

Berardo NATICCHIA, Alessandra CORNELI, Alessandro CARBONARI

Framework based on building information modeling, mixed reality, and a cloud platform to support information flow in facility management

© Higher Education Press 2020

Abstract The quality of information flow management has a remarkable effect on the entire life cycle of buildings. Manual retrieval of technical specifications and features of building components and their performance assessment leads to increased cost and time and efficiency reduction, especially during the facility management (FM) stage. The introduction of building information modeling (BIM) in the construction industry can provide a valuable means of improving the organization and exchange of information. BIM tools integrate multiple levels of information within a single digital model of a building. Nevertheless, the support given by BIM to FM is far from being fully effective. Technicians can benefit from real-time communication with the data repository whenever the need for gathering contextual information and/or updating any data in the digital model arises. The framework proposed in this study aims to develop a system that supports on-site operations. Information requirements have been determined from the analyses of procedures that are usually implemented in the building life cycle. These studies set the standard for the development of a digital model of a building, which will be shared among various actors in charge of FM and accessed via a cloud platform. Moreover, mixed reality is proposed to support specific information that is relevant to geometric features and procedures to be followed by operators. This article presents three use-cases supported by the proposed framework. In addition, this research article describes the first proof of concept regarding real-time support for FM.

Keywords information flow management, BIM, mixed reality, common data environment, facility management

1 Introduction

The facility management (FM) stage is the longest phase of the entire life cycle of buildings and incurs the highest amount of expenses (Lee et al., 2012; Pishdad-Bozorgi et al., 2018). This stage addresses many issues affecting building management. The majority of these issues are caused by fragmentation, which hinders the smooth information flow among various actors in the construction industry (Becker et al., 2018). Hence, the management of information flow itself is a critical challenge (Lee et al., 2012). For example, the retrieval of specific information required for maintenance operations within a building is a time- and cost-consuming process for all stakeholders (Gallaher et al., 2004; Keady, 2013). Parties that use the provided information must, at best, pay to have the data keyed into the relevant data systems. At worst, facility maintenance contractors are paid to survey an existing building to capture the as-built status. In these cases, building owners pay twice: Once for the construction contractor to complete the documents at the end of construction and again for the maintenance contractor survey (East and Brodt, 2007). Moreover, in most cases, the procedures for handling the information flow require the handover of paper documents and lead to errors, delays, and ultimately higher costs (East and Brodt, 2007; East et al., 2013).

Information from previous stages is often insufficient to ensure the correct implementation of maintenance operations in the FM stage (Becerik-Gerber et al., 2012a). Information, such as manuals, technical specifications, and renovations, is difficult to collect, whereas information, such as operational and asset management, is usually missing (East and Brodt, 2007).

Received June 30, 2018; accepted August 30, 2019

Berardo NATICCHIA, Alessandra CORNELI (✉), Alessandro CARBONARI
Department of Civil and Building Engineering and Architecture (DICEA), Polytechnic University of Marche, Ancona 60131, Italy
E-mail: a.corneli@pm.univpm.it

To date, digital transition in the construction industry provides an excellent opportunity to enhance the efficiency of information flow and FM. The automation of processes can be the correct path toward improving efficiency. The support of machines to human tasks has made saving time and avoiding errors possible. However, the intended automation in this study is not achieved by eliminating human intervention but rather by supporting it with tailor-made applications for the automation of processes.

Digital transformation has its own cost. First, building information modeling (BIM), which has been increasingly adopted in the architecture, engineering, and construction (AEC) industry, can improve efficiency. BIM models should also act as unique repositories of building information. However, the modeling process requires effort, especially for existing buildings, whose design drawings need to be translated into their BIM versions. Second, to move toward a digital work environment, digital formalization of procedures is recommended. When this transition involves the retrieval of process information, procedures become complex because they may refer to several teams and skill sets. Finally, the digital workflow integration represents another cost of this transition.

Fragmentation in the construction industry is a well-known issue. Given that multiple stakeholders are involved in a building's life cycle from the design to its management, interoperability is a crucial aspect. Thus, interoperability must be considered not only among different stakeholders but also among different input formats. In addition to data exchange, information flow occurring in real time during interventions must also be considered especially when managing emergencies. Interoperability between different input formats and real-time information flow represents important goals, and the digital availability of multidisciplinary skills can significantly improve the actual performance. Cloud platforms can meet these needs and provide a virtual place that users may adopt as a data repository. Data can be uploaded in real time and continually enriched with several types of information. Accordingly, mixed reality (MR) can be used to manage real-time information well. The MR capability of overlaying the virtual and real world represents a powerful tool for the direct visualization of on-site information and then overlaying it on the object undergoing maintenance work.

The study starts with an in-depth analysis of issues and related needs in the maintenance sector. Assisted diagnoses, automatic detection of components, automatic surveys for the collection of information, and remote support for troubleshooting are scenarios offering excellent opportunities for improvement. The automation of procedures will trigger efficiency and productivity improvements. For each of the aforementioned processes, the appropriate on-site management of information is necessary for the correct execution of procedures.

This study aims to demonstrate the feasibility of a

management system for information flow using all the aforementioned technologies, which have already been tested individually in the construction industry. However, to the best of the authors' knowledge, the combined use of such technologies has not been investigated. The technologies will allow the interaction between real- and digital-world users. Certain types of technology integration have already been tested in the construction industry but for different purposes. Studies have been carried out to display on-site drawings with holograms rather than through paper or digital supports (Chalhoub and Ayer, 2018). Moreover, the application of holograms is often tested in the construction phase of the building life cycle (Wang et al., 2004). This study focuses on the FM phase, and its innovation lies in the combination of the following factors:

(1) The use of BIM.

(2) The use of MR, which represents a powerful tool for connecting digital information with the real world. Due to recent advancements, MR can be used on-site without the need for sensor-equipped buildings and provide operators with the possibility of benefitting from digitized information.

(3) The use of a cloud platform, which can be taken as a tool to have constant access to data and as a link between digitized information and collected on-site data.

