1022,2	0	8
2022-02-11 03:00:00	6	3	81	0,3	0	230	8,3	18	1021,5	0	7
2022-02-11 04:00:00	5,8	3,3	84	0,4	0	230	9,4	18	1021,1	0	8
2022-02-11 05:00:00	5,5	3,7	88	0,9	0	230	13,7	27	1021,3	0	8
2022-02-11 06:00:00	5,2	3,4	88	0,6	0	240	16,2	33	1021,5	0	8
2022-02-11 07:00:00	4	2,2	88	0,8	0	260	16,9	34	1022,8	0	8
2022-02-11 08:00:00	3,6	2,3	91	0,9	0	300	15,5	33	1024,3	0	8
2022-02-11 09:00:00	3	1,5	90	0,5	0	300	19,4	43	1026,5	0	8
2022-02-11 10:00:00	2,1	0,2	87	0,4	0	300	20,9	41	1029	0	8
2022-02-11 11:00:00	2,7	-0,1	82	0	0	290	17,3	35	1030,1	2	8
2022-02-11 12:00:00	3,3	-2	68	0	0	290	22	40	1030,9	21	4
2022-02-11 13:00:00	3,5	-3,1	62	0	0	270	19,4	41	1030,8	25	3
2022-02-11 14:00:00	4,2	-3,3	58	0	0	270	17,6	33	1030,8	32	4
2022-02-11 15:00:00	4	-4	56	0	0	280	16,6	34	1031,1	2	4
2022-02-11 16:00:00	4	-3,3	59	0	0	290	16,2	36	1031,8	0	4
2022-02-11 17:00:00	3,8	-3,9	57	0	0	300	14,4	29	1032,1	30	1
2022-02-11 18:00:00	3	-3,8	61	0	0	290	12,2	27	1032,8	22	1
2022-02-11 19:00:00	2,8	-3,6	63	0	0	270	8,6	21	1033,6	0	4

Fig. 2 Weather data (from meteostat.net) as a typical example for flat data which can be represented by the CSV format



c) CSV representation

elementId	elemenType	location	actionId	taskType	contractor	processStart	processEnd	ressourceId	quantity	utilizationRate	material_id	material_name	material_density
21321	wall	(321.32,23.66,435.45)	fef32fds	concreting	XYZbau	74952:13:27	74952:13:56	hzde7213	40	0,02	3145	C20/25	2300
21322	wall	(319.22,24.27,432.45)	fef32fds	concreting	XYZbau	74952:13:27	74952:13:56	hzde7213	40	0,02	3145	C20/25	2300
21323	wall	(325.32,26.44,432.45)	fef32fds	concreting	XYZbau	74952:13:27	74952:13:56	hzde7214	40	0,02	3145	C20/25	2300
21324	wall	(321.32,26.12,432.45)	fef32fds	concreting	XYZbau	74952:13:27	74952:13:56	hzde7215	40	0,02	3145	C20/25	2300
21325	wall	(325.83,20.45,432.45)	fef32fds	concreting	XYZbau	74952:13:27	74952:13:56	hzde7216	40	0,02	3145	C20/25	2300
21326	wall	(328.02,25.76,432.45)	fef32fds	concreting	XYZbau	74952:13:27	74952:13:56	hzde7217	40	0,02	3145	C20/25	2300
21327	wall	(321.32,24.44,432.45)	fef32fds	concreting	XYZbau	74952:13:27	74952:13:56	hzde7218	40	0,02	3145	C20/25	2300
21328	wall	(321.32,24.44,432.45)	fef32fds	concreting	XYZbau	74952:13:27	74952:13:56	hzde7219	40	0,02	3145	C20/25	2300

Fig. 3 The example shows **a** an object-oriented data model, **b** a network of instances as provided by object-oriented approaches and graph databases, and **c** the same data in a flat-data representation using CSV. The red-boxed part resembles repeated data that must be created in CSV and results in redundancy and larger data footprint

aggregation structures, facilitate the navigation of complex information by both, end-users and application programmers.

6 The BIM2TWIN Data Model

For the reasons discussed above, the BIM2TWIN project has decided to use the linked data approach for implementing the information layer of the DIKW pyramid. A number of existing ontologies for covering specific aspects (such as the building structure) are re-used and integrated. At the same time, however, it was necessary to define a core ontology that reflects the precise requirements of the Digital Twin of construction projects as listed in Sect. 5.1.

6.1 Key Model Characteristics

As a starting point, the BIM2TWIN Core data model was developed as UML diagrams, as shown in Figs. 4 and 5. This leaves the model file format agnostic and allows various implementation strategies. One of its main characteristics is the separation of the project intent (Fig. 4) and the project status, representing the current situation on the construction site (Fig. 5). These two sides of the model can be understood as two containers that use a set of classes specific to the model side but also classes that both have in common. Even though the two sides are visualized separately, there are clear connections between them. The intention is to link every node from one side to its corresponding node on the other side. This allows direct comparison of the project plan to its actual realization and results in precise information about the deviation between them.

The Core data model classes can be grouped into four categories. These are the construction processes, the resources that are their input parameters, the working zones where they are executed, and finally, the elements of the building structure, which are their output. All four categories are explained in more detail in the following section.

Processes: The processes are the main aspect of the model and can be found in the center of Figs. 4 and 5. We differentiate between three different process levels. The most general level of the processes is the *work package*. It holds information about the used construction method and can be seen as an aggregation of more detailed processes. Every *work package* consists of multiple *activities,* representing the individual construction steps that are part of the *work package*. The *activities* are broken down even further into *tasks*. While an activity can refer to a construction step applied to a group of construction elements, the *task*s have one-to-one relations to the elements. Additionally, p*reconditions* can be connected *to any processes on any of the three levels*. They describe the initial requirements to allow a process to be started. Where the as-planned processes hold details about long-term averaged performance factors dependent on the construction company, the construction method, and the project's particularities [25], the as-performed processes (*construction*, *operation*, and *action*) need to support short-term performance evaluation. Fine-grained insight into performance variation and process disruption allows the development of timely countermeasures to improve the overall construction performance.

Products: The building elements are organized according to the spatial structure of the building. From high-level to low-level, the construction project is broken down into the *site*, one or multiple *buildings*, their *storeys*, and their *spaces*. Depending on their type, the *elements*, like walls, slabs, and columns, can be associated with any of these levels. Since there are no significant differences between the project intent and status regarding the building structure, both model parts use the same set of classes.

Resources: Various types of *resources* are modeled in the Core data model. They describe the input flows of the construction processes, which are essential for successful process execution. The included types of resources are the construction workers and worker crews representing the labor force, *equipment* like heavy machinery and small tools, *materials*, and *temporary equipment* like formwork and guardrails. In Figs. 2 and 3, they can be found on the upper half of the diagram. While the *resource* classes are foreseen to model the resources available on the construction site, the *resource assignment* class is used to specify the amount and time frame during which a resource is assigned to a specific process. The *resources* differ between project intent and project status because, during execution, exact

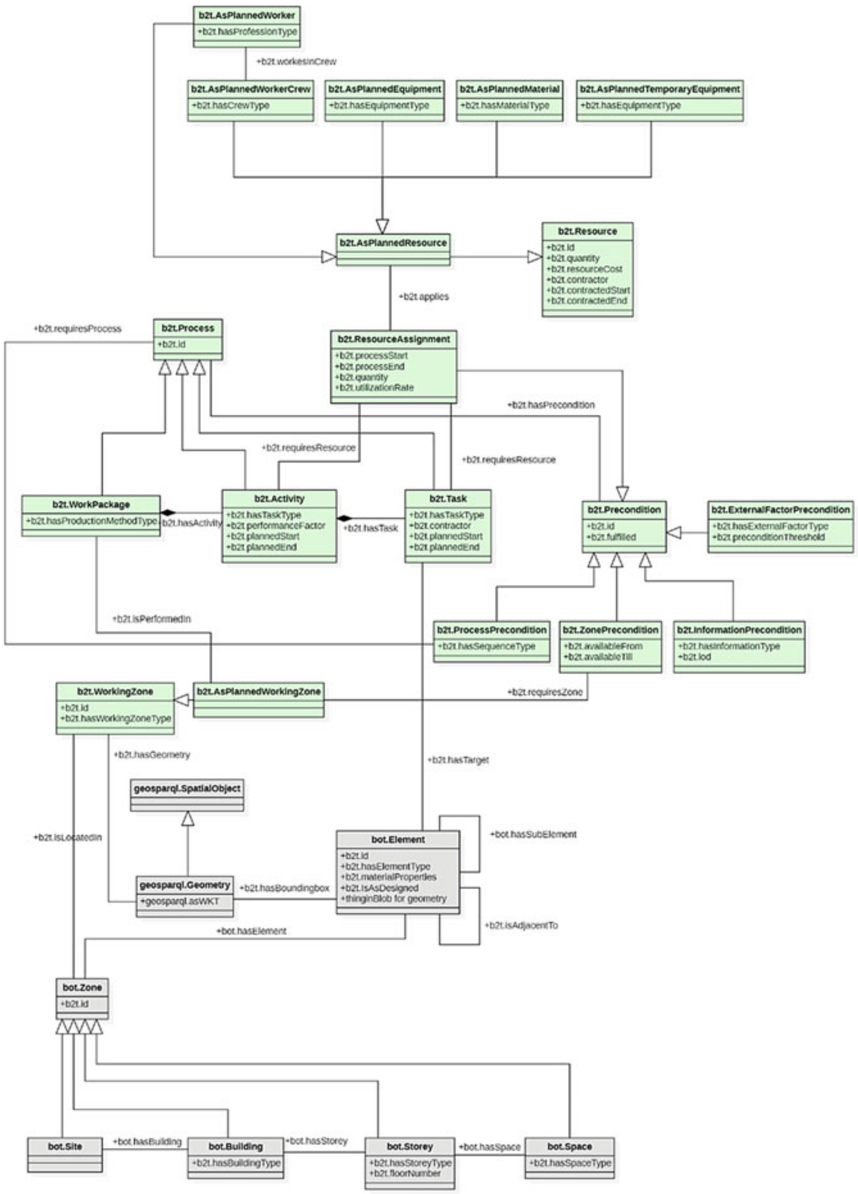


Fig. 4 UML model of the project intent information (as-designed and as-planned)

