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A Critical Study of the Existing Issues in Manufacturing Maintenance Systems: Can BIM Fill the Gap?

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Abstract

The use of smart and complicated technologies in manufacturing industries has brought new issues to the maintenance systems in recent years. In this research, an intensive literature review is performed to identify and classify these issues. Inspired by the recent advances that Building Information Modeling (BIM) has brought to the construction industry, the research proposes adopting BIM in manufacturing maintenance systems to address the existing issues. A list of BIM capabilities utilized for addressing maintenance issues of buildings is extracted from the literature. It is argued that these BIM capabilities can also solve similar maintenance issues found in manufacturing industries. A BIM-based corrective maintenance model for an aluminum casting plant is developed to investigate the application of sample BIM capabilities in a manufacturing maintenance system. Twenty maintenance experts are invited to interact with the developed pilot model. Rapid locating of equipment requiring repairs, easy access to documents and records, efficient collaborative cloud environment, and expedited operations are among the identified advantages of BIM capabilities in the case. This research contributes to the body of knowledge by providing a comprehensive list of categorized manufacturing maintenance issues. Nominated BIM capabilities to address the identified manufacturing maintenance issues are recommended. The achieved results of this research can inspire manufacturing maintenance practitioners and researchers to adopt similar technologies to BIM to improve manufacturing maintenance systems.

Keywords Maintenance System, Manufacturing Industry, Building Information Modeling, Maintenance Issues

1 Introduction

The average cost of equipment maintenance in manufacturing is estimated at 25% of the total production cost [1]. The significant impact of the maintenance systems on the manufacturing industry has inspired many researchers to address the existing gaps and improve different aspects of the maintenance systems. Despite the achieved advances, many identified gaps could not be adequately addressed by currently adopted technologies in manufacturing maintenance systems. Furthermore, the emergence of smart and advanced manufacturing technologies in the recent decade has created unprecedented challenges in maintenance systems. [2]. Effectively addressing the existing gaps in the maintenance systems can significantly contribute to the profitability of manufacturing operations.

Building Information Modeling (BIM) is an emerging technology that has established itself in the last decade as a leading tool for the life cycle management of buildings. According to the definition provided by the National Institute of Building Sciences [3], "BIM is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle, defined as existing from earliest conception to demolition." The revolutionary role of BIM in the maintenance of buildings has filled many gaps that were unresolved by previously adopted computer-based solutions. The use of BIM could address similar gaps existing in manufacturing maintenance systems. From this perspective, this research aims to investigate the potential benefits that BIM can bring to manufacturing maintenance systems. The findings of this research are organized as follows. Section 2 outlines the main stages of the research methodology. Section 3 presents the list of classified improvement points created as a result of an intensive literature review of manufacturing maintenance systems. Section 4 describes the nominated capabilities of BIM to map the identified needs in the manufacturing maintenance systems. In Section 5, the sample capabilities of BIM are demonstrated and evaluated in a pilot proof-of-concept implementation of a BIM-based maintenance system in an aluminum casting plant. Finally, in Section 6, the achieved results of the research are concluded.

2 Research Methodology

The following are three specific questions that this study seeks to answer.

1. What is the current state of maintenance of manufacturing units, and what are the existing challenges?
2. Which capabilities of BIM are utilized in building maintenance, and how are they solving building maintenance challenges?
3. How can manufacture maintenance leverage BIM capabilities to address its current challenges?

In the first part of the research, a list of classified improvement points of the manufacturing maintenance systems was created as a result of an intensive literature review. Scholarly papers with both "manufacturing" and "maintenance," along with one of the keywords "issues," "deficiencies," "shortfalls," "challenges," and "imperfection" in their title, abstract, and keywords were searched in the Scopus and Google Scholar databases. The search only focused on English papers in journals and proceedings published between 2001 and 2021. Papers published in non-refereed journals and conference papers without citations were filtered. The papers were initially reviewed by their title to remove those irrelevant. Secondly, the remaining papers were screened based on their abstracts. The remaining papers were then thoroughly reviewed. In total, 105 papers were thoroughly studied, and 59 were used and cited in the final manuscript.

The second part of the research was performed to identify the answer to the second question and form an intensive list of BIM capabilities in building maintenance systems. The

"Maintenance," "BIM," and "Capability" keywords were used to search scholarly articles in the Scopus database. Google Scholar was used as a complementary search engine for the specified BIM capabilities and narrowed-down topics. Here again, papers published in non-refereed journals and conference papers without citations were filtered. The topics and abstracts of 99 scholarly articles were found relevant. After the complete review of these articles, 43 of them were used and cited in the final manuscript. The focus of the third part of the research was to investigate whether BIM has proper capabilities to address the existing issues in the manufacturing maintenance system. This investigation was done by mapping the identified BIM capabilities used to address similar issues in the maintenance systems in the construction industry. In the fourth and the final part of the research, sample capabilities of BIM were demonstrated in a small-scale case study of a BIM-based maintenance system in a manufacturing line. The main aim of this case study was to test whether sample BIM capabilities can be beneficial in real manufacturing cases.

3 The need for improvement in manufacturing maintenance systems

This research created a list of 35 identified challenges and potential improvement points from an intensive review of past research. At the first level, these improvement points were categorized into four high-level categories, namely, 1) maintenance operation management, 2) communication and information, 3) technological, and 4) organizational. Improvement points under each high-level category were further categorized into several main categories at the next level. Table 1 represents the identified challenges and potential improvement points in manufacturing maintenance systems. Further explanations regarding the identified classification of the improvement points follow.

Table 1 Potential improvements identified in manufacturing maintenance systems in the literature

High-level Categories	Main Categories	Potential Improvement Point
Maintenance operation management	Maintenance operation planning	Strict limitations for maintenance scheduling
		Redundancy in maintenance activities
		Maintenance crew safety
		Environmental sustainability
	Maintenance cost management	High maintenance cost
		Difficulties in finding the balance point of costs
		Insufficient maintenance cost information
	Performance measurement	Inefficient maintenance performance measurement tools
		Ambiguous effects of maintenance on the company's performance
	Maintenance training	Training maintenance staff
		Training operators
Communication and information	Data collection	The high volume of various data
		Redundant and irrelevant data
		Unsystematic data collection and storage
		Expensive data collection equipment
	Information security	Security of high volume and various data
	Communication	Ineffective communication between stakeholders
	Inefficient access to information	Time-consuming access to information
		Lack of access to the baseline information
		Uncategorized information
		Lack of physical models of the equipment
		Limited access to information from outside of the manufacturing plant
		Improper visualization tools
Technical issues	Ineffective data analysis	Lack of synergy between human and machine intelligence
		Inability to analyze the failure root causes
		Inability to predict failures
		Inefficient warning systems
	Inflexibility to changes	The inflexibility of the existing systems to change
		The resistance of the workforce to change
	Interoperability issues	Lack of interoperability
Organizational issues	Senior management share	Lack of a clear maintenance policy
		Improper relationship with employees
		Insufficient maintenance resources procurement
	Connected departments	Production and maintenance conflict
		Inventory and spare part supply

3.1 Maintenance operation management

The evolution of manufacturing technologies and the expanded level of automation have increased the pressure on the maintenance crews in the manufacturing industry [4]. This extra pressure has caused unelucidated issues that could be classified into four main categories, including 1) maintenance operation planning, 2) maintenance cost management, 3) performance measurement, and 4) maintenance training. Each main category is explained below.