Moreover, this study aims to define the procedures for three use-cases toward efficient interventions in FM. The first use-case refers to building surveying. The second use-case is considered an efficient support system to building diagnosis. The third one is intended to support on-site operations via a preliminary assessment of on-site information retrieval by means of MR in a maintenance scenario.

2 Literature review

2.1 Information management

Information generation and management are serious challenges in the construction and FM stages in the construction industry (East and Brodt, 2007; Lee et al., 2012). The generation of information can be understood easily because it starts from the design phase of the project and is involved in each type of data collection even in the following phases of the life cycle. However, information management is complex. It includes information availability (discussed in detail later in this part), which can exist only in conjunction with the development of information systems. Information management defines all processes regarding information (acquisition, storage, retrieval, processing, interpretation, communication, and use), which must be performed in a timely and continuous manner to be efficient (Chen and Lu, 2019).

In this study, the word "information" refers to data that

have been processed, interpreted, and sorted to obtain a specific meaning. For instance, when an operator submits a query in a database, he/she is collecting information. The word “data” refers to raw data that have not been processed, and the Cambridge dictionary defines data as collected information for use. In managing information flow, the properties of data must be taken into account. According to Wand and Wang (1996), these properties can be defined as follows: Accuracy and correctness, timeliness and currentness, and completeness and consistency. However, Daft and Lengel (1986) report that organizations usually process information to reduce uncertainty and resolve ambiguity. These two features refer to accuracy and correctness and completeness and consistency. In maintenance operations, compliance with these aspects is unclear because of the large amount of information required. Information is varied and requires the resolution of uncertainty and even ambiguity. To this end, knowledge on various types of information, such as maintenance records, work orders, and causes and knock-on effects of failures, from different members of construction teams is required for the decisions of facility managers. The increased fragmentation in the production and management of information leads to considerable difficulties in the correct transmission of data.

Furthermore, other aspects that must be considered along with the information required for intervention are the completeness and timeliness of data for the relevant parties (Chen and Lu, 2019). In this study, the completeness and timeliness of data are defined as “availability”. Another key challenge in the operation and maintenance stage is the need for sufficient information on products readily available (e.g., specifications, previous maintenance work, specialist professionals recommended for the work) (Motawa and Almarshad, 2013). Moreover, one key issue about maintenance information is the know-how created from operations, such as lessons learned from the causes of failure, reasons for selecting specific maintenance methods, selection of specialist contractors, and the ripple effects on other building elements (Motawa and Almarshad, 2013). This knowledge produces the fundamental know-how for training new personnel; hence, it should be properly retrieved.

2.2 BIM for operation and maintenance

The FM stage of a building is the main contributor of costs in a building’s life cycle. Many studies agree that the life cycle cost is five to seven times higher than the initial investment costs and three times more than the construction cost (Kelly et al., 2013). Therefore, FM is crucial for identifying increasingly efficient methods used in the management of the building life cycle.

At the same time, BIM has become the new international benchmark for improved efficiency and collaboration in

the different stages of the building life cycle (Ibrahim et al., 2017). Despite this recognition, certain studies continue to focus on the contribution of BIM in the operation phase of buildings. Furthermore, studies on several information areas have not been performed (Ding et al., 2014). The literature shows consistent findings on the benefits that BIM may offer to FM. These benefits stem mainly from:

- Improving the current manual process for information handover;
- Enhancing data accuracy;
- Increasing efficiency in work execution.

These remarks are derived from the precise localization of elements, which the BIM model provides, and the potential to enrich the digital models of buildings (Kelly et al., 2013). Spatial information required in emergency management proves the importance of BIM application. Organized data displayed logically are essential during an emergency to respond with appropriate actions. A link between the BIM model and FM databases can help in the detection and diagnosis of construction equipment on the basis of the information required (Ibrahim et al., 2017). Effective and immediate access to information during operations minimizes the effort required and helps avoid potentially ineffective decisions made in the absence of information (Ergen et al., 2007).

2.3 Cloud-based systems for information management

Several studies have focused on cloud applications in the construction industry because of their ability to support projects in sharing documents and information. Although BIM tools support the enhanced management of information, the increases in the amount of data, exchange, and sharing of addresses present a series of challenges (Zhang et al., 2014). Furthermore, the format of industry foundation classes (IFC) cannot store and transport information over several stages of the construction process. Therefore, developing a “cloud BIM information exchange mechanism” that allows users to query only the required information in the field of building maintenance is necessary (Redmond et al., 2012).

Chuang et al. (2011) used cloud computing to develop a visual system for viewing and manipulating BIM via the web with no time or distance limits. A main advantage of cloud computing is its ability to support information exchange in real time (Miller, 2008; Zhang et al., 2014).

2.4 MR for operation and maintenance

Although the FM stage of construction predominantly affects the costs in the life cycle of buildings, little consideration is offered to the improvement and “free thinking”, namely, the search for new methods and procedures, in the delivery of services for building maintenance (Royal Institution of Chartered Surveyors

(RICS, 2009), probably because building maintenance and FM are seen as noncore functions that merely provide supporting services in organizations (Waheed and Fernie, 2009). The latest technological applications are being tested in combination with other sectors of the construction industry. In this regard, MR is a type of innovative technology.

By definition, any environment incorporating the aspects of physical and computer-generated realities that overlap with virtual objects over a user's field of view of a real space is MR. MR is initially tested for on-site operator support, operator training, and on-site access to information about equipment management. This technology can improve users' perception of the real environment by showing information that users cannot directly acquire otherwise (Wang et al., 2004).

This study focuses on the integration of the BIM virtual model and the real environment and operators and the testing of the MR approach in three new scenarios, that is, inventory/survey support, diagnosis, and remote support to operations.