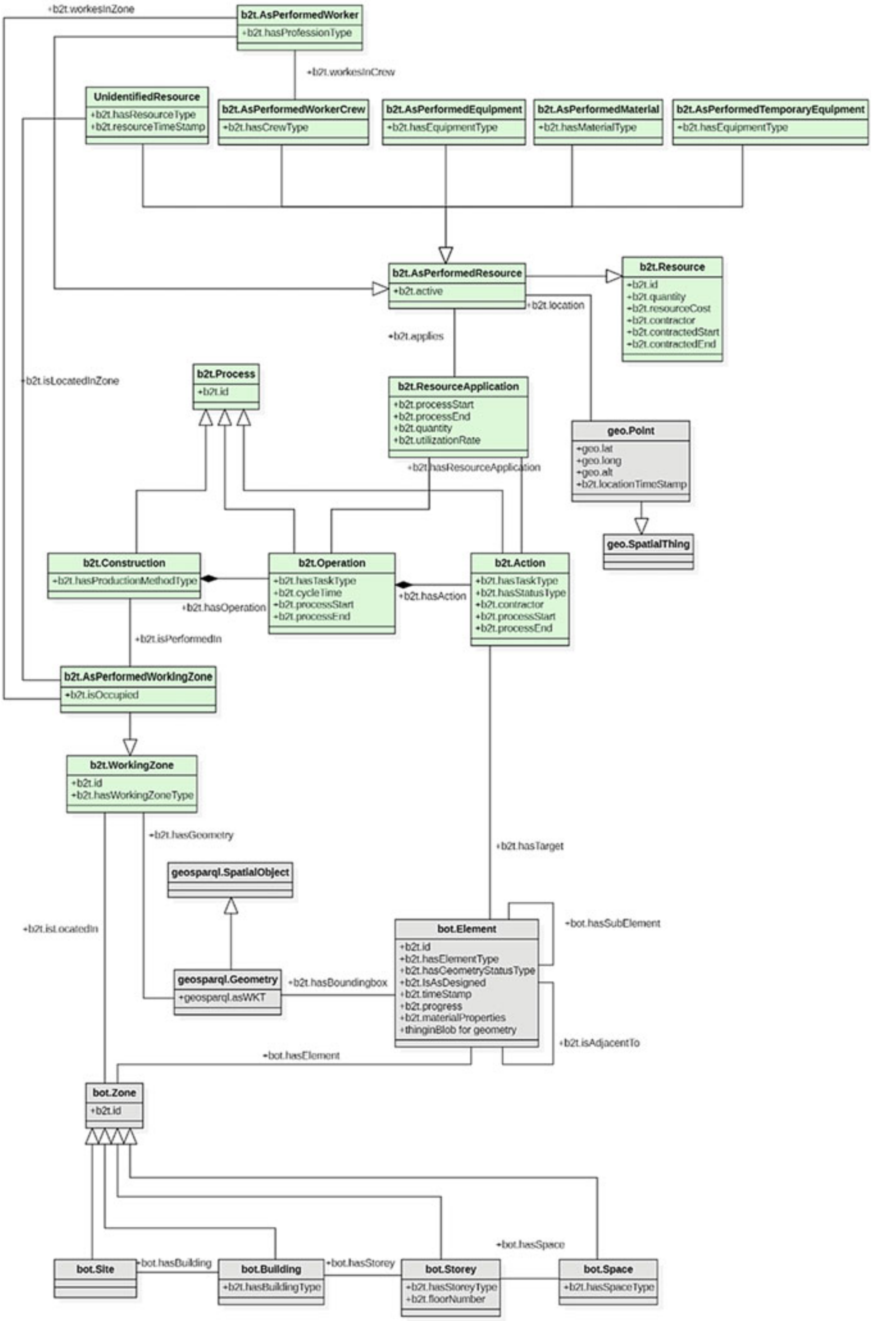


Fig. 5 UML model of the project status information (as-built and as-performed)

location and current activity/ inactivity can be monitored. At the same time, this information is not planned ahead of time.

Zones: Finally, the *zones* enable modeling of the location breakdown structure of the construction project, describing dedicated zones where processes are executed, represented through a direct link between them. Unlike the zones related to the building structure, they do contain geometric information. *Zones* can be equivalent to, e.g., a *storey* or a *space*, but a direct relationship is not always given. Overall, the *zones* are an essential indicator of the construction flow because flow can be judged on the occupation rate of worker crew and flow of materials but also on the occupancy of working locations [42].

6.2 BIM2TWIN Core Ontology

Based on the UML diagrams above the BIM2TWIN Core Ontology was implemented by translating the diagrams into the corresponding ontology classes, object properties, and data properties. Additionally, only domains and ranges of object and data properties were defined to improve reusability.

The lightweight BOT ontology is reused in the BIM2TWIN Core ontology for the classes related to the building structure. For the data layer of the DIKW-pyramid, SOSA/SSN and QUDT are reused to represent sensor data from the construction site and their units. The data layer is not shown in the UML diagrams above. The status of the BIM2TWIN data model and ontology presented here are the first stable version but will be further refined through testing on dedicated pilot projects. Once thoroughly tested, the ontology will be published online and freely accessible.

6.3 BIM2TWIN Platform

To provide access to a large number of applications and services providing and retrieving digital twin data, the described ontology is used as underlying schema of a central platform. In the BIM2TWIN project this platform is formed by the commercial product Thing' In by Orange, which in turn is based on the property graph database Arango DB. The platform allows to upload ontologies in the OWL format and transform its content into a graph meta model. By supporting various rule-checking languages like SHACL and ShEx, data manipulation requests can be checked for compliance with the used ontologies and further ensure the data structure. Instances of the ontology classes are represented by graph nodes with respective properties and edges to related nodes. Access to individual nodes is provided through a dedicated REST API.

7 Conclusion

In this paper, we have discussed the relevance of well-defined data structures for handling the complexity of digital twin information. We use the notion of the data-information-knowledge-wisdom pyramid to clearly distinguish between the different layers of abstraction. We show that simplistic approaches such as flat CSV structures can be suitable for handling bulk data such as temperature time series, but have clear limitations when it comes to the information level. Here, well-defined data structures are required providing clear and unambiguous specifications of the relevant information. Object-oriented modeling has been proven to be the gold standard of information modeling for many years now, providing powerful concepts such as encapsulation, inheritance and associations.

These concepts are also very suitable for representing digital twins of construction projects, which are dominated by a complex network of objects reflecting processes and products on various levels of granularity. We see ontology modeling as a suitable implementation of the object-oriented paradigm and presented the core ontology of the BIM2TWIN platform to underline this statement. In the project, the ontology is mapped to a property graph which is hosted by a dedicated cloud database, allowing fine-grained access for the distributed digital twin ecosystem.

With this paper, the authors hope to contribute to the discussion on suitable data structures for digital twins. We emphasize that in our view, digital twin technologies are a natural evolution of the BIM technologies, as both concepts are based on well-defined data structures. In this sense, many of the elaborated information models laid down in standards such as the Industry Foundation Classes remain absolutely valid and provide a solid foundation to build on. At the same time, however, a more flexible combination with small-scope ontologies is essential for digital twins, as well as a much more fine-grained data access that must replace conventional file-based data exchanges.

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Industry 4.0-Based Digital Twin Approach for Construction Site Tracking Purposes

Simon Kosse, Dennis Pawlowski, and Markus König

Abstract Construction sites are dynamic and complex systems with significant potential for time and cost efficiency improvement through digitization and interconnection. Construction 4.0 is the use of modern information and communication technologies known from Industry 4.0 (I4.0) to interconnect construction sites with cyber-physical systems (CPS). In these decentralized systems, construction workers, machines, and processes become smart I4.0 components that can exchange data and information with each other in a decentralized and self-controlled manner. The basis for informed decision-making to control and optimize relevant on-site processes is real-time detection of the current construction progress and the machines used on the construction site. Computer vision (CV)-based tracking systems offer a technical solution that can reliably detect construction workers and machines and track construction progress and processes. These tracking systems generate large amounts of data that must be processed and analysed automatically. The goal is to integrate the tracking system into the CPS as an I4.0 component. Essential for this is the digital twin as a virtual representation of an I4.0 component that centrally collects, processes, and provides data for the respective component. This paper presents an I4.0-based digital twin approach for digitizing and interconnection of the construction site into a CPS. The approach integrates a CV-based tracking system as an I4.0 component to locate construction equipment on the construction site. The tracking system is a multi-camera multi-object tracking system that uses stereo vision cameras and a real-time capable detector. The asset administration shell (AAS) is used as the platform for the digital twin.

Keywords Digital twin · Building information modelling · Asset administration shell · On-site · Industry 4.0 · Tracking · Monitoring

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1 Introduction

The construction of building structures is a complex process in which construction workers construct structures in manual processes according to precise instructions using various building materials, machines and equipment. Many of these processes can be partially automated through developments in the field of modern robotics. The prerequisite for end-to-end automation of the construction site is the digitization and interconnection of all actors and processes on-site. Construction 4.0 refers to introducing I4.0-concepts in the construction industry, through which the construction site is interconnected into a cyber-physical system (CPS). In this way, construction machines can autonomously exchange data and information and navigate around the construction site to accomplish individual tasks enabled through modern information and communication technologies such as the digital twin. Tracking systems that provide information about the position, pose, and velocity of construction machines and equipment are essential to the control and monitoring of the construction site. These tracking systems must be seamlessly integrated into the cyber-physical system of the construction site, so that they become I4.0-components.

Up to now, the current construction site situation has been recorded manually by site managers and foremen, who usually have to walk through the working areas of the construction machines [38]. Manual documentation records a momentary picture that is not suitable as a basis for informed decision-making. This process is labor-, time-, and cost-intensive. Continuous digital tracking of the construction site situation in real time provides reliable data for coordinating machines and manual labor. This purpose requires methods to detect and monitor the work of construction machines and equipment. A promising technology is the automatic evaluation of video data using CV techniques [37]. A significant advantage compared to other technologies, such as wireless sensors or laser scanners, is that camera-based approaches are much more cost-effective. A camera provides meaningful visual information and is widely used on construction sites through, e.g. surveillance cameras [22, 38].

This paper presents a concept for interconnecting the construction site to a CPS using the asset administration shell (AAS) to implement the digital twin. A camera-based tracking system is presented that is integrated into the CPS as an I4.0 component. The conceptualized tracking system is a first step to replacing the manual recording of the situation on-site. It can be used for the on-site location of construction equipment and to calculate key performance indicators such as equipment utilization rate as the rate of the construction site and utilization time. Furthermore, the tracking system is described in architecture and hardware, as well as its digital representation. The tracking system comprises a central system serving as a data aggregation layer consisting of individual camera components. The contents of the AASs are described in terms of data requirements. In a case study, the AAS of the central system and a camera component is implemented as prototypes. This paper aims to describe how a construction site can be interconnected into a cyber-physical system and how a tracking system can be implemented as an I4.0 component in it. The implementation demonstrates how an interface for I4.0-components can be modeled, which is suitable for the construction industry.

2 State of the Art

2.1 Digital Twin

Since its introduction in product lifecycle management, the digital twin concept has been adopted in many industries. As a result, there is no universal definition of the concept but rather a variety of definitions based on industry-specific characteristics [15]. For example, NASA defines the digital twin as an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system in its as-built state that uses the best available physical models and sensor updates to represent the life of the corresponding flying twin [7]. The manufacturing industry defines the digital twin as a data-based, virtual description of an asset connected to its physical twin via a data link so that processes along the value chain can be supported and made more efficient through the exchange of data between the physical and virtual worlds [32]. In this respect, the Digital Twin goes beyond a simulation and is a dynamic and intelligent model with a high degree of autonomy [3, 28]. The different definitions can be reduced to three main components: a real existing physical object, a virtual representation, and a data link connecting the two. Several works deal with the differentiation of the digital twin from other concepts [15, 29]. Kritzinger et al. [15] examine publications that address the digital twin as part of a literature review. Based on the degree of integration of the implementations, they distinguish the Digital Twin from the concept of a digital shadow and digital model. They define the Digital Twin as a digital representation with the bidirectional data flow. In contrast, they define the digital shadow as a digital representation with unidirectional data flow and a digital model as a representation without any form of data exchange. Their results show that it is not a digital twin in most publications, which again highlights the different understandings of the concept. In civil engineering, a digital twin is generally understood to be a virtual representation of building structures beyond simple digital models. The role of BIM in the context of digital twins is a controversial topic in the literature. It is either an evolution, complementary, or independent of BIM [30]. According to Boje et al. [2], BIM provides methods and data schemas, while the digital twin is much more process-oriented due to a bidirectional data flow. Furthermore, BIM does not have real-time data integration capabilities for which dynamic data exchange is essential. According to Davila Delgado et al. [6], both approaches offer answers to different industry requirements.