3.1.1 Maintenance operation planning

The existing variety of failure modes and production line limitations of various manufacturing equipment components complicate inspection and maintenance intervals [5]. The common practice of the predetermined inspection and maintenance intervals leads to over-maintained or under-maintained programs [6]. More efficient strategies such as predictive maintenance can provide a more realistic maintenance plan [6]. The unexpected delay for the spare parts, machinery and staff arrival, unnecessary travel between the shop floor and inventory, and excessive loads applied to equipment also complicate the maintenance planning process [7]. Baluch et al. [7] suggest strengthening the lean concept in maintenance planning and considering maintenance as a long-term strategy to reduce such losses. Safety is another concern to address in maintenance planning. Improper risk assessment, time pressure, lack of vision, and incomplete guidelines can cause safety issues during maintenance activities [8]. Many companies use simple tools such as Job Safety Analysis, What-if analysis, Event Tree Analysis, and HAZOP to analyze maintenance procedures and identify risks [8]. Additionally, appropriate maintenance planning needs to cover environmental risks such as greenhouse gas emissions and water and soil pollution [9]. The conflicts between production and business interests with sustainability purposes are the key impediments in applying sustainable maintenance[10]. It is required to define the impacts of maintenance processes on the sustainable performance of the manufacturing industry [11]. Employing data-driven approaches and DTs could help maintenance managers strike a balance between different objectives of maintenance stakeholders [10]. Data analysis is another challenge to sustainable maintenance in manufacturing units that have been alleviated by expanding smart sensing technologies and big data analysis methods [12].

3.1.2 Maintenance cost management

The cost of equipment maintenance has increased in production systems in recent years [13]. A considerable portion of the maintenance activities is allocated to preventive maintenance, predictive maintenance, and diagnostic and health management strategies, which are per se expensive methods [6]. Finding a balance for maintenance activities is an issue that needs to be addressed in maintenance planning [5]. Optimization models such as Particle Swarm Optimization [5] and Differential Evolution algorithm [13] are used to find the balance between maintenance costs and equipment reliability. On the other hand, the implementation of smart technologies, such as the DTs, for maintaining the manufacturing plants is costly and limited to maintaining critical assets [2]. In some cases, the costs of adopting advanced maintenance techniques have not been tracked, or manufacturers are reluctant to provide information about them [14].

3.1.3 Performance measurement

The emergence of smart manufacturing urges the real-time estimation of the maintenance's key performance indicators [15]. However, measuring the performance of the maintenance crew is not an easy task. Some criteria such as overall equipment effectiveness, return on net assets, and return on capital employed are used to measure and monitor maintenance performance in manufacturing plants [16]. Nevertheless, mechanisms typically used to measure equipment performance do not provide a clear view of the maintenance teams' performance [16]. Key performance indicators used to measure maintenance system performance mainly focus on the outputs, but not the process [17]. The complex interactions between maintenance, inventory, and production systems prevent the proper definition of the maintenance system's key performance indicators [18]. The consistent record of the maintenance work orders can pave the ground for measuring the key performance indicators of the real manufacturing units [19]. There are also few empirical studies to examine the effects of smart maintenance technologies on the performance of production plants [20]. The maintenance performance indicators must also be defined to reflect the business context and overall strategies of the company [4].

3.1.4 Maintenance training

Despite its significant financial impacts on smart manufacturing performance, maintenance engineering is usually low on the priority list [15]. Lack of training programs or contents for maintenance crews is an issue in many manufacturing plants [21]. Maintenance crews must be trained adequately to understand the overall structure of their maintenance systems and digest the rapid flow of information in their companies [22]. Furthermore, the emergence of artificial intelligence in smart maintenance systems urges the maintenance teams to acquire the relevant knowledge [23]. The main goal of personnel training is to improve their acquaintance with the new technologies, change their mindsets, and adapt them to modern systems [24]. Maintenance staff must learn a vast amount of complex information in a limited time. This challenge increases their stress levels, decreases their performance, and exacerbates life and safety hazards [25]. Additionally, many operators are not adequately trained to efficiently operate production line equipment and thus increase the likelihood of equipment damage and maintenance costs [21], [26]. Virtual and augmented reality are emerging tools to improve the training quality of maintenance crew and respond to the existing training gap [23, 25].

3.2 Communication and information

Organizational complexity and different specialties create complications during the establishment of information and communication flow among the stakeholders [27]. This research classifies this category of challenges into four main groups, including; 1) Data collection, 2) Information security, 3) Communication, 4) Inefficient access to information.

3.2.1 Data collection

Manufacturing maintenance systems involve large amounts of data. Catalogs, drawings, manuals, spare parts, lubricants, and maintenance history are among the information to be collected for equipment maintenance. One significant challenge of maintenance systems is properly collecting and managing all this detailed information [28]. Maintenance data is collected from different sources such as RFID tags, sensors, personal digital assistants, and maintenance operators over the life cycle of assets [29]. Neglecting the required data or collecting unnecessary data could reduce the quality of information [7]. Predictive maintenance requires real-time monitoring and processing of large volumes of data. This process leads to obtaining poorly structured data with missing values or no annotations [30]. In many cases, various maintenance data are stored in multiple separate datasets. Effectively linking these separately managed datasets poses another challenge for maintenance activists [31]. The emergence of new informatics paradigms in the smart manufacturing context stipulates new data collection standardization [32]. However, a standard, pre-planned data collection method is missing in many manufacturing units [21]. Systematically collecting asset and product data and disseminating it among different stakeholders enhances the system's efficiency and facilitates information retrieval for decision-making [31]. Many manufacturing units still use manual and paper-based methods to collect and store their data. This maintenance approach, however, is uneconomical and unsafe in the currently risky business environments [33]. Furthermore, manually collected data mainly relies on personal judgments and negatively affects information quality [29]. The counter-intuitive user interfaces of electronic data collection methods is another reported challenge [13]. Although manufacturing industries have been equipped with automated data collection sensors in recent decades, using sensors to collect every piece of maintenance-related information imposes a high cost on the organization [34].

3.2.2 Information security

The high volume of data created and transferred in the maintenance systems increases data theft risk [28]. Therefore, ensuring user privacy, service security, information security, network security, data locality, data integrity, authentication, and authority allocation are essential in maintenance systems [35]. However, the high volume and variety of the information exchanged [28], and the use of external platforms and internal networks [23] in maintenance systems challenge the security of data stored and transferred, especially in the case of using cloud spaces. Information security can be addressed by network security protocols, network authentication services, and data encryption services [28].

3.2.3 Communication

The emergence of smart manufacturing systems has urged the need for specialized groups of maintenance service providers [36], increased the number of stakeholders, and highlighted the importance of effective communication methods. The ineffective connection between system stakeholders, however, is a challenging issue reported in the past (e.g. [32], [36], [37]). This issue prevents instantaneous understanding and reduces the applicability of the collected data in manufacturing maintenance systems [29]. Designing a standard template for exchanging messages, choosing a secure communication protocol, and defining terminology for information flow can improve communication between departments [38].