3 Issues and needs in the FM phase

FM involves multidisciplinary activities; consequently, it poses extensive information requirements (Ibrahim et al., 2017). The most important preconditions suggested in the literature include maintenance work, assisted document/information retrieval, component localization, automated support for procedural management, personnel training, and automated identification and modeling of components—all of which are fields of particular interest. Assisted document and information retrieval is based on the use of BIM software tools. The digital model, apart from containing different types of information, can be supported by cloud-based data storage systems for any procedure or extended information that cannot be included in the model itself (RICS, 2009; Volk et al., 2014; Scherer and Katranuschkov, 2017).

The literature presents that the information needed in FM depends largely on the type of facilities and operations to be carried out. Hamledari et al. (2018) outlined the details associated with the inspection process, including the person/head of the organization, defects, as-built type, as-designed type, data capture tools, time/date of the inspection, inspector's notes, and the images captured. Pishdad-Bozorgi et al. (2018) performed a detailed analysis of the identified on-site components by using OmniClass classification and integrated it with field data in a COBie (Construction Operations Building information exchange) worksheet.

A further requirement for information involves component localization. On-site maintenance personnel traditionally relies on paper-based blueprints or on their experience,

intuition, and judgment in finding and locating equipment. However, the as-built digital model can be useful despite the clear visualization provided by the 3D model (Krukowski and Arsenijevic, 2010; Ibrahim et al., 2017).

Another crucial type of information involves the procedures that must be followed, for example, the type of maintenance and repair work that must be performed, when it must be done, how it can be safely undertaken, and which one takes precedence (RICS, 2009). These information requirements are currently provided in personnel training, which is managed mainly through presentations, on-site visits, hands-on demonstrations, and self-study. However, such requirements are time-consuming and their results depend largely on the skills and experience of trainers (Ibrahim et al., 2017). This practice will certainly benefit from organized information management and advanced visualization and support tools (Oesau et al., 2014; Quintana et al., 2017).

Finally, the final geometry of buildings often differs from the original plans. Thus, the reconstruction of a precise 3D model is a common requirement. Efforts in automated modeling have focused on the segmentation and recognition of large structural components, often on external rather than internal components. In addition, the majority of studies have focused on capturing geometric data rather than other semantic representations of buildings (Brilakis et al., 2010; Tang et al., 2010; Adan et al., 2011; Klein et al., 2012; Mill et al., 2013; Ma and Sacks, 2016; Lu et al., 2018). Specifications about assets, for instance, can be beneficial to further operations. To this end, Quintana et al. (2017) developed an early example of a recognition system for small components. In recent years, with the worldwide adoption of the BIM methodology, additional studies have increasingly focused on the semantic enrichment of BIM models (Bloch and Sacks, 2018; Xue et al., 2018). Nevertheless, minimal achievements have been reported on reduced modeling and conversion efforts into BIM objects with a high semantic value from construction data (Oesau et al., 2014; Previtali et al., 2014).

4 Proposed method and system architecture

The analysis of FM issues and needs identifies many challenges encountered in the construction industry. The architecture depicted in Fig. 1 shows the various components for managing information in different ways.

The first one is represented by the BIM model containing the necessary information to support operations, including the geometric building model and database. The complete definition of information required in the BIM model is not covered in this study because of its dependence on the specific use of the model within the FM

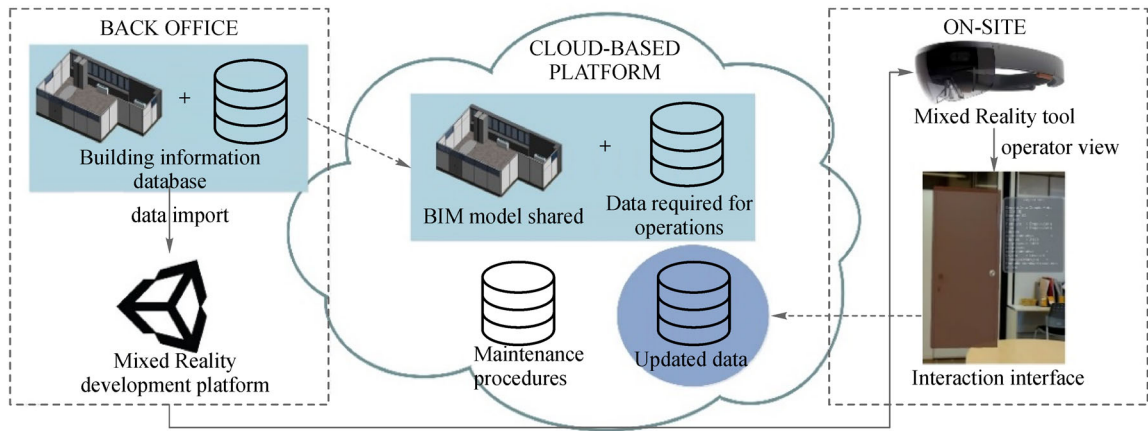


Fig. 1 System architecture of the three different places of action, namely, back office, cloud-based platform, and on-site. The arrows represent the flow of information, whereas the dashed lines show the transfer points toward the cloud-based platform. The back office and on-site sides of the system share data with the cloud-based platform, which is designated as the sole repository.

phase. This topic has been continuously studied. Motawa and Almarshad (2013) defined a methodology for knowledge management and developed a case-based reasoning system to provide technicians with information related to the BIM object. Chang and Tsai (2013) suggested treating maintenance records as medical records especially in systematization and verification. Finally, Becerik-Gerber et al. (2012a) conducted surveys and interviews to outline all the needs of a BIM model supporting FM. This information, once translated into a BIM model of the building, is then imported into the MR development platform (Unity) to set up the on-site application that will run on the HoloLens.

Furthermore, a cloud database has been indicated as the correct tool for managing large amounts of data (Phan et al., 2014). Cloud databases allow the enrichment of building models with information in formats differing from those of the IFC. Given that all the maintenance information must be on-site and constantly updated and managed in real time, online management through the cloud database is important.