2.2 Industry 4.0 and the Asset Administration Shell

Industry 4.0 refers to the digitalization of the manufacturing industry through the interconnection of embedded systems. The connection of assets creates cyber-physical systems where products, machines, and processes are virtually connected via digital twins and can autonomously exchange data and information [10]. The AAS is considered the technical implementation of the digital twin in Industrie 4.0. As an information container, it provides all relevant data and information for production centrally for each asset and suitable interfaces for communication and interaction. The AAS consists of several submodels that combine to form the overall digital representation, each representing an aspect or use case. The submodels contain the static and dynamic data contents in properties and attributes. References to external files can also be stored. All data in the AAS is semantically described by concept descriptions, ensuring machine readability, which is the basis for machine-to-machine communication and interaction. Concept descriptions can be self-created or added by external repositories such as E-CLASS. Serializations in XML, JSON, OPC UA, or MQTT are available to ensure interoperability. In addition, there is a container format that includes external files referenced in the AAS in addition to serialization in XML or JSON. AAS can be used as type 1 for interoperable data exchange. This type contains only files and is not capable to communicate. Server-based systems with API-based access are type 2 AASs that allow content to be retrieved, modified or deleted. Type 3 AASs are server-based but have an active communication capability with other Industrie 4.0 components. The specially developed I4.0 language is used for this type of communication [25]. For more information, please refer to the official AAS documentation [26].

2.3 Computer Vision Technologies on Construction Sites

Image-based detection and tracking of construction equipment require an object recognition method in which a bounding box delineates the area of a target object in the image. This has recently been done by using a Convolutional Neural Network (CNN) [17], which determine the bounding box coordinates of each object and the corresponding class label. The use of bounding boxes allows equipment to be located later and avoids the need to obtain image segmentation masks, which require a more computationally intensive process. One branch of research uses this development to detect objects on construction sites. For example, two-stage detectors are used to evaluate the productivity of multiple excavators [5], measure the probability of cooperation or coexistence between two construction-related objects [21], improve safety [39], or detect small objects on construction sites [33]. Other contributions focus on single-stage detectors that achieve a higher inference rate than two-stage detectors and are, therefore, real-time capable [8]. Notwithstanding the lower localization and object detection accuracy, a single-stage detector can detect excavators, wheel loaders, and workers from the top view [12] or the terrestrial view [23]. It is also possible to check the status of construction machines [35] or detect small equipment [34] on construction sites.

However, a detector is insufficient for creating trajectories because it does not account for past images and does not estimate future positions of detected equipment. As a result, motion paths cannot be determined. A visual tracker is required to link a bounding box coordinate from image i - 1 to the new coordinate from image

i. This has already been identified in research and addressed in various papers. With visual trackers, it is possible to continuously track construction equipment, materials, and personnel with multiple cameras across multiple images [4, 14], even under challenging conditions on large construction sites [9]. This can provide movement paths that can be used for activity analysis during earthworks [27] or in proactive safety monitoring systems [31] since estimating future positions is possible. Similarly, if equipment or workers are temporarily obscured in the image, the position can be determined using the estimation [13, 36], which is why a combination of detection and tracking methods should be sought.

In addition to determining the trajectories, another step is required to obtain the 3D coordinates of the tracked equipment since the positions otherwise refer to the image coordinates. Related work in this area already uses stereo vision cameras to determine three-dimensional coordinates. For example, they are used to track construction resources such as construction vehicles, construction workers, or construction materials at a distance of up to 50 m from the camera with a maximum error of 0.658 m and a reliability of 95% [24]. Also, the method has been extended over time to generate corresponding 3D trajectories to different and multiple construction resources [18, 19]. Similarly, a study has shown that stereo vision cameras are sufficiently accurate to assist human inspectors in inspecting steel bars in quality control applications [11].

3 Concept

On construction sites, buildings are erected under high cost and time pressure with limited resources and space by construction workers and the use of heavy machinery. The interaction of the stakeholders is often very complex and unclear, so efficient planning and coordination of the construction work are a particular challenge. By providing a data and information basis that virtually mirrors the situation on the construction site in real-time, a possibility for efficient coordination and control of the construction process, as well as informed decision-making by the responsible parties, is given. The prerequisite for this is the continuous digitization and networking of the construction site, as well as a suitable tracking system for recording the construction process. Camera-based tracking systems are ideal for recording the position of construction machinery and equipment, as they can capture information not only about the position of the machines but also about orientation, pose, and speed. For smooth integration of a camera-based tracking system into an I4.0-based CPS, the system must be modeled as an I4.0 component. In this way, the tracking system can capture the environment of the construction site and communicate and interact with the actors. In the following sections, a concept for an I4.0-based CPS based on the administration shell is presented. In addition, a camera-based tracking system is developed and integrated into the construction site CPS as an I4.0 component. The tracking system is described in terms of its architecture, hardware, and virtual representation through an AAS. Data and information requirements are compiled for the development of the data structure of the AAS.

3.1 Construction Site as Cyber-Physical System

Figure 1 shows a schematic representation of a CPS for construction sites based on the concept of the I4.0 component from I4.0. The system is shown to consist of physical and virtual space. All assets on the construction site, such as construction machinery, equipment, and the building structure under construction, are represented as part of the physical and virtual space through an AAS, which functions centrally for each asset as a data container for collecting, evaluating, and providing relevant data. All assets are connected to their AASs via a data connection, e.g., via Open Platform Communications United Architecture (OPC UA). For implementing a CPS, a bidirectional data exchange is essential in a sense that a change of the asset on the real construction site results in a change of its virtual representation. This data exchange is also possible autonomously via advanced machine-to-machine communication methods. Essentially, this creates a decentralized system where participants can communicate to achieve individual goals. A dump truck, for example, can navigate autonomously across the construction site. To do this, it constantly exchanges information about its position, route, and speed with other actors present and operating on the construction site. Through further interaction with an excavator or crane, e.g., it can initiate loading and unloading processes. Humans, as one of the main actors on the construction site, do not have automated interaction capabilities with their environment or a digital representation. Interfaces to the virtual space are used,

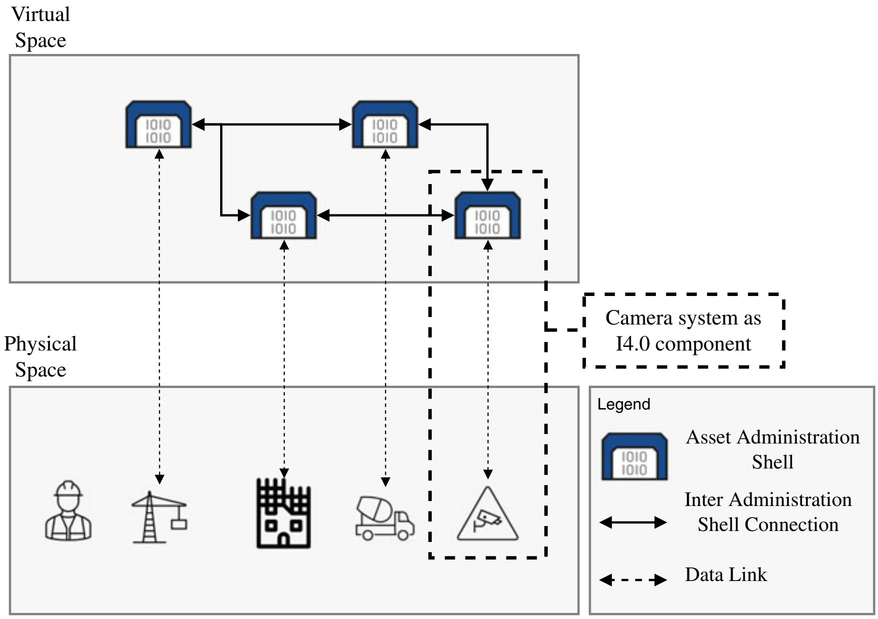

Fig. 1 Schematic representation of a CPS for construction sites

e.g., in the form of hand-held devices, with which data can be retrieved, manipulated, and visualized. In addition, humans can be recognized by the autonomously acting machines on the construction site through modern Artificial Intelligence (AI), and CV approaches to ensure safety.

3.2 Camera System

Figure 2 shows the camera system consisting of the central system and its individual components. In order to achieve full coverage of the construction site by the camera system, the site is divided into work areas. Work areas are spatially defined areas where construction work such as earthworks, concreting, or material delivery and storage is carried out. Several camera components cover each work area with partially overlapping capture areas enabling reliable coverage even if parts of the work are obscured, e.g., by buildings parts, machines, or piles of construction material.

Stereo vision cameras capture the position of machines and equipment in three-dimensional space [19, 24] by two horizontally offset cameras through which two different views are recorded. By comparing the images, the depth information can be obtained as a disparity map [16], encoding the difference in the horizontal coordinates

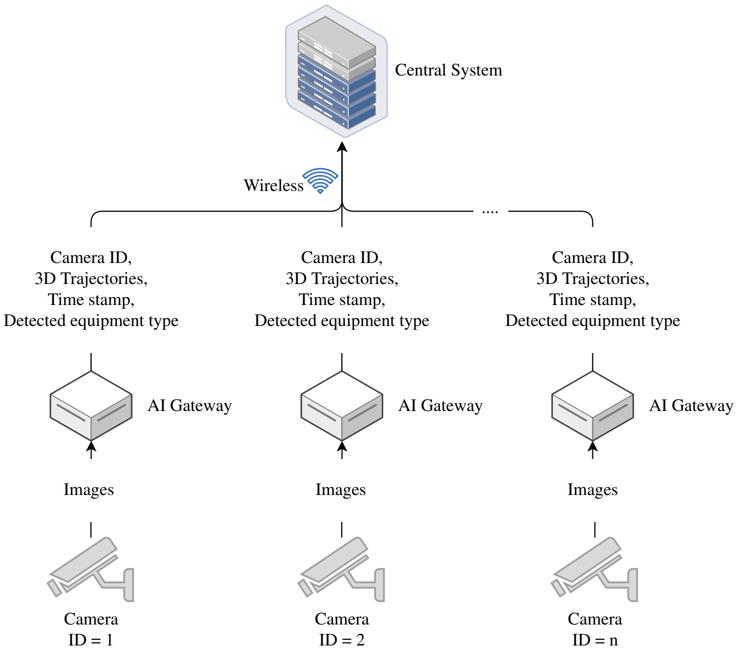

Fig. 2 Camera system for localisation of construction equipment.