3.2.4 Inefficient access to information

Recent advancements in Information and Communication Technologies (ICTs) and smart sensors have provided maintenance practitioners with new data sources [10]. However, accessing the required information such as warehouse information, equipment locations [7], and manuals of equipment [38] require considerable time in many manufacturing companies. In some manufacturing industries, engineers have difficulty accessing maintenance baseline data [6]. Maintenance teams face challenges in installing and repairing equipment due to limited access to machines' precise geometric information in their plants [6]. Smart manufacturing suggests integrating the equipment through the internet to provide a versatile and robust maintenance system [15]. However, these systems require a high-speed and reliable internet connection to efficiently access the information [23]. Local networks' limitations in providing access to information from outside is another issue for manufacturing maintenance teams [33]. Another challenge is the improper visualization tools to show the results of engineering analyses. Augmented reality (AR) has recently been utilized as an effective technique to overcome this issue [10].

3.3 Technical issues

The continual need for upgrading equipment creates technical issues in many manufacturing industries. These issues are divided into three main groups, including 1) ineffective data analysis, 2) inflexibility to change, and 3) software issues.

3.3.1 Ineffective data analysis

With the emergence of smart manufacturing systems, effective data analytic methods are sought by manufacturing companies [16]. However, developed technologies are still far behind this goal [23]. These technologies do not provide the necessary synergy between human and machine knowledge, leading to inaccurate decisions [39]. In some cases, recently evolved smart systems benefit from machine learning to detect and predict failures [40]. However, both the low and excessive data heterogeneity impair the performance of these algorithms [30]. In addition, the analysis of large and diverse maintenance data, including sensor information, text reports, and multimodal data, also disrupts the performance of prediction tools [41]. Such complexity discourages the manufacturing enterprises from implementing data analysis techniques [42]. Equipment is repaired or replaced before it is severely damaged in preventive maintenance operations. This approach averts data collection for the entire equipment life cycle, impairs the prediction process, and reduces maintenance crews' insight into the equipment condition [6], [30]. Additionally, data sparsity decreases algorithms' accuracy in predicting the time between equipment failures [34]. In some cases, besides the high variability of parameters, the technical constraints of sensor installations impose difficulty on the failure prognosis of equipment [43]. Various factors such as inaccurate semantic expressions, dependence on specific machines, deficiency in incorporating the external influence factors, improper management of data uncertainty [44], inability to analyze new types of failure, and limited transplantation [45] restrict the performance of the fault diagnosis models. From this perspective, many production maintenance managers are not alert to equipment failures and the resulting hazards [33]. Even if these systems are implemented, the high rate of false warnings is the outcome [6]. As utilizing the single analytical models is hardly fulfilling the challenges, the combination of the different models is proposed to address these complexities [44].

3.3.2 Inflexibility to change

Many manufacturing maintenance systems do not properly adapt to the newly evolved systems [46]. The commonly used client-server paradigm is typically not compatible with cloud-based technologies for storing and transferring the required data for preventive maintenance [35]. A shift in the current paradigm to the mobile agent approach has been suggested to enhance the data storage and transmission problems [35]. In addition, there is a lack of scientific action plan to guide the organizations to transform the conventional maintenance systems [23]. The reluctance to recent changes by the maintenance team and considering new strategies as interferences on conventional methods add to the barriers of adopting new maintenance systems [2]. Besides, manufacturing industry personnel need the training to adapt to new emerging setup [38]. All these challenging issues may discourage top management's desire to implement new technologies. Highlighting the benefits of the latest technologies by the scientific community, integrating the advances by technology providers, and the managers' openness to the new paradigms are identified as the key factors to overcome the challenges [2].

3.3.3 Interoperability issues

In the manufacturing context, interoperability is defined as various organizational systems' ability to communicate and exchange information seamlessly [47]. Although numerous data silos exist in manufacturing plants, collecting and integrating information from these databases are missing [2]. The integration of predictive maintenance processes is also one of the significant challenges for the company. These processes generally include collecting data from sensors installed on machines, processing data, developing and training machine learning algorithms, and integrating with other information sources [30]. Lacking information exchange standards and incompatible file formats are two main issues inherited from new manufacturing technologies [28]. Although recent studies, such as [48], attempted to delineate the problem and proposed an approach to develop a data scheme within the context of smart manufacturing systems, the challenge remains open for future research.

3.4 Organizational issues

Inefficient, intra-organizational communication affects maintenance performance and reduces the quality of the final product and productivity of the organization [49]. In this section, two main groups of intra-organizational communicational challenges reported in the literature are described below.

3.4.1 Senior management share

Many manufacturing maintenance systems suffer from outdated and/or unstable maintenance policies due to senior management's non-engagement [38], [50]. Poorly defined maintenance activities by senior management adversely affect decision-making, and the mandated strategies may inflict strict and non-optimal strategies [2]. Studies on modern maintenance systems do not explain which model should be used by maintenance teams; therefore, there is a lack of systematic approaches to developing the maintenance strategies [44]. Mutual distrust between senior management and maintenance crews can also worsen the condition [21]. Furthermore, providing a proper amount of resources to the maintenance system is another challenge senior management face [51]. Resource over-allocation leads to a waste of resources. On the other hand, resource under-allocation reduces productivity and creates safety risks [52]. Recent studies utilized the simulation methods to find the most optimum level of resource allocation for maintenance teams (e.g. [60], [61]).

3.4.2 Connected departments

In many manufacturing companies, production operators are indifferent to the maintenance team's concerns, and the two departments often suffer a conflict of interest [55], [56]. The production staff is reluctant to do maintenance-related tasks, and the maintenance teams do not trust the production crews [16]. Furthermore, maintenance planning usually considers equipment reliability as the only determining factor and does not take into account the production orders and planned product mix [57], extending the production time and delivery dates of the final product [58]. As a result of constraints imposed by production teams, the maintenance team is forced to postpone operations, which increases the failure rate, especially during peak production periods [5]. Reinforcement learning-based [59] methods and stochastic digital twin [60] have been used to establish an optimal trade-off between conflicting production and maintenance goals. The maintenance's efficiency is also tightly related to the spare part management by the inventory department; thus, the integration of the inventory policies in the maintenance planning is of particular importance [61]. Poor inventory management in the timely supply of required parts delays the maintenance operations and increases the maintenance costs [7]. There exists a strong interest during recent years in investigating the integration of maintenance strategies with spare part management to address this challenge [61].

3.5. Discussion on the manufacturing maintenance challenges

The manufacturing industry is experiencing significant changes and evolution due to the expansion of new and smart technologies. With such developments, engineers are facing new challenges in maintaining the equipment. These challenges range from managing maintenance processes and communication issues to technical and organizational problems (see Table 1 for the details). These issues prevent the maintenance teams from performing optimally and indirectly affect the quality of the end products. Researchers have so far addressed a number of these challenges and offered solutions. For instance, adopting lean manufacturing has been proposed as a way to prevent maintenance losses in factories. Newer technologies, such as data-driven analysis, machine learning, optimization algorithms, and simulation have been utilized to alleviate environmental side effects of maintenance activities, reduce costs, and resolve conflicts between maintenance and production plans. Training staff using virtual and augmented reality has also become popular in recent years. The use of the cloud environment has also been proposed as a solution to the storage and access of information problems. However, many proposed solutions to the identified challenges are tailored for the specific context of the issue and are not comprehensive enough to be widely adopted in production units. Many of the proposed solutions are only theoretically stated, and their effectiveness has not been tried in practice. Furthermore, solutions offered to some of emerging manufacturing maintenance issues have remained unresolved. For instance, no solid solutions are proposed for the maintenance stakeholders' communication issues, the interoperability challenges, and the maintenance knowledge base integration. There is a strong need to introduce a new infrastructure capable of including and connecting existing maintenance systems, information, and stakeholders across manufacturing industries.