The last tool is the on-site MR application. This tool requires the development of interfaces between the two previous methods (i.e., BIM and cloud) and virtual data. These data must be able to flow from the office to on-site operations and vice versa. Therefore, the interfaces between MR and data collection systems should allow the necessary information to be displayed on-site and record and transmit information. This interface is developed using the software Unity (Fig. 2), which allows the creation of holograms placed in the real world while adding procedures to them (Ammari and Hammad, 2014; Chalhoub and Ayer, 2018; Silva et al. 2018). The operator can enter new data or change existing data through specific procedures by updating the BIM model of the building.

All of these components can be grouped into three different locations, namely, those carried out at the back

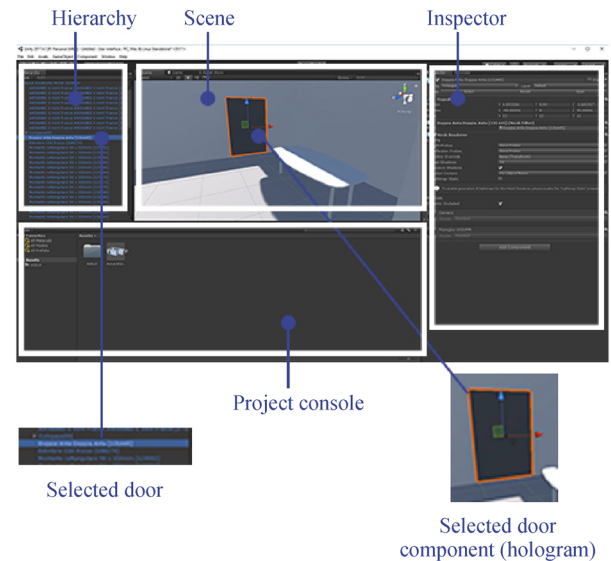


Fig. 2 Unity environment for the creation of the interface executed in HoloLens.

office level, the cloud-based platform level for big data management, and the on-site level (Fig. 1). The back office is where all documents (BIM model and data sheet) are collected and examined to provide support to on-site operators. The cloud-based platform is where the BIM model updates and all information, such as the BIM database and procedures, are shared. The on-site equipment provides technicians with the MR perspective and the interfaces that allow information transfer.

4.1 Cloud-based system—BIM server

Although the AEC industry is information-dependent, communication remains mainly paper-based (Das et al., 2014). Thus, information retrieval is remarkably difficult

and often confined to the physical location of documents and therefore discourages sharing. The key benefit of cloud platforms is their accessibility from any location. Hence, each FM participant is granted access to all information from any location. Using the same platform means having a sole virtual space where data can be shared.

The choice of using a cloud-based platform to support data flows also depends on the need to have a schema allowing fast and efficient queries among the data input from different technologies or with different purposes. Besides, as some researchers have shown, IFC is an unsuitable choice for real-time applications (Becerik-Gerber et al., 2012b). The cloud-based platform chosen in our application is the BIM server. Such platform can carry out all the operations described above and facilitate the interoperability between different platforms. The BIM server platform can run queries and even allows files to be attached from a variety of sources.

To select the necessary information for the inclusion of FM in a cloud system, two aspects must be considered, namely, a specific in-depth analysis of the components containing all of technical information necessary for the interventions and the procedures that relevant personnel must follow to complete the operations.

4.2 Information flow management

In the essential FM tasks, information flow considers not only single pieces of information but also refers to knowledge packages required to perform operations. Current practices can barely capture and reuse knowledge. These difficulties in the capture–retrieval–reuse phase are likely due to fragmentation in the construction process (Park et al., 2013; Ammari and Hammad, 2014).

The system proposed in this study attempts to solve this challenge by means of continuous information flowing through the different components of the system. The cloud platform is the repository where the data converge from different sources. Hence, a two-way flow exists from the back office, that is, from the documents providing the information basis for those performing operations and passing through the cloud. Conversely, on-site operators update the data being transferred through the cloud and back to the office. The interfaces between the different systems guarantee interoperability and allow the different actors in the processes to work together.

The final information flow will move in both directions from the office to the site and vice versa, resulting in the continuous exchange of information, the availability of continuously updated documents, and a complete overview of the asset status.

4.3 On-site development and testing

The development of the on-site section of the proposed system is carried out with the support of MR. The MR

functions provided by a head-mounted display (HMD) allows us to see through a screen, which displays 3D objects on top of existing physical surfaces (Chalhoub and Ayer, 2018). These functions are realized through automated localization performed by the tool even without the use of markers. The holograms superimposed on reality are instead provided by the elements modeled in the Unity Game Engine. Starting from the BIM model, a file can be exported in the “.fbx” format, which is supported by Unity. Once all the objects are uploaded in Unity, controls can be added to them. Finally, applications can be developed to project holograms on the HMD. The Unity application allows MR to enable the interaction between maintenance personnel with the building and with virtual building objects. Thus, MR is driven toward a specific goal to promote its widespread use (Du et al., 2018). This interaction also makes capturing real-time data possible (e.g., update maintenance operation results), which in turn, allows the model to be constantly updated, resulting in a permanently updated version of the digital building.

After the development of this system, the solution is expected to go through a test phase to verify the proposed method. The aforementioned analysis of the current methods adopted in the maintenance sector has focused on certain critical issues, which have only been resolved partially to date. Starting with the use of the three different methods, the system is tested for information flow management and on-site support. Preliminary tests have been performed in a predefined environment allowing us to test the reliability of the system, which is the basis for calibration and verification of the main functions. At a later stage, additional tests will be performed in the real world and in new environments.

4.3.1 Automatic inventory/survey support

The creation of BIM building models, especially in large structures, is time-consuming and expensive. In the case of existing buildings, a large amount of varied information essential for FM must be collected. This collection of information is challenging because as-built documents usually do not exist or are unreliable. In addition, certain information is difficult or impossible to source (Oesau et al., 2014; Scherer and Katranuschkov, 2017). These issues refer to the availability of data, which is a well-known problem especially in existing buildings (Yang and Ergan, 2017). In recent years, additional studies on fast and efficient survey techniques have been carried out (Quintana et al., 2017). These applications often do not allow the automatic transfer of data to the BIM model (Previtali et al., 2014) because captured data are unrelated to the BIM objects and cannot even be translated into IFCs.