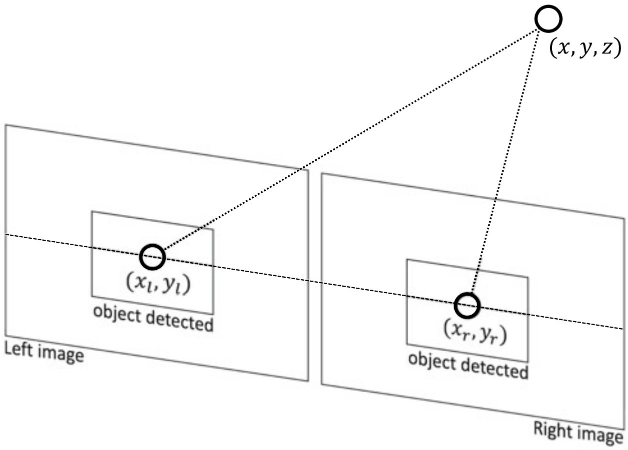

Fig. 3 Detection and triangulation to determine the 3D coordinates of an object.

of the corresponding pixels. When calculating the 3D coordinates of a target object, it is assumed that it is visible in both views since to determine the 3D coordinates of the detected object, a 2D tracking procedure is performed for both views, followed by a matching procedure to find pairs from both views. Triangulation is performed to calculate the 3D coordinates for the tracked objects (Fig. 3). The calculations are performed on a powerful edge device such as the Nvidia Jetson [1]. By providing an edge device for each camera component, the 3D coordinates of the detected equipment are determined in a decentralized manner rather than centrally, thereby distributing the computational load across the entire system. When construction equipment is detected, the 3D coordinates are combined into trajectories with unique IDs associated with the equipment. The edge device sends this information regularly to the central system, which collects and aggregates data from all edge devices. In addition, the device type for each trajectory and a time stamp for each 3D coordinate are transmitted. The Central System creates a 3D model of the construction site based on the transferred data to visualize machine and equipment positions. For site logistical reasons, the data transfer is wireless. The data transmission, as well as the power supply of the cameras, can be done either by Power of Ethernet (POE) or Power over USB (PoUSB) [20].

With the initialization of the system, each camera is assigned a unique ID and associated with a work zone. In addition, the position of a camera within the assigned work zone is stored in the model, which is located in the central system, which can be done automatically by transmitting GPS coordinates or manually entering them into the model. The position of the camera center and the camera's orientation are transferred to the global coordinate system to later display the positions of the detected equipment in the model after calibration.

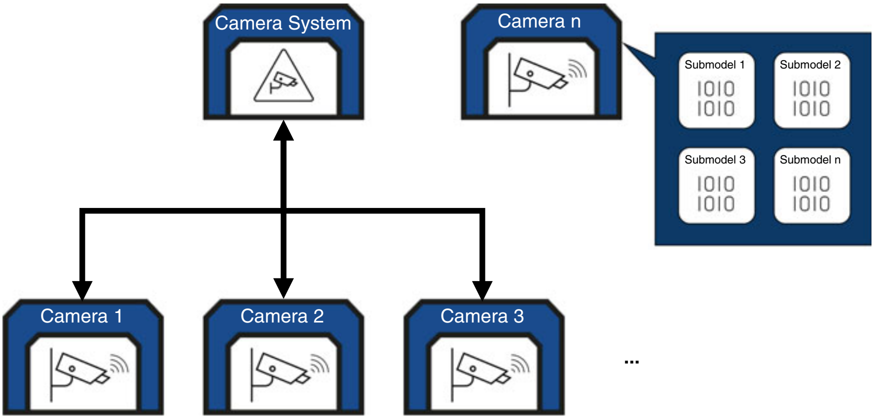

Fig. 4 Structure of a camera system as an I4.0 component.

3.3 Camera System as I4.0-Component

To integrate the tracking system into the CPS construction site, it must be implemented in an I4.0 component-compliant manner. In this way, other participants in the CPS can access the data content and interact and communicate with the tracking system. Figure 4 shows the structure of a camera system as an I4.0-component. The tracking system and each camera component consisting of a camera and AI edge device are represented in virtual space by an AAS. The AASs contain all relevant data and information required for tracking. Especially for tracking occluded objects, the data exchange made possible by interconnection is essential. Components can transmit tracking data of occluded objects for detection by neighboring components. Data of tracked objects are transferred to the AAS of the central system for aggregation and location in the central system. AASs of the camera components and the central system must be modeled to implement an I4.0 compliant tracking system. For this purpose, the data and information requirements must be identified and assembled.

Data Requirement of the Central System. The AAS of the central system contains data and information about the overall architecture, including information about contained cameras, their position, and Globally Unique Identifier (GUID). If the construction site is divided into work areas, information about the layout is stored. Furthermore, the tracking data of the camera components are aggregated. For each tracked object, position, orientation, and velocity are stored. For visualization of the aggregated data, data and information for visualization of the central system are available, for example, in the form of an IFC model.

Data Requirement of a Camera Component. The AAS of a camera component contains information about its hardware and position in the central system. If the construction site is divided into work areas, each component knows its work area. Optionally, each component knows its neighbor to help with occurring connection errors. Tracking data can then be transmitted to the AAS of the central system via neighboring components. For unique identification, each component has a GUID. In this way, tracked objects can be permanently assigned to the tracking camera. Essential for the precision of camera-based tracking is the calibration of the cameras. For this, information about the installed sensors must be available, as well as real-time data recorded via the sensors. Furthermore, the extrinsic and intrinsic calibration parameters are stored. Data on the position, trajectories, orientation, object type, tracking GUID, and optionally velocity of the objects tracked by the component need to be recorded.

4 Case Study

The contents of an AAS are stored in submodels that enable a self-contained view of one use case or aspect at a time. The Standardization Council Industrie 4.0 already offers standardized submodels that provide a reasonable basis for content for standard aspects such as identification, documentation, and technical data. Subject-specific submodels must be developed separately for each use case. In this case study, templates for AAS for a central system and individual camera components are developed based on the data requirements elaborated in Sect. 3.3. For each submodel, both the envisioned use case and contents are described. In addition to properties and attributes, submodels may contain Submodel Element Collections (SMC) to further structure the data within a submodel.

4.1 Asset Administration Shell for a Camera Component

The AAS of a camera component is responsible for collecting, evaluating, and providing all relevant data and information for tracking construction machinery and equipment. It serves as an interface for communication with the central system and other camera components. In addition to the standardized submodels for identification, documentation, and technical data, the AAS of a camera component contains submodels for the acquisition of tracked objects, installation, and calibration as well as the integration of real-time sensor data (cf. Fig. 5).

Submodel Tracking. The Tracking submodel is used to capture objects that are tracked by the camera component. For this purpose, the submodel is extended with SMCs for each tracked object. In each SMC, all relevant tracking parameters are captured, which are necessary for further processing. In the planned use case, objects tracked by the camera component are captured via their tracking parameters. The tracked objects are provided with a globally unique ID and made available for further processing in the central system. The SMC for the acquisition of the tracked objects includes further SMCs that contain position, orientation and velocity data as well as

Fig. 5 AAS of a camera component.

the dimensions of a virtual bounding box. Furthermore, a globally unique tracking ID is assigned, and the object type and status are recorded. A history of the data is stored in a .csv file that can be used to create motion trajectories.

Submodel Installation. The installation submodel provides data for the calibration of the camera and contains the position of the camera in the central system. In the planned use case, the camera queries data required for setup. In regular construction operations, it must always be expected that cameras will be repositioned by workers, which will result in recalibration. The submodel consists of three SMCs for capturing the camera's position in the central system, the orientation of the camera, and calibration parameters. The SMC for capturing the position contains the coordinates of the camera component in the central system. The coordinates can be GPS coordinates to visualise the location of the camera on a site plan. In the SMC orientation, rotation and tilt angles of the camera are recorded. The SMC calibration includes further SMCs to capture sensor data and intrinsic and extrinsic camera parameters. Sensor data includes real-time data from the gyroscope, accelerometer, magnetometer, barometer, and temperature sensor.

Submodel Sensor Data. The Sensor Data submodel is used to capture the real-time data from the various sensors of the camera component. The data recorded here is redundant to the sensor data recorded in the Installation submodel. An essential property of submodels is the completeness concerning the data requirements of the considered use case. Given the above, data redundancy is acceptable. The user receives all sensor data when accessing the Sensor Data submodel and does not have to query further data from other submodels. The data stored in this submodel correspond to the data described for the Installation submodel.

4.2 Asset Administration Shell of the Camera System

The primary purpose of the of the central system is to aggregate the tracking data from the individual camera components. The data is collected and made available for further applications. In contrast to the AAS of a camera component, the AAS of the central system only contains the standardized submodels identification and documentation. The AAS of the central system is essentially a virtual aggregation level for which the recording of technical data is not required. In addition, the AAS of the central system contains submodels for aggregating tracking data from the camera components, visualization, and capturing the central system's architecture. A description of the purpose and intended use case of the submodels follows (cf. Fig. 6).

Submodel Tracked Objects. The Tracked Objects submodel is used to aggregate the objects tracked by the individual camera components, including their tracking parameters. In the intended use case, all data and information of the objects tracked in the system are managed centrally and made available for further use. This submodel

Fig. 6 AAS of a the central system.

stores the SMCs received from the AAS of each camera component. The SMCs are only extended by further property to capture the camera ID of the tracking camera component, which is named "TrackedBy". In addition, the total number of objects tracked in the central system is captured by the property "CurrentlyTrackedObj".

Submodel Visualization. The visualization submodel provides all relevant data for visualizing the tracked objects in the central system. The visualization is based on an IFC model of the construction site. In the intended use case, it should be possible to display the objects in the model in real-time and to retrieve the tracking data interactively by the user. The submodel contains an external IFC-model of the construction site. In addition, a reference to the Tracked Objects submodel containing all data and information of the tracked objects is included.

Submodel System Architecture. Information on the layout of the central system is stored in this submodel, including the camera components' number and position and the construction site's division into working zones. In the intended use case, the submodel provides information on the central system's layout. The information can be used, for example, to optimize the layout. Construction sites are dynamic constructs for which it should be possible to constantly change the camera components' positioning to enable the cameras' densest possible coverage.

5 Discussion and Conclusion

Construction sites are highly dynamic environments where people interact with machines to build structures. It is essential to know the position, status, and current tasks of all actors on the construction site as well as the current work progress and upcoming work, to ensure efficient coordination. By digitally recording this data and information and interconnecting the various stakeholders, it is possible to control better and coordinate work and make an essential contribution to safety on construction sites. Furthermore, digitalization and networking are prerequisites for more autonomy and modern robotics use. As part of I4.0, the manufacturing industry is being digitized and networked into cyber-physical systems in which intelligent products seek an optimal path through the production system under their control. Smart products can communicate and interact with people and machines. Using technologies from the context of I4.0 on the construction site has great potential to transform construction site operations with lasting effect.

This work extends state-of-the-art with an approach to implementing an I4.0-based cyber-physical system on the construction site. The presented approach has a camera-based tracking system that captures important data of the stakeholders on the construction site. The AAS is used to implement the digital twin, enabling the collection and machine-readable provision of data. Standardized interfaces give access to this data. The presented approach is the basis for efficient coordination, control, and informed decision-making.