4 Mapping BIM capabilities to the identified needs for improvement

The powerful BIM capabilities have encouraged practitioners to use BIM to cover the existing gaps in building maintenance systems. Significant improvements made by BIM applications in building maintenance systems have sparked the idea of applying a similar tool to overcome the current challenges within manufacturing companies. Table 2 summarizes the literature review results for the applicable BIM capabilities in improving building maintenance systems. The table also lists proposed manufacturing maintenance issues that the identified capabilities can address. These suggestions are based on the literature review and the authors' insight, and the study of their practicality can be a subject for future research and experiments. In the rest of this section, each of these capabilities and their possible application in manufacturing maintenance systems are discussed.

Table 2 BIM capabilities and the proposed issues to be covered in manufacturing maintenance systems

Category	BIM Capability	Proposed manufacturing maintenance issues to be covered
Object-oriented and 3D visualization	3D interface augmented and virtual reality	Lack of physical models of equipment, Strict limitation of maintenance scheduling, Redundancy in maintenance activities, High maintenance cost, Time-consuming access to information, Improper visualization tools, Training maintenance staff, Training operators
	Integration of the required maintenance information	Uncategorized information, Unsystematic data collection, and storage, Redundant and irrelevant data, Time-consuming access to information
	Historical data storage platform	Time-consuming access to information, High maintenance cost, Insufficient maintenance cost information, Redundancy in maintenance activities, Inefficient maintenance performance measurement tools, Access to baseline information
	Connection to the maintenance schedule	Strict limitation of maintenance scheduling, Maintenance crew safety, Production and maintenance conflict, High maintenance cost, Redundancy in maintenance activities
Collaborative environment	Communication between stakeholders	Ineffective communication between stakeholders, Limited access to information from outside, Production and maintenance conflict, Inventory and spare part supply
	Design for maintenance	Ineffective communication between stakeholders, High maintenance cost, Redundancy in maintenance activities, Maintenance crew safety
Interoperability	Interoperability with existing maintenance management systems	Lack of interoperability, Time-consuming access to information, Redundancy in maintenance activities, Inability to analyze the failure root causes
	Interoperability with engineering analysis tools	High maintenance cost, Redundancy in maintenance activities, Environmental sustainability, Difficulties in finding the balance point of costs, Lack of synergy between human and machine intelligence
Space management	Digital equipment layout	Inefficient maintenance performance measurement tools, Redundancy in maintenance activities
	Maintenance safety management	Maintenance crew safety, Training maintenance staff

4.1 Object-oriented and 3D visualization

Due to the object-oriented and 3-dimensional (3D) nature of BIM, modelers can virtually define various building components and store their lifecycle information on digital replicas. Different benefits that 3D visualization represents for maintenance operations are explained below.

4.1.1 3D interface augmented and virtual reality

BIM allows managers to retrieve, analyze, and process information which facilitates buildings' maintenance and operating processes [62]. The information extracted from the 3D interface of BIM provides spatial relations between different building components for maintenance engineers [63]. It helps them to accurately locate the broken items inside the components [64]. BIM also reduces the time required to perceive the building elements' geometric information [62] and prevents misinterpretations [65]. Manufacturing maintenance teams may use the 3D interface of BIM to better understand the spaces and relationships between elements and provide accurate schedules for their operations. This approach to maintenance operations reduces redundancies and operating costs.

BIM-based technologies are also used in augmented and virtual reality environments for buildings. With the help of a virtual environment, users will accurately identify facilities and their hidden or inaccessible parts on-site [66]. Moreover, they review the equipment's information on its real image, which relieves them from the hassle of reading 2D maps and diagrams [67]. This approach has reduced the maintenance operating time by up to 65% compared to using 2D maps [68]. These technologies can also be used to train maintenance trainees. Using BIM, the maintenance trainees can move virtually between facilities, inspect different building spaces, elements, and equipment, and review relevant semantic data [64]. Therefore, manufacturing maintenance teams may use virtual and augmented reality technologies to retrieve and visualize the required information. These tools can also train production and maintenance employees safely and remotely from the actual equipment.

4.1.2 Integration of the required maintenance information

In addition to geometric information, BIM provides non-geometric and functional information of each element, including sensors' information [69]. This information can include instructions, baseline information, working parameters of each equipment, maintenance reports, images, operation videos, and manufacturer's information [62], [70]. By integrating this information, maintenance crews may access the 3D elements of each piece of equipment and its classified information by entering its ID, scanning its barcode, or reading its RFID tag [71]. Moreover, information models can receive and store the real-time data of each piece of equipment [72]. The BIM integration as a database compensates for the data unavailability in the manufacturing maintenance systems [2]. Thus, the manufacturing maintenance staff may access the information they need to plan and perform operations in the shortest possible time, even from outside of the complex.

BIM has facilitated the management of the vast amounts of information created and used in the operation and maintenance of buildings [73]. The Construction Operations Building Information Exchange (COBie) is the standard protocol for collecting and delivering non-geometric information required during the building operation phase [74]. This protocol has prevented duplicate information and has reduced the cost and time of collecting the data necessary [75]. In this perspective, BIM can also be effectively used to classify and gather information needed for maintaining equipment in manufacturing companies. This platform can prevent the collection of duplicate and unnecessary information and the loss of information, thus ensuring the quality of the collected data.

4.1.3 Historical data storage platform

Maintenance-related decisions are usually highly dependent on historical data, such as design documents, equipment inspection records, and sensors' data [76]. BIM allows maintenance experts to store each piece of equipment's historical data on its 3D element in the model [77]. Accessing the most up-to-date history of any building element's failures through the BIM platform is an essential contribution to decision-makers to prioritize the implementation of maintenance measures required [78]. By creating such a rich source of historical data, maintenance managers and engineers can analyze and identify the cause and effect patterns of failures [62]. Such patterns can help prepare a benchmark for future activities and effectively invent new, creative, and improved solutions [65]. Maintenance managers can also identify the root causes of failures by analyzing the recorded results of past operations, thus avoiding wasting time on unproductive activities [79]. Analyzing the historical information gathered on BIM will also create a valuable insight for managers to measure the performance of maintenance operations [80]. BIM plays a pivotal role in aggregating the history of equipment failures in manufacturing plants. Rapid and integrated access to the historical costs and resource information for each equipment component can provide the desired insight for maintenance crews to efficiently manage maintenance operations and develop cost-effective strategies. The historical data can also be used to measure maintenance performance and prepare the performance baseline.