Hence, the first application tested is for automated data acquisition forming the basis of the entire information flow (Fig. 3). In this initial case, the on-site operator sends data

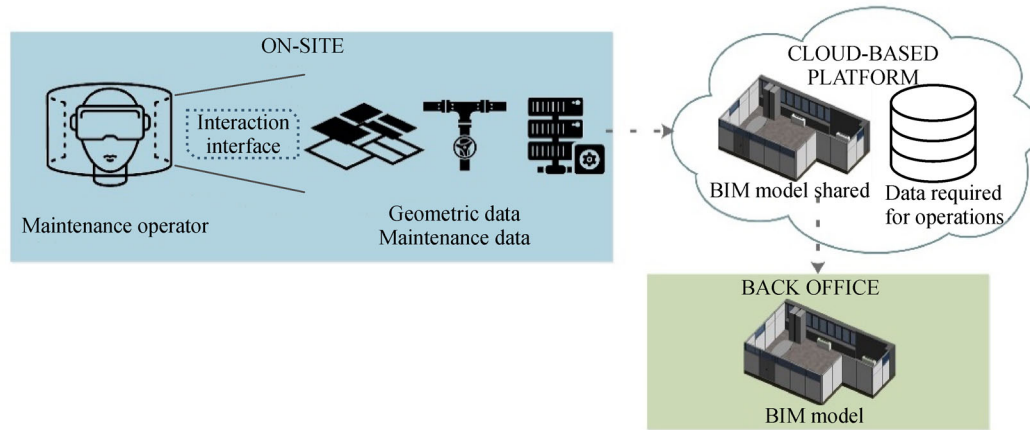


Fig. 3 Inventory/survey support for information flow.

about the geometric features and building components to the BIM database in the cloud-based platform. The back-office BIM model can be updated with these data. The collection of point clouds or generic surfaces involves the time-consuming analysis of data interpretation. The innovative contribution of this research survey is to work specifically with IFC objects and their features by attempting to minimize the post-processing work. The proposed procedure intends not only to perform building surveys rapidly but also to assist in resolving the information availability issue.

Therefore, an in-depth analysis of the relevant attributes of the objects being serviced is carried out. The support provided in this case by the MR tools lies in the possibility of automatically detecting on-site information and the ability to transmit it to the online database in real time.

4.3.2 Diagnosis support

The second task in which this system can benefit is diagnosis (Fig. 4). The BIM model is first used to develop

the MR application, and any information not contained in the BIM model or considered too cumbersome to be uploaded through an application is then sourced directly from the cloud-based platform into the HoloLens. The accurate and instant localization of the objects flagged for maintenance work requires considerable effort and may introduce an increased potential for errors in the case of complex buildings. The use of the MR display viewer avoids having to rely on paper documents, lowers the likelihood of introducing errors, and helps to locate objects and provide all necessary geometric information.

Moreover, the MR capability of overlaying virtual reality on real objects allows maintenance personnel to display hidden attributes and components (e.g., steel in concrete or cable pathways in walls or under the floor).

In addition to geometric data, technical specifications and descriptions of components must also be updated and stored after maintenance work has been completed successfully. Diagnosis can also benefit significantly from the on-site visualization of causes and analysis of defects. Relevant ontologies in the literature can be linked

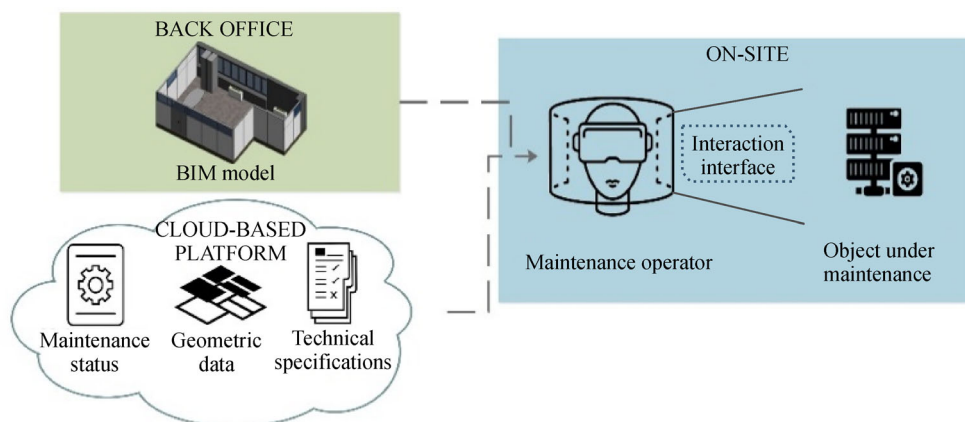


Fig. 4 Diagnosis of the support information flow.

to the BIM objects and displayed on-site.

All of the aforementioned data originates from BIM and cloud databases and can subsequently be visualized directly on-site using the HMD.

4.3.3 On-site operation support

The final scenario is that of on-site operations support from the back office (Fig. 5). This scenario, such as in an emergency, is similar to the diagnosis support during critical operations, such that the maintenance operator can consult a back-office expert in real time and also share his/her view. Consequently, the information exchange in this case is bidirectional and shown by the red arrow. In the case of standard operations, procedures can be shown through the on-site MR. This process initially involves the careful collection of procedures currently in force. This information is part of the background that must be included in the database. The opportunity to consult the standard procedures using this on-site method will not only reduce errors but also shorten the training time for new personnel.

However, reducing maintenance operations to a standard procedure displayed as a property object is sometimes impossible. For instance, in the event of an emergency, a standard procedure is not always available. Such circumstances can be resolved by real-time decision support. Consultation with experienced personnel from a remote location can be decisive, and the powerful visualization capabilities of the digital viewer will allow the sharing of information and images in real time. Sometimes, not all of the required information can be displayed automatically as this scenario will require a large volume of data to be handled on-site.