The approach presented is a theoretical concept that the authors have not yet been able to validate in a practical example. Future work envisages validation on a model. In recent years, significant progress has been made in the field of sensor technology, which is not integrated by the approach presented in this paper. Integration of sensor technology could diversify the data set and make tracking more precise. Furthermore, a hybrid tracking system could improve accuracy.

Future work will extend the present work by the possibility of autonomous machine-machine communication. The I4.0 platform is currently developing a special I4.0 language that will be used for this purpose. In addition, submodels are to be standardized as far as possible to enable flexible integration and compatibility with different systems. For the data visualization, a platform is planned to display the collected data in real time and enable interaction with the digital twins.

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Requirements Management for Flow Production of Precast Concrete Modules

Simon Kosse, Oliver Vogt, Mario Wolf, Markus König, and Detlef Gerhard

Abstract For efficient and sustainable use of precast concrete modules, all relevant information must be collected digitally and in real-time and made available in digital twins. Digitization should be carried out in such a way that continuous quality management is possible at all times. This also includes whether the produced concrete modules also meet all the requirements from the initial design. For example, the precast concrete parts must be able to absorb certain forces or have precise connections and joining options. The Requirements Interchange Format (ReqIF) can be used to describe requirements digitally and exchange them between different IT systems and stakeholders. The creation of automated quality control (QC) protocol for the flow production process can be implemented based on this already structured and formalized requirements format. In this paper, the Asset Administration Shell (AAS) from the context of Industry 4.0 is enhanced to enable the formal description and automated verification of requirements for precast concrete based on the ReqIF interchange format. For this purpose, a smart service integrates the ReqIF-compliant requirements into an AAS submodel. Via this smart service, a mapping assistance tool lets stakeholders assign measurable properties of the precast concrete modules to the requirements, thus enabling an automated quality check. The presented approach is validated based on a virtual precast concrete wall for which a chain of linked requirements is described and automatically checked within the scope of a case study.

Keywords Industry 4.0 · Digital Twin · Precast Concrete · Requirements · Rule-based Checking

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1 Introduction

Industry 4.0 refers to using Internet of Things (IoT) technologies to automate the manufacturing industry. Products, machines, and processes are interconnected to form decentralized cyber-physical systems within which data and information are exchanged for self-controlled and self-managed production. These systems are made possible by the use of modern information and communication technologies. Initial applications to the production of precast concrete modules show the potential for significantly increasing efficiency through end-to-end digitized and automated production of precast concrete modules in modern flow production processes. In terms of precast construction, building structures are segmented into modules. As part of this segmentation, modules must fulfill certain functions and requirements, such as the transfer of specific forces, compliance with tolerances, or fulfillment of building physical properties such as fire resistance, thermal insulation, and sound insulation. Requirements also exist regarding the components' connections, dimensions, and weight. Concepts for automated testing must be developed to verify the requirements imposed on the components.

A prerequisite for implementing cyber-physical systems according to the I4.0 model is the digital twin, which manages and provides data and information in a centralized manner for each asset. It contains all data and semantic information relevant to an asset throughout its life cycle. Intelligent and consistent requirements management is essential for smart products as well as smart production systems. Faults or deviations from requirements must be detected and corrected early to guarantee the quality of the end product. The digital twin should not only have information about its state but also be able to represent and check requirements. A prerequisite for automated testing is the formal description of requirements, which can be functional or quality requirements. The requirements brought into the digital twin of a concrete module must be complete, unambiguous, consistent, and verifiable.

This paper presents an approach for formally describing requirements for precast concrete modules in the context of industrialized manufacturing based on the Requirements Interchange Format (ReqIF). The ReqIF format is an exchange format based on the XML schema that enables the formal description of requirements. The requirements described in ReqIF are integrated into the AAS, which is the technical implementation of the digital twin. A submodel extends the AAS for capturing requirements described in ReqIF format and mapping of the requirements to properties and characteristics in the AAS. Verification of the requirements is performed using an external service. The following research questions are answered:

- How can requirements be formally described and integrated into the digital twin?
- How can the AAS be extended to facilitate the automated verification of requirements?
- How can the automated verification of requirements be integrated into the industrialized production of precast concrete modules?

2 Related Work

2.1 Industry 4.0, Digital Twin, and the Asset Administration Shell

Industry 4.0 refers to the digitalization and automation of the manufacturing industry by networking products, machines, and processes into cyber-physical systems. Real and virtual space are linked through innovative communication and interaction technologies, enabling industrialized production in which intelligent products independently seek an optimal path through the production system, interacting and communicating with machines and processes. For the implementation of Industry 4.0, the digital twin plays an essential role as a virtual representation for collecting, evaluating, and providing data and information.

Since introducing the concept of the digital twin as the conceptual ideal of Product Lifecycle Management (PLM) [1], the concept has been taken up by many different industries, each developing its definition. As a result, no universal conceptualization of the digital twin exists [2]. However, in most definitions, the digital twin is described as consisting of a physical and virtual representation and a data link that connects the two. A key issue in construction deals with the role of Building Information Modeling (BIM) in the context of the digital twin. In their paper, Davila Delgado and Oyedele [3] state that both concepts are unique approaches for different industry requirements in each case. While BIM has been designed to increase efficiency in design and construction, the digital twin has been designed to represent the current state during manufacturing operations through real-time data that enables data-driven decision-making and simulation of what-if scenarios [3–5].

The AAS corresponds to the technical implementation of the digital twin in I4.0. It is composed of many individual submodels to form an overall digital representation. Each submodel represents an aspect or use case. The submodels have all the relevant data and information required to represent the corresponding use case. The actual contents of the submodels can include attributes and properties in the form of key values and references to external files. All data have concept descriptions that uniquely specify the data ensuring machine readability and thus enabling automated data exchange between AAS and machines. File formats include serializations in.xml and. json. In addition, a package format (.aasx) is available that has all other contents and references in addition to serializations in.xml or. json. The AAS can be used as a passive AAS for interoperable data exchange or as a passive or active server component. The AAS data can be accessed via standard REST query, OPC UA or MQTT [6]. A special I4.0 language is being developed for autonomous communication and interaction between AASs [7].

2.2 Requirements Management in Construction

Requirements management has its origins in systems and software engineering. Here, it is a branch of software technology that deals with the objectives, functions, and constraints of software systems, as well as the specifications of software behavior and their evolvement over time [8]. The main activities of requirements management include eliciting, modeling and analyzing, communicating, agreeing, and developing requirements [9]. According to Fernie et al. [10], transferring requirements management to the construction industry helps comply with costing and time schedules, view project decisions from a life-cycle perspective, and improve overall customer satisfaction. Several types of requirements exist in the construction industry. Customer requirements combine with site, environmental, and regulatory requirements to form design and construction requirements [11]. The goal of requirements management in construction is to fulfill all needs and requirements of all stakeholders involved in the construction of a building [12]. In the construction industry, requirements management is often not considered over the entire life cycle of a building but is increasingly applied in the early planning phases. Requirements are assessed once, not updated, or made available in a central repository for later lifecycle phases and use [13]. In their work, Jallow et al. [14] present a platform for managing requirements across all life phases of a building project. For the platform, they follow an information-centric, process- and service-oriented approach. Compliance with tolerance requirements is integral to requirements management, especially for precast concrete structures. Talebi et al. [15] report that the construction industry lacks a systematic practical process to avoid tolerance problems that often occur during assembly on construction sites. Their study reviews existing guidance in the literature and divide tolerance management into the stages of identification, planning, communication, and control. They present a holistic conceptual framework that integrates all stages of tolerance management and aims to improve conventional tolerance management. Rausch et al. [16] developed a domain model for tolerance management that consolidates scattered knowledge on tolerance management into a standardized uniform framework. The tolerance knowledge is formalized to make it unambiguously interpretable by software systems enabling automated tolerance management. Their approach is based on an initial BIM and an analysis of key tolerance relationships through a sequence of inference rules to create a semantically rich BIM with tolerance management concepts. The enriched BIM can support effective tolerance management through analysis and simulation.

2.3 Requirements Interchange Format - ReqIF

The Requirements Interchange Format (ReqIF) is an open, non-proprietary exchange format with which requirements can be exchanged in a formalized and interoperable manner [17]. The metamodel of ReqIF is based on XML schemata and contain the requirement meta data and content in the form of attributed data elements and other associated data such as documents and images. The XML schema consists of a root element consisting of a header and the requirement data. The requirement data consists of the data elements SpecObjects, by which the requirements are represented, Specification, that a hierarchical structure of SpecObjects represents, SpecRelations, that represents links between SpecObjects as well as SpecType, which specifies which data types an element can have. Further information can be found in the documentation of the exchange format. For further information please refer to the official documentation [18].

3 Concept

Requirements of various categories are relevant to concrete modules during and after modularization and for prefabricated construction. This is true especially for structural requirements in the form of minimum load-bearing capacities and dimensional accuracy, as well as functional requirements regarding heat, moisture, and fire protection. In addition, industrialized production imposes requirements for each process step that must be checked either during or after a process step. These can include, for example, minimum concrete strengths for stripping the modules of their formwork or temperature ranges to be maintained during heat treatment of the modules. The technical requirements for construction are distributed over several standards and guidelines, such as DIN EN 13,369 [19], which specifies general rules for precast concrete components, or product standards that specify component-specific requirements, such as DIN EN 14,992 for wall elements [20]. For quality-assured production in the sense of I4.0, requirements must be integrated into the digital twin of the modules to enable automatic verification and ultimately informed decision-making for the humans in the production process.

Figure 1 shows the schematic representation of the concept for integrating requirements into the AAS. Initially, the requirements are created, maintained and distributed across the various planning phases, from initial planning, through the preliminary, draft, and approval planning, to detailed design. Through these planning processes, the requirements for individual building components evolve based on customer requirements in conjunction with requirements for the construction site, environment, and regulatory requirements into design and, finally, construction engineering requirements for the individual building components. During the planning phases, the digital representation of a concrete module exists only as a type AAS, which already has the required data structure but does not yet contain any instance-specific

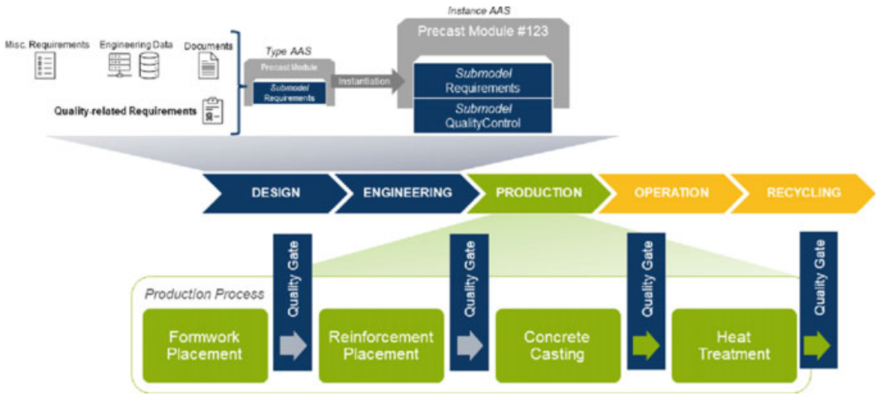


Fig. 1 Concept for the integration of in ReqIF formalized requirements into the AAS

values, as there is no physical counterpart yet. The instance AAS of the respective concrete module is created only by transferring the planning data into the AAS at the end of the detailed design phase. It is assumed that the requirements determined during the planning phases are available in a digital building model.