4.1.4 Connection to the maintenance schedule

Maintenance work orders can be attached to the BIM elements to visualize the maintenance operation and identify spatiotemporal relationships between maintenance activities and ongoing processes. This will help to prioritize better and streamline operations and maintenance tasks [81]. During the operation, the maintenance crew can use mobile platforms to access the 3D model, visually view the connected schedule, and communicate with the engineers [82]. BIM can also be used to generate maintenance schedules automatically [83]. Maintenance experts can examine various aspects of the operation and optimize it by connecting 3D models of the shop floor to the maintenance schedule. This feature can provide sufficient information regarding the existing safety risks of the operation. This capability can also play a role as a visualized instruction for the maintenance team during operations to eliminate redundancies and reduce costs.

4.2 Collaborative Environment

The BIM virtual environment enriched with the information from different building life phases paves the path for stakeholders' effective collaboration. In this section, the capabilities of the BIM-based collaborative environment that can bridge a part of the industrial maintenance system's shortcomings are discussed.

4.2.1 Communication between stakeholders

A BIM-based collaborative environment gathers various building maintenance stakeholders in a single platform [84] and expedites consensus processes [85]. This platform provides an exclusive access route for each stakeholder to extract their required information [86]. The standard protocols developed for managing interactions, such as BIM Collaboration Format (BCF) [87], facilitate the management of changes made by each stakeholder. During maintenance operations, the operation crew on-site and the supporting staff in the office can collaboratively work using the BIM platform [82], [88]. This capability can also be adopted in the manufacturing industry to facilitate communication between different stakeholders, including the maintenance crews, production operators, and inventory staff.

4.2.2 Design for maintenance

Efficient interaction between different working groups and the design team improves the design quality and the risk management of the building projects [89]. The BIM-based collaborative environment provides an interactive platform to transfer maintenance needs to the design team efficiently. These needs include identifying high-risk settings [90], visualizing the designed workspaces [91], controlling the equipment maintainability, and checking the protection level of equipment [64]. Manufacturing maintenance managers can also use the BIM interactive environment to efficiently communicate with the plant designers, equipment manufacturers, and suppliers.

4.3 Interoperability

Industry Foundation Classes (IFC) [92] and COBie are two standard formats in BIM that deliver integrated access to information of different origins. In the following, the interoperability provided by BIM and its possible applications in manufacturing maintenance systems is discussed.

4.3.1 Interoperability with existing maintenance management systems

Inadequate interoperability among different computer-based systems is one of the main challenges in adopting new systems [93]. This issue, however, has been dealt with in the BIM-based systems by introducing standard open-source formats, such as IFC, to connect different information databases with BIM models [94], [95]. The BIM-based systems support various use cases with different stakeholders involved by providing flexible access routes to extract heterogeneously created information from multiple sources [86]. Since BIM model information needs to be exchanged with other systems before it is used by end-users, interoperability has become an essential BIM-based system capability [96]. It is expected that prospective BIM-based manufacturing maintenance systems can properly interconnect and complement the existing computer-based maintenance tools.

4.3.2 Interoperability with engineering analysis tools

BIM is also a source of information that provides engineering analysis for buildings [97]. It can effectively provide the prerequisites for life cycle cost analysis and life cycle sustainability assessment of buildings [98]. BIM is also an appropriate information source for optimizing buildings' energy consumption by providing building geometry, material type, and energy-related information visualization [99]. This optimization minimizes the need for changing the building components during the operation phase and reduces the cost of repairs caused by the relevant changes [100]. It is also possible to estimate the maintenance cost by combining the information available in BIM and artificial intelligence, such as machine learning [101]. The integrated model of BIM and Bayesian networks proposed by TohidiFar et al. [102] enables the risk-informed diagnosis and prognosis of the building systems. Moreover, the newly developed BIM-enabled machine learning algorithms can classify maintenance work order reports and automatically structure collected information [81]. A similar approach can also be followed in manufacturing industries to integrate machine intelligence with human knowledge stored on BIM models. Energy analysis, environmental sustainability review, and maintenance cost analysis are possible benefits of this BIM capability in manufacturing industries.

4.4 Space management

Space management includes the processes that measure the performance of allocated spaces and ensure each space effectively serves its specified purpose. This section investigates the BIM space management capability in digital equipment layout planning and safety management.

4.4.1 Digital equipment layout

BIM is presented as a virtual environment that simulates and evaluates different layouts of facilities [65]. BIM can quantify and visualize the available space and balance it against the required space. The virtual environment enriched with information facilitates measuring the performance of maintenance spaces, tracking space changes, and anticipating future spatial needs of the business [64]. Using the digital display of space provided by BIM, manufacturing maintenance activists can simulate different equipment layouts and evaluate the performance of the maintenance process under each of these layouts.

4.4.2 Maintenance safety management

By presenting spatial information, such as the location of the power supply systems and mechanical installations, BIM provides the necessary information to identify the safety risks of maintenance operations [103], [104]. Managers can also train maintenance staff with safety-related information in a codified, orderly, and integrated way through the BIM environment [104]. This BIM capability can help manufacturing maintenance managers ensure their employees' safety while planning and provide adequate training to the maintenance operation team.

5 A pilot proof-of-concept implementation

A pilot BIM-based corrective maintenance model was implemented in an aluminum casting plant case in the south of Iran for evaluating the applicability of BIM capabilities in the manufacturing maintenance systems. The plant operation commenced in late 2019, and the research team approached the company in the early stages of their operation period. Despite the company's short operation period, involved practitioners in the study were experienced professionals who moved into the company from other similar manufacturing companies. The first step of the pilot implementation was to identify the data flow of best practices of maintenance procedure in this manufacturing unit and incorporate BIM into the existing procedures. Consequently, a pilot BIM-based collaborative corrective maintenance model is developed. The developed BIM-based corrective maintenance software was then demonstrated to and evaluated by the practitioners from different company departments. Different steps taken to develop and evaluate the pilot model are presented below.

5.1 Developed model specification

As the first step of model development, the dataflow and main stakeholders of the selected manufacturing unit were identified. The equipment was maintained periodically, and corrective maintenance was performed in emergency breakdowns. Four main procedures were identified, and five types of stakeholders are considered the best practice of maintenance in the unit. By incorporating BIM into the data flow of this best practice, a BIM-based corrective maintenance model was designed, which worked as a complement to the existing maintenance system of the unit. Figure 1 represents the schematic view of the developed BIM-based corrective maintenance model. The production line's BIM model was developed and uploaded into a BIM server to form a collaborative environment accessible for different stakeholders through an internet connection. Various stakeholders, including maintenance management crews, maintenance executive crews, production operators, control room staff, and inventory personnel, could use their laptops, desktops, smartphones, and tablets to log into the collaborative environment with the specified levels of access to the BIM model and perform their assigned tasks.