In this case, remote support can be of great benefit due to its efficiency (e.g., showing which items are out of production or in stock). It facilitates the handling of a wide variety of data that may be required by combining the

selection of on-site information from the BIM cloud database and the real-time support of an expert back-office technician.

5 On-site display of technical information

The first test carried out shows the relevant information of any component subjected to an on-site maintenance intervention. The MR HMD provides holograms, which are superimposed onto the real world. Thus, on-site operators can rely on MR tools rather than paper documents. In this experiment, virtual reality is overlaid on the real world and only the components whose holograms are displayed represent those requiring maintenance based on an order, which may have been sent by the back office. The on-site display of information leads to the reduction of errors and is a valuable tool for training new personnel in understanding operations and procedures. Accordingly, the visualization provided also enables the hands-free operation of technicians and the improvement of their efficiency.

When a user calls to report a fault in the building, the company in charge of building FM can rely on the system components, as shown in Fig. 6. A building occupant can access a web service linked to the BIM model and report the faulty component. The BIM model is connected to a database containing all the non-IFC type of data, including the procedures to be followed. The component that needs checking is displayed to the on-site technician via the MR tool.

Conversely, an off-site technician can provide external maintenance and has access to the information about the on-site object (Fig. 6). As a result of the user calling the FM company, the information flow follows the schema explained in the main text according to the type of intervention required. An on-site technician can use the

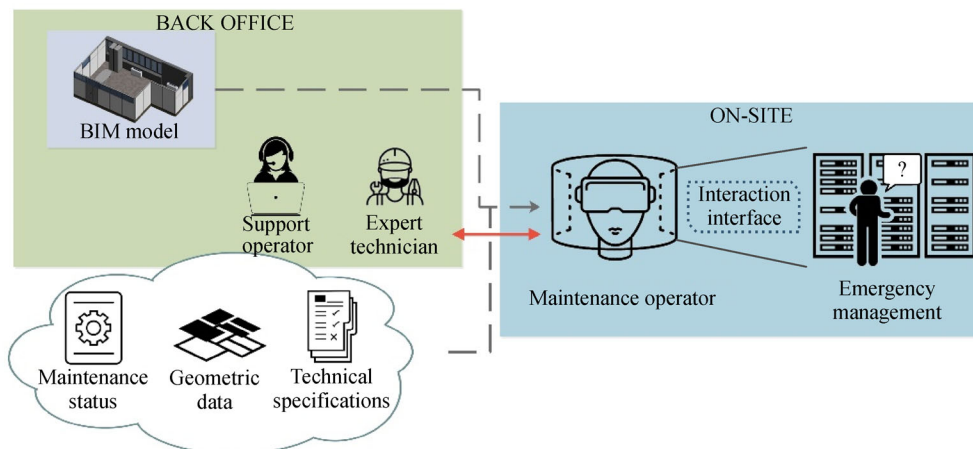


Fig. 5 Remote support to operation information flow.

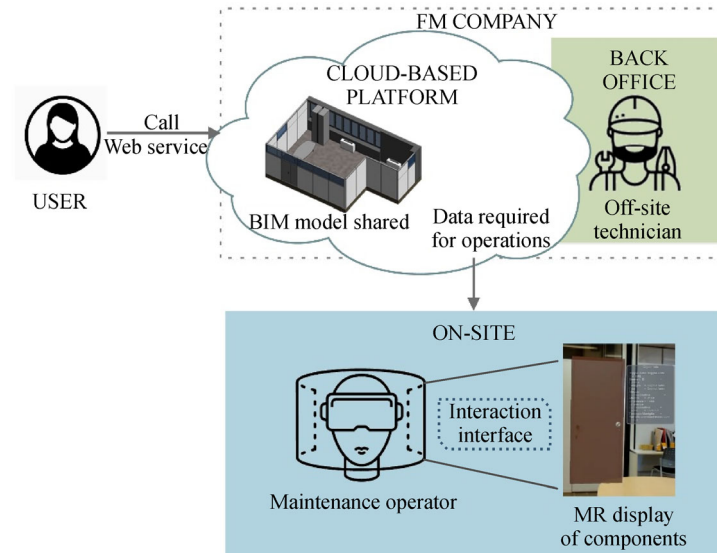


Fig. 6 On-site display of technical information.

information displayed by the holograms, and an off-site technician can also access the same information and provide advice when necessary.

5.1 Technology setup

To conduct the preliminary test, the MR environment must be created. Different devices can be used to reproduce the MR and holograms. However, the HoloLens chosen for this specific test is an HMD device with a transparent screen that places 3D virtual objects on top of existing physical surfaces. The HoloLens can project an image using infrared scanners to map the area and produce a stable and markerless visualization of the model.

The selected device does not need to be physically connected to a computer when in use. The MR environ-

ment has been developed with the use of a gaming platform (Unity). The Revit model has been imported into the gaming software, and the application to run the holograms in HoloLens is developed in Unity.

5.2 Visualization environment and testing

The first test assumes that a door requires maintenance. The Revit object is imported into Unity with the relevant information for the maintenance operation. Then, the application for HoloLens is created in Unity. Finally, the spatial mapping feature of the MR device enables the display of the hologram on top of the real object in the room in question.