These requirements can be defined in different software tools, which can result in them having different structures and formats. This means that simple integration into the digital twin is not possible. Therefore, an interoperable data format is necessary that stores requirements in a structured manner independent of the software platform. For this purpose, the ReqIF data exchange format, known from mechanical engineering and based on an XML data structure, is ideally suited.

Since ReqIF is only an exchange format, certain defined attributes must still be specified for the requirements description so that the requirements have a uniform structure. A template is developed for this purpose in this paper. Based on this template, the requirements can be exported as an ReqIF-File and then be integrated into the digital twin. To transfer the requirements data to the AAS, the requirements are exported to a ReqIF file and send to the'AAS' import service.

For this purpose, an AAS submodel definition for managing the requirements is developed. To make the requirements automatically testable, it is also necessary that a mapping to measurable properties is stored in this submodel. Likewise, rules or conditions must be stored for the mapped properties, which must be met for the condition to be fulfilled. The submodel contains a data structure for storing the requirements and their metadata, as well as information for mapping the requirements to other properties and characteristics in the AAS, e.g., data stored in the QualityControl submodel as part of quality control.

Requirements for concrete modules differ with respect to the module type. This enables the predefined requirements to be mapped to the data contained in the AAS enabling fast integration and automated checking of these requirements. At the end of the detailed design, the digital twin of a precast concrete module is created that has all relevant data for production, including production and quality requirements.

During production, services can continuously check the requirements, e.g., against collected quality data.

The work is based on the template of an AAS for general precast concrete modules, which was developed as part of the authors' extensive preliminary work [21]. The template is extended by a submodel for capturing and mapping requirements to properties and features in the AAS.

In the following, an attribute schema is proposed for a ReqIF template. Attribute schemas are not standardized and must be specified separately for each use case, similar to submodel definitions in AASs. In addition, the requirements submodel developed within the scope of this work is described concerning contents and intended use cases.

3.1 ReqIF Template for Requirements of Precast Concrete Modules

Essential for the development of ReqIF templates for the formalization of precast concrete requirements is the definition of an attribute schema. Attributes add important semantic information to requirements that, among other things, allow requirements and their intentions to be defined, maintained, and verified. Attribute schemas are not standardized and must be defined for the particular application. Different sources in literature recommend structures for such attribute schemas, e.g., [22]. In general, adding attributes to the schema is only recommended if a clear added value or use case exists through the attribute so that the schema is not cluttered with unnecessary information and eventually becomes confusing. Besides standard attributes like GUID, name and description, some use case specific attributes were selected (cf. [22]):

VerificationMethod: Specifies the recommended method for checking the requirements. Verification of tolerance requirements can be performed, for example, by a 3D point cloud acquired by laser scanning and a nominal/actual comparison.

VerificationPhase: Time or life phase in which the requirement is checked. For example, the time for checking a minimum compressive strength for stripping could be specified here. The attribute is particularly essential for coordination with regard to automated checking.

VerificationResults: This attribute specifies the result of the verification of the requirement. Document verification results are summarized by a short string, e.g., successful, or unsuccessful. Some requirements required verification of multiple properties and characteristics.

VerificationStatus: Status of the review of the requirement. The attribute summarizes the result of all performed checks.

ComparisonOperator: This attribute specifies a comparison operator that is used for automated requirements testing by an external service as part of quality assurance.

Mapping: Assignment of the requirement to the corresponding properties in the AAS.

LimitValue: Defines the outermost value that must not be exceeded or fallen short of in order to comply with the requirement.

3.2 Submodel Requirements

Submodels are elementary components of administration shells that contain all essential data in a context-specific manner and provide the administration shell with functionality. Standardization of these submodels is sensible in order to maintain interoperability and adaptability. Some basic submodels, such as those for identifying, documenting, and representing technical data of assets, have already been standardized by the Standardization Council Industrie 4.0. For specific use cases, submodels and their data contents must be developed accordingly. For integrating requirements of precast concrete parts into the AAS, a submodel is developed that stores the requirements along with their metadata. It specifies a mapping of the requirements to the data contents of the administration shell as a basis for automated testing. The focus is in particular on:

- integration of requirements for precast concrete modules into the AAS using the ReqIF exchange format,
- mapping of requirements to properties and attributes in the AAS for requirements verification,
- machine-readable provision of requirements for automated compliance checking through an external service.

The requirements are first extracted from a ReqIF file in the intended use case and imported into the submodel. The enhanced semantic description in the AAS by concept descriptions enables the machine readability of requirements data. In conjunction with a reference link to the corresponding data in the AAS, it enables the requirements to be checked in a nominal/actual comparison.

The submodel represents every requirement by a Submodel Element Collection (SMC) containing the attributes specified in the ReqIF file (cf. Figure 2). Some requirements require the verification of multiple properties and attributes. Dimensional accuracy, for example, is a requirement for a precast concrete component that can only be verified by checking various tolerance values. The resulting partial requirements are each stored in a further SMC together with their metadata.

Fig. 2 Template of Submodel Requirements

4 Case Study

For validation, the concept is applied to the single-shell lining segment with conventional steel reinforcement, illustrated in Fig. 3. Linings are manufactured in precast plants with extensive quality assurance measures. The functions to be fulfilled by lining segments comprise essentially the absorption of actions from dead weight, superimposed loads, and sealing against groundwater. In single-shell structures, all structural and design requirements are taken over by the lining segments, which is

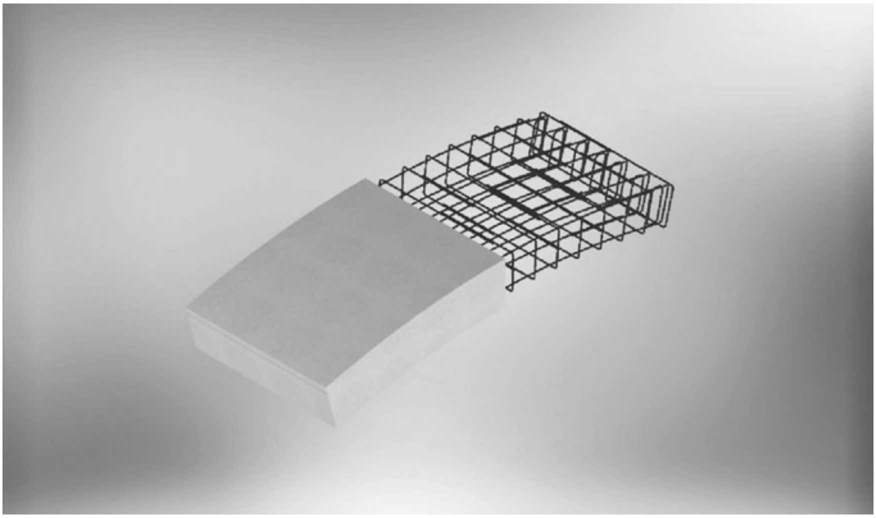


Fig. 3 Tunnel lining segment

why the requirements for single-shell structures are particularly high. The requirements placed on the lining segment in this case study are taken from the DAUB Recommendation for the Design, Manufacture, and Installation of Segments and from ZTV-ING Part 5, Sect. 3 [23, 24]. An type AAS is first created based on the template presented in [21] for the illustrated lining segment. Subsequently, the AAS is extended according to the presented approach by submodels for capturing the requirements formalized in ReqIF and mapping the requirements to the attributes and properties in the submodels of the AAS. The functionality is demonstrated by an external smart service that validates the requirements.

4.1 Integration of Requirements into AAS

Figure 4 shows the the ReqIF studio editor with the content of the ReqIF-file, which has been created for the tunnel lining module based on the attribute scheme presented in Sect. 3.1. The file contains exemplary requirements for the minimum compressive strength for stripping the module of its formwork as well as for the minimum reinforcement and dimensional accuracy based on [24]. Both the minimum reinforcement and dimensional accuracy requirements require the verification of several sub-requirements. Accordingly, a hierarchical arrangement of these requirements has been made. The result of the verification of all sub-requirements is indicated by the VerificationStatus attribute of the superordinate requirement. Figures 5 and 6 show the requirements and quality assurance submodel after successfully integrating the requirements and performing measurements for quality assurance.

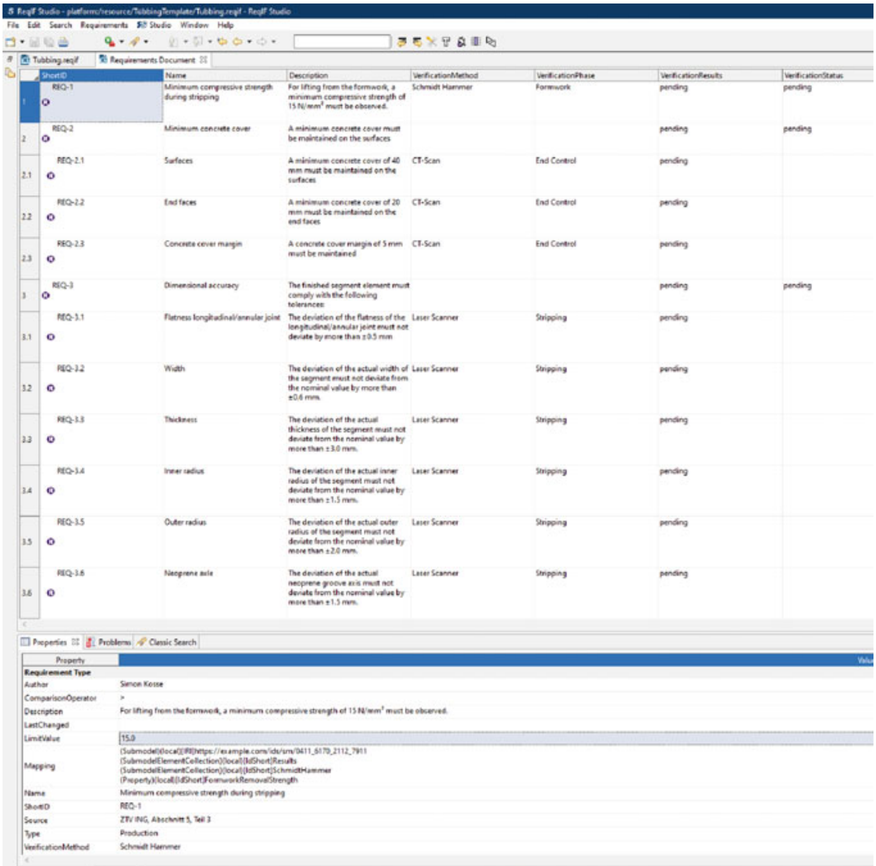


Fig. 4 ReqIF file of tunnel lining module

4.2 Compliance Checking of Requirements

The automated execution of the requirements compliance check is based on the submodel structure presented earlier in this paper. The AAS is made available on a server so that the contents of the AAS can be queried, updated or modified via the Rest API. The server used in this case study is an instance of the open-source AASX server [25]. Initially, the AASX file is loaded by the AASX server's services, making its contents retrievable via a standardized REST API.