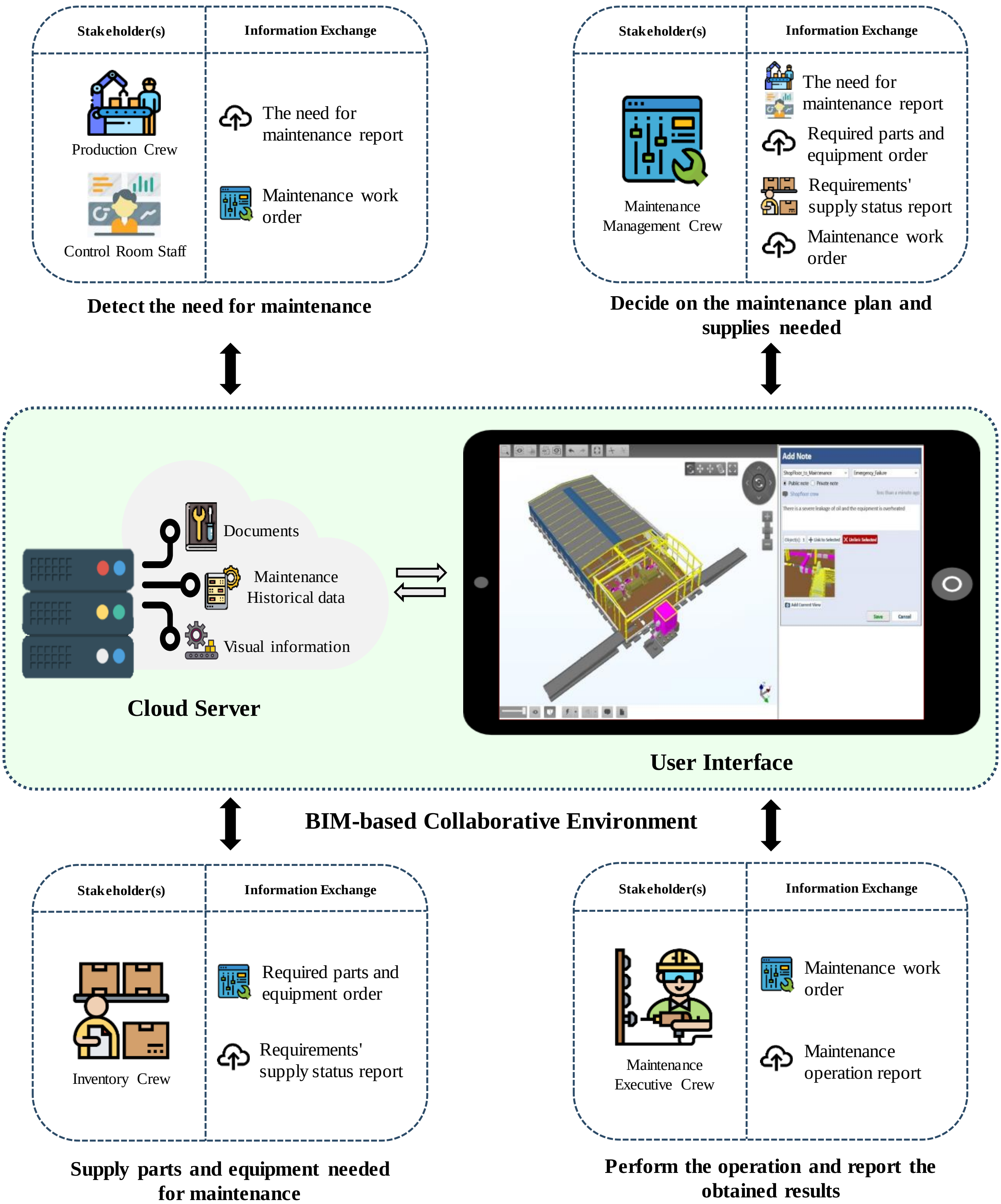

Figure 1 The schematic view of the developed pilot BIM-based collaborative corrective maintenance model

The research team utilized BIMServer open-source package [105] as a BIM-based collaborative environment. BIMServer was installed on the server located outside of the manufacturing unit. The maintenance application's interface was developed in C# and connected to BIMServer using JavaScript object notion (JSON), a lightweight language-independent data exchange format [106]. As the primary communication protocol among the different stakeholders, BCF [87] was utilized. During every maintenance activity, BCF files were stored in the BIMServer, creating the historical trace of communications between different parties.

In the developed BIM-based corrective maintenance scenario, production operators initially identify issues in the production line. They then log into the BIM-based collaborative environment, create a BCF file, and report the issue to the maintenance management department. The BCF files contain an identification number of the affected equipment, the failure type, and the proper explanation of the raised issue. The maintenance team receives the reported issue. The 3D BIM environment, enriched with maintenance supporting information and BCF explanations, helps the maintenance team remotely locate, diagnose, and prepare for the operation. The maintenance team orders the parts required for the corrective maintenance activities from the inventory through the collaborative environment. The inventory views the list of the parts and responds to the maintenance team through the collaborative environment. The maintenance team then coordinates the operation schedule with the production crew using the BCF file. The maintenance team updates the BIM model after the operation, and the operation report remains as historical data in the BIMserver.

5.2 Results and discussions

The developed model and scenario were presented to 20 managers and experts from maintenance, production, and procurement departments who participated in a three-hour interactive workshop. The participants were asked to discuss and evaluate seven proposed capabilities of the model. A three-level Likert scale [107] was used in the evaluation, with 1 representing low, 2 representing moderate, and 3 representing the capability's high benefit. The final score of each target capability was calculated by averaging the received scores from different participants. Table 3 illustrates the scores achieved for the target capabilities in the experiment.

Table 3 Scores achieved for the target capabilities in the experiment

Target capability	Score	Rank
Fast and easy locating of broken items	2.82	1
Easy access to the instructions, warranty documents, and repair records	2.78	2
Efficient interactive platform in the cloud environment	2.76	3
Facilitated access to the list of the required spare parts	2.56	4
Improved organization of the repair and maintenance activities	2.28	5
Expedited troubleshooting process and analysis of the broken items	2.28	5
Facilitated decision making during emergencies	2.22	7

According to Table 3, the participants evaluated all proposed capabilities with above-average scores and found the proposed BIM-based model and its capabilities beneficial. The participants' strong support indicates the high potential application of the BIM-based collaborative corrective maintenance model in the large manufacturing industries.

The "Fast and easy locating of broken items" was recognized as the most prominent capability. The interviewees highlighted that a large manufacturing unit encompasses numerous, complex, and inter-related equipment distributed in an extensive area. Identifying the exact location of broken items through the textual work-orders can be a challenging and time-consuming task. The object-oriented, visual, and component search capability of BIM models can expedite the locating process of the broken items. The "Easy access to the instructions, warranty documents, and repair records" was considered the second most beneficial capability. The participants stated that accessing the equipment information through 2D maps and paper-based databases is a time-consuming task. The object-oriented database of BIM stores and integrates the equipment information on its digital replica, facilitating information retrieval and knowledge management. BIM's capability in providing an "Efficient interactive platform in the cloud environment" was also ranked third. The participants stated that the current communication system could not satisfy the simultaneous interaction of several stakeholders. Well-developed and standard interaction protocols in BIM (such as BCF) can gather various stakeholders in a single platform, connects them, and ease the information exchange between different parties. Moreover, Analyzing 2D information for estimating the spare part was reported to be highly prone to errors. Experts stated that the maintenance teams analyze the high volume of uncategorized, mainly 2D information for providing maintenance required parts, which is a highly error-prone and inefficient process. Creating access to integrated information and connecting the inventory and maintenance units by leveraging the BIM models makes the "Facilitated access to the list of the required spare parts" the fourth most important capability of the proposed model from the experts' standpoint.