Figure 7(a) shows the on-site operator wearing the HoloLens device. The hologram of the door requiring

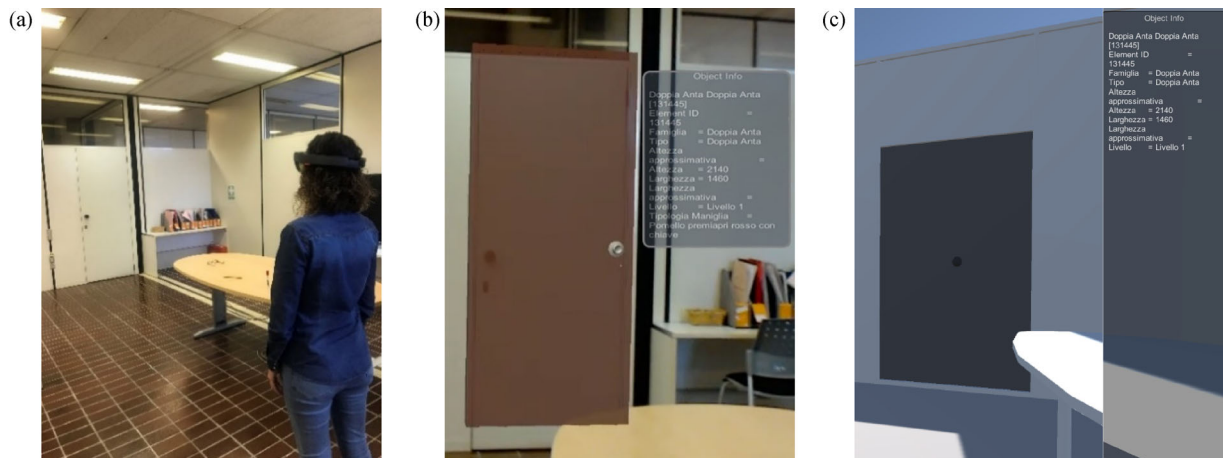


Fig. 7 (a) On-site operator using HoloLens to display the hologram of the object for inspection; (b) hologram of the door requiring maintenance with the relevant on-site information displayed; (c) door information displayed on the computer providing the off-site view.

maintenance is displayed on-site (Fig. 7(b)). The door information is displayed on the computer presenting the view of the off-site technician in charge of providing maintenance support (Fig. 7(c)).

6 Conclusions

This research project aims to provide support for the management of information during the building life cycle. The main innovation of this study lies in exploring the advantages provided by the combined use of state-of-the-art technologies and development of new procedures in support of the three use-cases in the FM phase. This study focuses on the possibility of combining three tools, namely, the BIM methodology for information management, a cloud-based system for managing information flows, and MR allowing the continuous interaction among operators, the digital model of the building, and information flow. The new procedures are intended to exploit all the advantages derived from these technologies and achieve an improved level of efficiency. The current digital transition in the construction industry is an excellent opportunity and a source of expenses due to the rethinking of all relevant processes.

The system proposed in this study also highlights a different technique in addressing automated work. The support given to operators lies predominantly in the man-machine interaction, which allows the exploitation of both benefits. Although digital tools help operators during their work, they also have real-time control of the machine that reduces the number of off-site interventions.

References

- Adan A, Xiong X, Akinci B, Huber D (2011). Automatic creation of semantically rich 3D building models from laser scanner data. *Automation in Construction*, 31: 325–337
- Ammari K E, Hammad A (2014). Collaborative BIM-based markerless mixed reality framework for facilities maintenance. In: *International Conference on Computing in Civil and Building Engineering*, 657–664
- Becerik-Gerber B, Jazizadeh F, Li N, Calis G (2012a). Application areas and data requirements for BIM-enabled facilities management. *Journal of Construction Engineering and Management*, 138(3): 431–442
- Becerik-Gerber B, Klein L, Li N (2012b). Image-based verification of as-built documentation of operational buildings. *Automation in Construction*, 21(1): 161–171
- Becker R, Falk V, Hoenen S, Loges S, Stumm S, Blankenbach J, Brell-Cokcan S, Hildebrandt L, Vallée D (2018). BIM-towards the entire life cycle. *International Journal of Sustainable Development and Planning*, 13(1): 84–95
- Bloch T, Sacks R (2018). Comparing machine learning and rule-based inferencing for semantic enrichment of BIM models. *Automation in Construction*, 91: 256–272
- Brilakis I, Lourakis M, Sacks R, Savarese S, Christodoulou S, Teizer J, Makhmalbaf A (2010). Toward automated generation of parametric BIMs based on hybrid video and laser scanning data. *Advanced Engineering Informatics*, 24(4): 456–465
- Chalhoub J, Ayer S K (2018). Using mixed reality for electrical construction design communication. *Automation in Construction*, 86: 1–10
- Chang C Y, Tsai M D (2013). Knowledge-based navigation system for building health diagnosis. *Advanced Engineering Informatics*, 27(2): 246–260
- Chen K, Lu W (2019). Bridging BIM and building (BBB) for information management in construction: The underlying mechanism and implementation. *Engineering, Construction, and Architectural Management*, 26(7): 1518–1532
- Chuang T H, Lee B C, Wu I C (2011). Applying cloud computing technology to BIM visualization and manipulation. In: *Proceedings of the 28th International Symposium on Automation and Robotics in Construction*, 201(1): 144–149
- Daft R L, Lengel R H (1986). Organizational information requirements, media richness and structural design. *Management Science*, 32(5): 554–571
- Das M, Cheng J C P, Kumar S S (2014). BIMCloud: A distributed cloud-based social BIM framework for project collaboration. In: *2014 International Conference on Computing in Civil and Building Engineering*. Orlando, Florida, USA: 41–48
- Ding L, Zhou Y, Akinci B (2014). Building Information Modeling (BIM) application framework: The process of expanding from 3D to computable *n*D. *Automation in Construction*, 46: 82–93
- Du J, Shi Y M, Zou Z B, Zhao D (2018). CoVR: Cloud-based multiuser virtual reality headset system for project communication of remote users. *Journal of Construction Engineering and Management*, 144(2): 04017109
- East E W, Brodt W (2007). BIM for construction handover. *Journal of Building Information Modelling*, 28–35
- East E W, Nisbet N, Liebich T (2013). Facility management handover model view. *Journal of Computing in Civil Engineering*, 27(1): 61–67
- Ergen E, Akinci B, Sacks R (2007). Life cycle data management of engineered-to-order components using radio frequency identification. *Advanced Engineering Informatics*, 21(4): 356–366
- Gallaher M P, O'Connor A C, Dettbarn J L, Gilday L T (2004). Cost analysis of inadequate interoperability in the US capital facilities industry (NIST GCR 04–867). US Department of Commerce, National Institute of Standards and Technology
- Hamledari H, Rezazadeh Azar E, McCabe B (2018). IFC-based development of as-built and as-is BIMs using construction and facility inspection data: Site-to-BIM data transfer automation. *Journal of Computing in Civil Engineering*, 32(2): 04017075
- Ibrahim K F, Abanda H, Vidalakis C, Wood G (2017). BIM big data system architecture for asset management: A conceptual framework. In: *Proceedings of the Joint Conference on Computing in Construction (JC3)*, 289–296
- Keady R A (2013). Financial impact and analysis of equipment inventories. *Facilities Engineering Journal*, 27(5): 13–17