Since it is possible to communicate with the server via the Rest API, different implementation options for the requirements checking service are possible. For this case study, a web-service based on Python (respectively PyWebIO) is developed, which communicates directly with the AASX server. The accordingly created user interface can be used to select which asset the automated check should verify. To do this, the service queries all type-matching AAS hosted on the server and provides

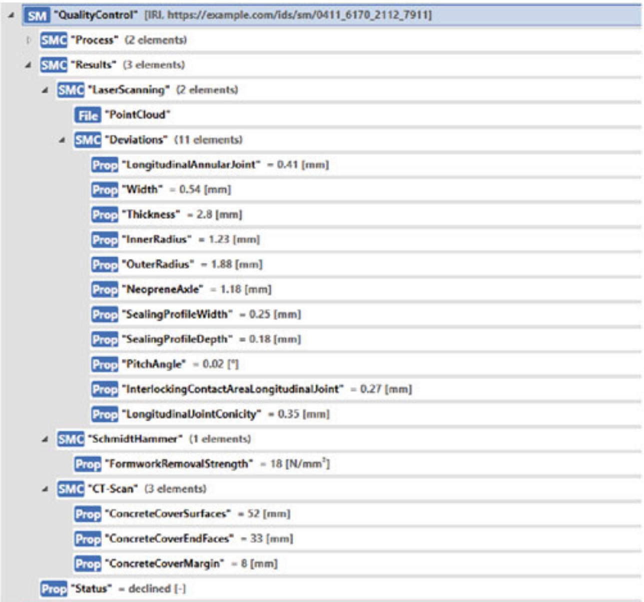


Fig. 5 Submodel Quality Control of tunnel lining module

the user with the results as a drop-down selection. Once the desired asset has been selected, the service queries the contents of the requirements submodel of the selected AAS. The web service presents this content graphically to the user. For this purpose, the requirement as such is displayed with its status as well as each individual condition that is required for the fulfillment of the requirement (see Fig. 7).

At this point, no check has been performed yet. The check is started by clicking the "run requirements check" button. The service now processes the requirements to be checked one after the other. For each requirement, the individual conditions are checked, provided the status of the requirement is not already set to "fulfilled". To do this, the service queries the actual value stored in the AAS for the property to be checked and compares this with the NominalValue specified in the requirements file on the basis of the comparison operator selected. If the condition was met, the status of the condition is set to "fullfilled" and the next condition is checked. If all conditions of a requirement were checked, the status is set to "fulfilled" or "not fulfilled" depending on the status of each condition. The individual statuses and the current value of the property are also displayed to the user in the web interface.

Since these values are stored temporarily in the web service, they must finally be transmitted to the AAS via the Rest API. Thus, the results of the check are stored and can be used for further use cases.

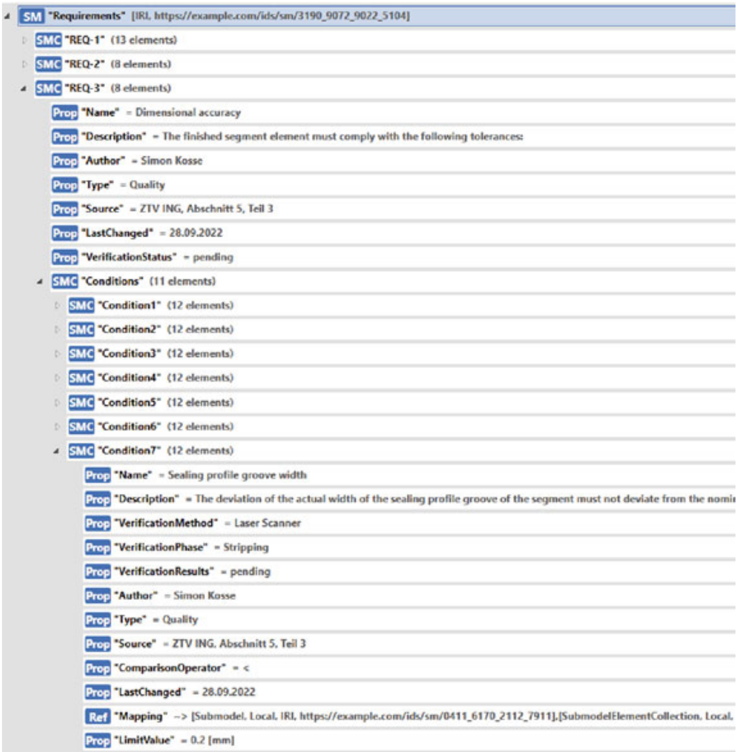
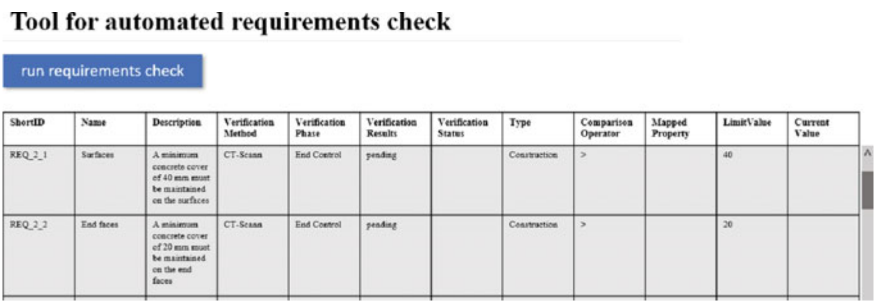


Fig. 6 Requirements submodel of tunnel lining module



ShortID	Name	Description	Verification Method	Verification Phase	Verification Results	Verification Status	Type	Comparison Operator	Mapped Property	LimitValue	Current Value
REQ_2_1	Surfaces	A minimum concrete cover of 40 mm must be maintained on the surfaces	CT-Scann	End Control	pending		Construction	>		40	
REQ_2_2	End faces	A minimum concrete cover of 20 mm must be maintained on the end faces	CT-Scann	End Control	pending		Construction	>		20	

Fig. 7 Tool for automated requirements check

5 Conclusion and Outlook

Precast construction is characterized by the segmentation of building structures into individual modules, which have to fulfill specific requirements and functions. In the context of industrialized production based on the I4.0 model, compliance with these requirements must be continuously checked in an automated manner in order to ensure the quality of the precast concrete part. A prerequisite for the automated verification of the requirements is their formal description. This paper presents an approach to extending the AAS known from I4.0 by requirements specified in ReqIF format and automated verification. A submodel was developed to capture the formalized requirements, mapping the requirements to the features and properties available in the AAS. An external smart service was developed for automated verification. The results of the checks are the basis for information-based decision-making and are an essential prerequisite for implementing a decentralized and autonomous production system.

This paper shows the first prototypical implementation of automated requirements testing. It has not yet been applied in the context of a fully automated and digitized production system. The approach is limited to the requirements of single modules. The verification of requirements of multiple components is essential in the context of a modularized design.

Future work will address the handling of the results of the verification. The question of how to deal with concrete modules that do not meet the requirements is to be clarified. The handling of rejected modules has a direct impact on production planning. Integration of a real-time simulation of the production system for continuous optimization and control in order to be able to react dynamically to these changes is planned.

For the testing of geometric and material requirements, measurement data are usually used that have a certain degree of uncertainty. Consequently, a test of these requirements does not always provide a discrete result. Concepts of probability logic can be integrated into the presented approach. Finally, all resulting changes regarding human, technology and organization will be investigated further in the coming implementation phases.

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Embedding RFID Tags into Precast Structural Components for Tracking and Holistic Real-Time Lean Construction Management

Abduaziz Juraboev and Joaquín Díaz

Abstract Building Information Modeling (BIM), Lean Construction Management (LCM) and many other methods are already used to optimise the processes and increase the efficiency in the construction industry. Construction site management can be digitalised using common Industry 4.0 technologies, like smart devices and assets (tablets, smartphones, sensors, beacons, etc.). Mobile devices are nowadays an essential tool in our everyday life, and applications that can be used on construction sites support staff in organisation and communication. Furthermore, they can aid with project control and monitoring, as well as with supply chain management processes.

This paper presents a concept for connecting precast structural material with integrated RFID tags with BIM models in real time by using electronic readers and mobile device applications. In order to connect the physical components with their virtual or digital representations, the attributes of BIM models were used, into which the unique ID of the RFID transponder were implemented.

As a novel approach, BIM models were connected wirelessly to physical building materials by using RFID and wireless IoT technologies in a cross-platform application, thereby enabling the BIM models to be actively used throughout the life cycle of a building (planning, production, construction, maintenance and operation). Application areas include material tracking, warehouse inventory management, transportation planning, real-time model-based scheduling and model based navigation.

Keywords Precast Component Tracking · Radio Frequently Identification (RFID) · Building Information Modeling (BIM) · Lean Construction Management (LCM)

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1 Introduction

1.1 Background Research

The actual state, the control and the monitoring of the construction progress are an integral planning process that involves specialists of various trades to carry out the construction measures. The execution of a construction project is successful if the quality and the costs are met with regard to the schedule. For this, timely delivery of construction materials with proper installation at the construction site are significant. The use of digital technologies in construction compared to other industries lags behind [1]. According to a 2017 McKinsey Company report, productivity in construction is slow and many construction projects do not meet the cost and time schedule requirements. This is mainly due to communication problems and a poor performance management control [3]. Most construction companies use email as a communication tool, in which planning documents and information are shared with partner companies. In this process the overview is easily lost and a lot of time may be spent searching for information [11].

The precast construction industry in Germany has a yearly total turnover of more than 3 billion euros. In 2021 around 27,100 new buildings were completed using modular precast construction methods. Around 20,000 of these buildings were residential. The number of prefabricated constructions completed represents about 20% of all built structures per year. In 70% of new buildings the use of prefabricated wood, and in 25% the use of prefabricated concrete and steel reinforcements were approved [13]. Modular construction using prefabricated products offers several advantages over conventional construction: The readily to be used prefabricated materials allow a faster construction process, and the manufactured precast building materials are of consistent quality, reduce the risk of work accidents on construction sites and are more environmentally friendly, due to less wastage.

1.2 Motivation

A fully digitalised construction site is still a considerable way away, but the work presented here are the first steps towards this and can already be implemented. The tools and peripheral devices are nowadays already available, however, what is missing is the coordinated implementation of track-and-trace technologies for material tracking. Track-and-trace technology enables consistent tracking of components and materials. The technology is used for parcel tracking by the well-known parcel logistic companies, such as FedEX, UPS, DHL etc. In order to create a broad application to use track-and-trace technologies, passive RFID tags can be integrated into construction materials. In order to be compatible with the 'Construction Industry 4.0', a standard that can be used effortlessly by all participants must be developed.

The motivation to connect physical objects (e.g. buildings, roads) with digital technologies (e.g. ERP systems, BIM) in the construction industry, was to avoid production and construction delays, material delivery standstills and unnecessary storage spaces in urban areas.