6 Conclusions

New technologies introduced to the manufacturing industry in the recent decade have caused unprecedented challenges in this industry. The performed literature review in this research identified the emerging manufacturing maintenance challenges as applications of digital and smart technologies are expanded in manufacturing industries. Inspired by the recent advances in the construction industry, this study proposed applying BIM capabilities in addressing the emerging challenges of manufacturing maintenance systems. The proposed BIM-based maintenance model was applied to a pilot proof-of-concept implementation to demonstrate its applicability to recover some of the existing issues in the corrective maintenance system of an aluminum casting unit. Managers and experts from different departments participated in an interactive workshop to evaluate the capabilities of the developed model. They found the adopted BIM capabilities quite effective to respond to the identified corrective maintenance issues.

This research contributes to the body of knowledge by identifying and classifying the emerging challenges in manufacturing maintenance systems. The study sheds light on the opportunities to respond to the maintenance challenges by leveraging the BIM technology potentials motivated by the approach followed in the construction industry. The prepared list of nominated manufacturing maintenance challenges to be recovered by specified BIM capabilities is another original outcome of this study. The nominated challenges, however, do not cover all identified challenges in the manufacturing maintenance systems. New research efforts are encouraged to investigate other technologies and methods to respond to these challenges. To the best of the authors' knowledge, the developed pilot BIM-based collaborative corrective maintenance model in this research is the first BIM-based manufacturing maintenance model developed for the manufacturing industry. The set of the deployed BIM-based methods and tools in this case practically demonstrates how the proposed notion of BIM application can work in real manufacturing cases. In this perspective, another contribution of this research is to prove the applicability of the proposed concept in practice.

One of the significant constraints of this study is the limited scope of the pilot proof-of-concept implementation. Since the adopted maintenance strategy of the pilot manufacturing unit relies on corrective maintenance, the proof-of-concept is mainly limited to the corrective maintenance activities. Consequently, a limited number of BIM capabilities were implemented in the pilot study. Furthermore, this study does not consider integrating the common manufacturing maintenance tools, such as operation monitoring and control technologies, with the BIM-based maintenance system. Future research is required to investigate the integration of the BIM-based maintenance models with other parts of the maintenance systems. The trace of BIM development in the construction industry demonstrates a continual improvement in this technology over the last decade to tailor BIM capabilities to its needs. The findings of this study reveal that the manufacturing industry can adopt a similar path to develop BIM-based maintenance systems suited to its needs.

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References

[1] Haroun Ahmed E., "Maintenance cost estimation: application of activity-based costing as a fair estimate method," *Journal of Quality in Maintenance Engineering*, vol. 21, no. 3, pp. 258–270, Jan. 2015, doi: 10.1108/JQME-04-2015-0015.

[2] I. Errandonea, S. Beltrán, and S. Arrizabalaga, “Digital Twin for maintenance: A literature review,” *Computers in Industry*, vol. 123, p. 103316, Dec. 2020, doi: 10.1016/j.compind.2020.103316.

[3] NIBS, "Frequently Asked Questions About the National BIM Standard-United States™," *National Institute of Building Sciences*, 2021. https://www.nationalbimstandard.org/faqs (accessed Jan. 23, 2021).

[4] A. Van Horenbeek and L. Pintelon, "Development of a maintenance performance measurement framework—using the analytic network process (ANP) for maintenance performance indicator selection," *Omega*, vol. 42, no. 1, pp. 33–46, Jan. 2014, doi: 10.1016/j.omega.2013.02.006.

[5] M. K. Loganathan and O. P. Gandhi, "Maintenance cost minimization of manufacturing systems using PSO under reliability constraint," *International Journal of System Assurance Engineering and Management*, vol. 7, no. 1, pp. 47–61, Mar. 2016, doi: 10.1007/s13198-015-0374-2.

[6] X. Jin *et al.*, "The present status and future growth of maintenance in US manufacturing: results from a pilot survey," *Manuf Rev (Les Ulis)*, vol. 3, pp. 10–10, 2016, doi: 10.1051/mfreview/2016005.

[7] N. H. Baluch, C. S. Abdullah, and S. Mohtar, "TPM and lean maintenance-A critical review," *Interdisciplinary Journal of Contemporary Research in Business (IJCRB)*, 2012.

[8] J. Bokrantz, A. Skoogh, and T. Ylipää, "The Use of Engineering Tools and Methods in Maintenance Organisations: Mapping the Current State in the Manufacturing Industry," *Procedia CIRP*, vol. 57, pp. 556–561, Jan. 2016, doi: 10.1016/j.procir.2016.11.096.

[9] F. G. Nezami and M. B. Yildirim, "A sustainability approach for selecting maintenance strategy," *null*, vol. 6, no. 4, pp. 332–343, Dec. 2013, doi: 10.1080/19397038.2013.765928.

[10] M. Jasiulewicz-Kaczmarek, S. Legutko, and P. Kluk, "Maintenance 4.0 technologies–new opportunities for sustainability driven maintenance," *Management and Production Engineering Review*, vol. 11, 2020.

[11] C. Franciosi, A. Voisin, S. Miranda, S. Riemma, and B. Iung, "Measuring maintenance impacts on sustainability of manufacturing industries: from a systematic literature review to a framework proposal," *Journal of Cleaner Production*, vol. 260, p. 121065, Jul. 2020, doi: 10.1016/j.jclepro.2020.121065.

[12] Y. Zhang, S. Ren, Y. Liu, and S. Si, "A big data analytics architecture for cleaner manufacturing and maintenance processes of complex products," *Journal of Cleaner Production*, vol. 142, pp. 626–641, Jan. 2017, doi: 10.1016/j.jclepro.2016.07.123.

[13] X. Wang, S. Guo, J. Shen, and Y. Liu, "Optimization of preventive maintenance for series manufacturing system by differential evolution algorithm," *Journal of Intelligent Manufacturing*, vol. 31, no. 3, pp. 745–757, Mar. 2020, doi: 10.1007/s10845-019-01475-y.

[14] D. S. Thomas, "Advanced maintenance in manufacturing: costs and benefits," in *Annual conference of the PHM society. September*, 2018, pp. 24–27.

[15] Navas Miguel Angel, Sancho Carlos, and Carpio Jose, "Disruptive Maintenance Engineering 4.0," *International Journal of Quality & Reliability Management*, vol. 37, no. 6/7, pp. 853–871, Jan. 2020, doi: 10.1108/IJQRM-09-2019-0304.

[16] Ahuja I.P.S. and Khamba J.S., "Strategies and success factors for overcoming challenges in TPM implementation in Indian manufacturing industry," *Journal of Quality in Maintenance Engineering*, vol. 14, no. 2, pp. 123–147, Jan. 2008, doi: 10.1108/13552510810877647.

[17] P. N. Muchiri, L. Pintelon, H. Martin, and A.-M. De Meyer, "Empirical analysis of maintenance performance measurement in Belgian industries," *null*, vol. 48, no. 20, pp. 5905–5924, Oct. 2010, doi: 10.1080/00207540903160766.

[18] P. Muchiri, L. Pintelon, L. Gelders, and H. Martin, "Development of maintenance function performance measurement framework and indicators," *International Journal of Production Economics*, vol. 131, no. 1, pp. 295–302, May 2011, doi: 10.1016/j.ijpe.2010.04.039.

[19] M. P. Brundage, K. C. Morris, T. Sexton, S. Moccozet, and M. Hoffman, "Developing Maintenance Key Performance Indicators From Maintenance Work Order Data," Volume 3: Manufacturing Equipment and Systems, Jun. 2018, doi: 10.1115/MSEC2018-6492.