- Kelly G, Serginson M, Lockley S, Dawood N, Kassem M (2013). BIM for facility management: A review and a case study investigating the value and challenges. In: Dawood N, Kassem M, eds. 13th International Conference on Construction Applications of Virtual Reality. London, UK: 191–199
- Klein L, Li N, Becerik-Gerber B (2012). Image-based verification of as-built documentation of operational buildings. *Automation in Construction*, 21: 161–171
- Krukowski A, Arsenijevic D (2010). RFID-based positioning for building management systems. In: Proceedings of 2010 IEEE International Symposium on Circuits and Systems (ISCAS). Piscataway, NJ, USA: IEEE, 3569–3572
- Lee S K, An H K, Yu J H (2012). An extension of the technology acceptance model for BIM-based FM. In: Construction Research Congress 2012: Construction Challenges in a Flat World, 602–611
- Lu Q, Lee S, Chen L (2018). Image-driven fuzzy-based system to construct as-is IFC BIM objects. *Automation in Construction*, 92: 68–87
- Ma L, Sacks R (2016). A cloud-based BIM platform for information collaboration. In: Proceedings of the 33rd International Symposium on Automation and Robotics in Construction (ISARC 2016), 581–589
- Mill T, Alt A, Liias R (2013). Combined 3D building surveying techniques—terrestrial laser scanning (TLS) and total station surveying for BIM data management purposes. *Journal of Civil Engineering and Management*, 19(sup1): S23–S32
- Miller M (2008). *Cloud Computing: Web-Based Applications That Change the Way You Work and Collaborate Online*. New York: Que Publishing
- Motawa I, Almarshad A (2013). A knowledge-based BIM system for building maintenance. *Automation in Construction*, 29: 173–182
- Oesau S, Lafarge F, Alliez P (2014). Indoor scene reconstruction using feature sensitive primitive extraction and graph-cut. *ISPRS Journal of Photogrammetry and Remote Sensing*, 90: 68–82
- Park C S, Lee D Y, Kwon O S, Wang X (2013). A framework for proactive construction defect management using BIM, augmented reality and ontology-based data collection template. *Automation in Construction*, 33: 61–71
- Phan T A M, Nurminen J K, Francesco M D (2014). Cloud databases for internet-of-things data. In: 2014 IEEE International Conference on Internet of Things (iThings), and IEEE Green Computing and Communications (GreenCom) and IEEE Cyber, Physical and Social Computing (CPSCom). IEEE, 117–124
- Pishdad-Bozorgi P, Gao X, Eastman C, Self A P (2018). Planning and developing facility management-enabled building information model (FM-enabled BIM). *Automation in Construction*, 87: 22–38
- Previtali M, Barazzetti L, Brumana R, Scaioni M (2014). Towards automatic indoor reconstruction of cluttered building rooms from point clouds. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 2(5): 281–288
- Quintana B, Prieto S A, Adán A, Bosché F (2017). Scan-to-BIM for small building components. In: Proceedings of the Joint Conference on Computing in Construction (JC3). Heraklion, Greece: 4–7
- Redmond A, Hore A, Alshawi M, West R (2012). Exploring how information exchanges can be enhanced through Cloud BIM. *Automation in Construction*, 24: 175–183
- Royal Institution of Chartered Surveyors (RICS) (2009). *Building Maintenance: Strategy, Planning and Procurement*. London: RICS Books
- Scherer R J, Katranuschkov P (2017). BIMification: How to create BIM for retrofitting. In: Proceedings of the Joint Conference on Computing in Construction (JC3). Heraklion, Greece
- Silva H, Resende R, Breternitz M (2018). Mixed reality application to support infrastructure maintenance. In: International Young Engineers Forum (YEF-ECE). Costa da Caparica: IEEE, 50–54
- Tang P, Huber D, Akinci B, Lipman R, Lytle A (2010). Automatic reconstruction of as-built building information models from laser scanned point clouds: A review of related techniques. *Automation in Construction*, 19(7): 829–843
- Volk R, Stengel J, Schultmann F (2014). Building Information Modelling (BIM) for existing buildings—Literature review and future needs. *Automation in Construction*, 38: 109–127
- Waheed Z, Fernie S (2009). Knowledge based facilities management. *Facilities*, 27(7/8): 258–266
- Wand Y, Wang R Y (1996). Anchoring data quality dimensions in ontological foundations. *Communications of the ACM*, 39(11): 86–95
- Wang X, Dunston P S, Skibniewski M (2004). Mixed reality technology applications in construction equipment operator training. In: 21st International Symposium on Automation and Robotics in Construction (ISARC 2004), 21–25
- Xue F, Lu W, Chen K (2018). Automatic generation of semantically rich as-built building information models using 2D images: A derivative-free optimization approach. *Computer-Aided Civil and Infrastructure Engineering*, 33(11): 926–942
- Yang X, Ergan S (2017). BIM for FM: Information requirements to support HVAC-related corrective maintenance. *Journal of Architectural Engineering*, 23(4): 04017023
- Zhang J P, Liu Q, Yu F Q, Hu Z Z (2014). A framework of cloud-computing-based BIM service for building life cycle. In: International Conference on Computing in Civil and Building Engineering. Orlando, Florida, USA: 1514–1521