1.3 State of the Art

Almost everyone carries an item containing a Radio Frequency Identification (RFID) chip (e.g. bank and ID cards). RFID describes a technology for transmitter–receiver systems enabling automatic and wireless identification and localisation of objects using radio waves [6]. Generally, auto-ID technology's essential function and mission are to provide information about people, animals and items (e.g. goods and materials). RFID systems extend the traditional auto-ID method functionalities and application possibilities, and offer a high efficiency-improvement-potential [5]. RFID systems can be used in a large variety of industries and applications. According to a study by the German Federal Office for Information Security, an RFID system is defined by the following three characteristics: *1. Electronic Identification,* whereby the system enables objects to be uniquely identified by electronically stored data; *2. Wireless data transmission,* whereby the data can be send out wirelessly via radio frequency channels for identification of the object; *3. Send on call operation,* a marked object only sends its data when a particular reader calls up this operation [5].

In the construction industry the use of RFID technology in connection with Building Information Modeling (BIM) work methodology has been widely researched, for example, for automated construction progress recognitions, occupational health and safety, orientation and wayfinding in the case of fire, construction monitoring, as well as tunnel construction [4].

A BIM model is a comprehensive digital image of a structure. It typically contains the three-dimensional geometry of the single elements of the building in a defined level of detail. It also includes non-physical objects, such as rooms and zones, and a hierarchical project structure. These objects are typically associated with a well-defined set of semantic information, such as the component type, materials, technical properties, and the relationships between the components and other physical or logical entities ([10], p. 6).

One of the standardised BIM data exchange methods is the openBIM approach, which uses software products from different manufacturers and open, non-proprietary data exchange formats.

The basis for the openBIM data exchange is the Industry Foundation Classes (IFC) Standard (ISO 16739–1:2018). With the help of the IFC format, BIM data can be exchanged and shared between different software applications [8]. Furthermore, IFC is a general data scheme that includes all information of all life cycle phases involved in a construction project; it was developed by buildingSMART International (bsI) [2]. According to bsI, BIM is the basis for the development of digital twins in the Architecture Engineering Construction (AEC) industry [4]. A digital twin is a virtual representation of physical assets and objects [9].

Lean construction encompasses approaches for sustainable value creation and waste reduction in the construction industry. The associated project implementation structure is based on 'just-in-time tracking' and the principle of 'takt planning', transparency and collaboration, efficiency-enhancing methods, continuous improvement and learning. 'Takt planning' is a scheduling method that is highly visual, shows all three types of flow, is scheduled with rhythm, continuity, and consistency, that has buffers, in one-process flow. To implement lean project delivery, the 5Rs principle must be applicable in the areas of materials, information and trades. 5Rs stands for: (1) right material, information and trade with the (2) right quality, detail and qualification, at the (3) right time, in the (4) right quantity and at the (5) right place or construction stage.

This paper presents the integration of passive RFID tags into precast construction materials during their production phase, and the connection of those to IFC-based BIM models. The idea was to create a real-time digital representation of physical environments and to track construction materials in order to support lean construction management processes on construction sites.

2 Methodology

2.1 Concept

The used materials in this study were RFID, IFC, a cloud-based application framework and precast structural components. Methods of embedding passive RFID tags into building materials and linking serialised RFID numbers with cloud-based BIM data were investigated. The goal was to electronically capture building material specific data by assigning uniquely coded passive RFID tags to BIM models.

By digitally capturing building materials it is possible to assign unique and model-based data to it. This is possible in different phases of AEC processes, the fabrication, construction (4D/5D), logistics, operation and maintenance, renovation, and demolition. By scanning the materials in the above-mentioned phases, the status information is updated in a model-based approach. The basis for the development of a model-based digital twin is to provide a unique product identifier for the materials.

The concept was to integrate the passive RFID tags into the building materials, such as tiles, doors, windows, prefabricated steel and reinforced concrete parts, as early as in the material production stage. The advantage of RFID tags over commonly used QR-codes is that they are more robust and can be permanently implanted in the structural materials. The tags are battery-free and, depending on the installment method and power supply, have a long reading range. They can be used, due to their longevity, in operation phases after the construction is completed, and also in various application fields [12].

Fig. 1 Embedded passive RFID tags (rivTAG) in prefabricated steel structural profiles (Ed. Züblin AG)

The tags can be installed either on the surface or the inside of the structural materials. In dense materials (like steel and aluminum) the RFID tags have a reduced reading range and therefore should be placed on the surface in order for the emitted radio waves to reach the RFID scanner. Figure 1 shows passive RFID tags embedded in prefabricated steel structural profiles (used by the company Ed. Züblin for structural component tracking on construction site) [7].

By integrating the RFID tags into the construction materials, the tag UIDs were linked to the digital building objects via a programmed cloud-based platform. A RFID reader connects through the tag-UIDs with the mobile application. BIM models, based on the international open standard IFC-File, were uploaded into a web platform. Here it was possible to change the status information for tracking the construction materials.

2.2 Implementation

The implementation of passive RFID tags, IFC-based BIM models and a cloud-based open-source prototype application platform was investigated regarding precast tracking materials used on construction sites.

BIM models using Autodesk Revit were developed in the planning phase with all information in the form of attributes. Since RFID tags are not yet mapped in the current edition of the IFC standard ([10], p.56), they were integrated into the existing IFC file format by using proxy elements '*IfcBuildingElementProxy*' and property sets. RFID tag unique IDs were defined as attributes in Revit and exported to the IFC file format. This enabled the physical object to be linked to the virtual BIM model using peripheral devices (reader, smartphone) containing app (Fig. 2).

The passive RFID tags were inserted into different precast materials (e.g. concrete and steel slabs, paving stones). The construction materials were read by scanning

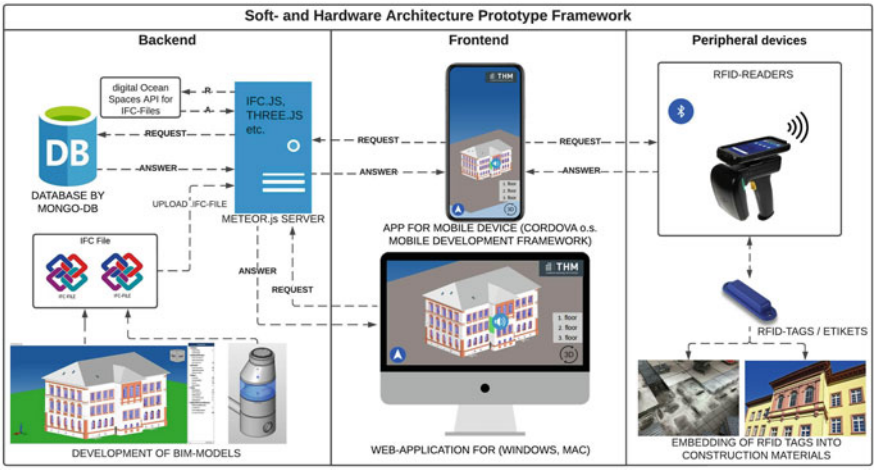

Fig. 2 Components for Embedding of RFID tags, and Soft- and Hardware Framework

them with the electronic peripheral device. The physical real building objects were linked by the app to BIM models when scanning the RFID tags.

As a cross-platform solution a mobile web app for smartphones was created that connects to the RFID reader using Bluetooth and Wi-Fi. When scanning an RFID tag embedded material, the data can be retrieved in the platform and status information can be updated manually in the app. Figure 2 shows the illustration of the developed application platform for the embedded RFID tags into construction materials and BIM models.

3 Precast Component Tracking on Construction Sites

Ed. Züblin AG is a construction company, which also manufactures trackable steel components for the use on their building sites. One of those sites was visited in order to firstly, gain knowledge about process of precast tracking, starting from the fabrication of the trackable precast materials to their use on the building site. Secondly, to learn about the practical production, application and implementation of trackable precast construction materials.

Component tracking, after material production, from the factory to the construction site has far-reaching advantages. The plant and assembly planners, as well as the site managers, get to know the exact delivery time of the materials at an early stage. This is accomplished through ability to update, using a mobile app or a hand-held scanner, the current status information embedded in the tagged structural material.

Tracking is mainly achieved by using QR codes or passive RFID tags. Ed. Züblin AG and the partner companies largely use QR codes for component tracking in order

Fig. 3 Example of QR codes attached to prefabricated staircase on a construction site

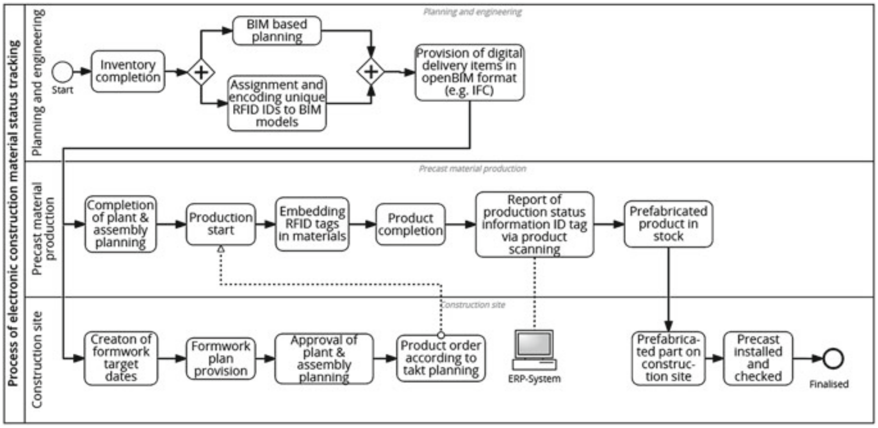

Fig. 4 Overview of electronic precast construction material tracking

to ensure timely delivery of building materials to the construction site and to ensure takt-planning. This is becoming more and more important in urban environments where there the lack of storage is increasing continuously. The production factory, assembly planning company and construction site only share the information status (e.g., manufactured, ready for delivery, delivered, built, tested, finished) of the precast material via a common platform by capturing the QR code stuck on the precast element. This kind of tracking eliminated the need to write numerous emails, as all involved companies can track the processes. BIM model components can be linked to the QR codes, and the status changes can be visualised and highlighted in different colours by scanning the item. To share information on a commonly shared platform, BIM models do not need to contain highly detailed information; this would slow down the data transformation. Therefore, it is sufficient if BIM models are developed to a low or medium level (Fig. 3).

In order to successfully implement precast tracking on construction sites, several process steps need to be carried out. Electronic component tracking is a basic tool for site management control, track and monitor scheduling, production, delivery and installation of components. With real-time component tracking, target/actual dates of construction site progress can be compared. The process steps of construction component tracking using passive RFID tags (embedded into precast structural components during their production), including their connection to BIM models, is illustrated in Fig. 4.

In future, Ed. Züblin AG plans to use passive RFID tags embedded in the precast products for the tracking-process. Therefore, the integration of RFID tags into precast construction materials must be standardised according to the material used.

4 Conclusion

In order to improve lean construction principles precast material tracking, employing passive RFID tags connected to IFC model-based platforms, were created. This approach can be utilised for real-time material tracking of construction components. Product information exchange between partner companies becomes possible by using a shared platform containing the updated status information.

Passive RFID transponders can be used for 20 to 30 years and longer, depending on the construction type. Embedded RFID tags precast components provide a permanent solution for manufacturers, logistics companies, construction contractors, facility managements and end users alike. In future automated tracking of construction materials containing RFID tags should be standardised.

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