[20] J. Bokrantz, A. Skoogh, C. Berlin, T. Wuest, and J. Stahre, "Smart Maintenance: a research agenda for industrial maintenance management," *International Journal of Production Economics*, vol. 224, p. 107547, Jun. 2020, doi: 10.1016/j.ijpe.2019.107547.

[21] Graisa Mustafa and Al-Habaibeh Amin, "An investigation into current production challenges facing the Libyan cement industry and the need for innovative total productive maintenance (TPM) strategy," *Journal of Manufacturing Technology Management*, vol. 22, no. 4, pp. 541–558, Jan. 2011, doi: 10.1108/17410381111126445.

[22] B. Iung and A. Crespo Márquez, "A review of e-maintenance capabilities and challenges," *Journal of Systemics, Cybernetics and Informatics, 6 (1), 62-66.*, 2008.

[23] L. Silvestri, A. Forcina, V. Introna, A. Santolamazza, and V. Cesarotti, "Maintenance transformation through Industry 4.0 technologies: A systematic literature review," *Computers in Industry*, vol. 123, p. 103335, Dec. 2020, doi: 10.1016/j.compind.2020.103335.

[24] A. Nembhard David, "Cross training efficiency and flexibility with process change," *International Journal of Operations & Production Management*, vol. 34, no. 11, pp. 1417–1439, Jan. 2014, doi: 10.1108/IJOPM-06-2012-0197.

[25] Y. Shi, Y. Zhu, R. K. Mehta, and J. Du, "A neurophysiological approach to assess training outcome under stress: A virtual reality experiment of industrial shutdown maintenance using Functional Near-Infrared Spectroscopy (fNIRS)," *Advanced Engineering Informatics*, vol. 46, p. 101153, Oct. 2020, doi: 10.1016/j.aei.2020.101153.

[26] Singh Rajesh Kumar, Gupta Ayush, Kumar Ashok, and Khan Tasmeem Ahmad, "Ranking of barriers for effective maintenance by using TOPSIS approach," *Journal of Quality in Maintenance Engineering*, vol. 22, no. 1, pp. 18–34, Jan. 2016, doi: 10.1108/JQME-02-2015-0009.

[27] Metso Lasse, Marttonen Salla, Thenent Nils E., and Newnes Linda B., "Adapting the SHEL model in investigating industrial maintenance," *Journal of Quality in Maintenance Engineering*, vol. 22, no. 1, pp. 62–80, Jan. 2016, doi: 10.1108/JQME-12-2014-0059.

[28] J. Campos, P. Sharma, E. Jantunen, D. Baglee, and L. Fumagalli, "The Challenges of Cybersecurity Frameworks to Protect Data Required for the Development of Advanced Maintenance," *Procedia CIRP*, vol. 47, pp. 222–227, Jan. 2016, doi: 10.1016/j.procir.2016.03.059.

[29] Razmi-Farooji Arian, Kropsu-Vehkaperä Hanna, Härkönen Janne, and Haapasalo Harri, "Advantages and potential challenges of data management in e-maintenance," *Journal of Quality in Maintenance Engineering*, vol. 25, no. 3, pp. 378–396, Jan. 2019, doi: 10.1108/JQME-03-2018-0018.

[30] J. Dalzochio *et al.*, "Machine learning and reasoning for predictive maintenance in Industry 4.0: Current status and challenges," *Computers in Industry*, vol. 123, p. 103298, Dec. 2020, doi: 10.1016/j.compind.2020.103298.

[31] K. Arif-Uz-Zaman, M. E. Cholette, L. Ma, and A. Karim, "Extracting failure time data from industrial maintenance records using text mining," *Advanced Engineering Informatics*, vol. 33, pp. 388–396, Aug. 2017, doi: 10.1016/j.aei.2016.11.004.

[32] D. L. Nuñez and M. Borsato, "OntoProg: An ontology-based model for implementing Prognostics Health Management in mechanical machines," *Advanced Engineering Informatics*, vol. 38, pp. 746–759, Oct. 2018, doi: 10.1016/j.aei.2018.10.006.

[33] F. T. Dwi Atmaji and J. Alhilman, "A Framework of Wireless Maintenance System Monitoring: A Case Study of an Automatic Filling Machine at SB Company," in *2018 6th International Conference on Information and Communication Technology (ICoICT)*, May 2018, pp. 227–232, doi: 10.1109/ICoICT.2018.8528722.

[34] C. Chen *et al.*, "Predictive maintenance using cox proportional hazard deep learning," *Advanced Engineering Informatics*, vol. 44, p. 101054, Apr. 2020, doi: 10.1016/j.aei.2020.101054.

[35] J. Wang, L. Zhang, L. Duan, and R. X. Gao, "A new paradigm of cloud-based predictive maintenance for intelligent manufacturing," *Journal of Intelligent Manufacturing*, vol. 28, no. 5, pp. 1125–1137, Jun. 2017, doi: 10.1007/s10845-015-1066-0.

[36] F. Chang, G. Zhou, W. Cheng, C. Zhang, and C. Tian, "A service-oriented multi-player maintenance grouping strategy for complex multi-component system based on game theory," *Advanced Engineering Informatics*, vol. 42, p. 100970, Oct. 2019, doi: 10.1016/j.aei.2019.100970.

[37] M.-H. Hung, K.-Y. Chen, R.-W. Ho, and F.-T. Cheng, "Development of an e-Diagnostics/Maintenance framework for semiconductor factories with security considerations," *Advanced Engineering Informatics*, vol. 17, no. 3, pp. 165–178, Jul. 2003, doi: 10.1016/j.aei.2004.07.004.

[38] A. Muller, A. Crespo Marquez, and B. Iung, "On the concept of e-maintenance: Review and current research," *Reliability Engineering & System Safety*, vol. 93, no. 8, pp. 1165–1187, Aug. 2008, doi: 10.1016/j.ress.2007.08.006.

[39] M. P. Brundage *et al.*, "Where Do We Start? Guidance for Technology Implementation in Maintenance Management for Manufacturing," *Journal of Manufacturing Science and Engineering*, vol. 141, no. 091005, Jul. 2019, doi: 10.1115/1.4044105.

[40] A. Kumar, R. Shankar, A. Choudhary, and L. S. Thakur, "A big data MapReduce framework for fault diagnosis in cloud-based manufacturing," *null*, vol. 54, no. 23, pp. 7060–7073, Dec. 2016, doi: 10.1080/00207543.2016.1153166.

[41] F. Ansari, R. Glawar, and W. Sihn, "Prescriptive Maintenance of CPPS by Integrating Multimodal Data with Dynamic Bayesian Networks," in *Machine Learning for Cyber Physical Systems*, Berlin, Heidelberg, 2020, pp. 1–8.

[42] E. Kozłowski, D. Mazurkiewicz, T. Żabiński, S. Prucnal, and J. Sęp, “Machining sensor data management for operation-level predictive model,” *Expert Systems with Applications*, vol. 159, p. 113600, Nov. 2020, doi: 10.1016/j.eswa.2020.113600.

[43] L. Fumagalli, L. Cattaneo, I. Roda, M. Macchi, and M. Rondi, "Data-driven CBM tool for risk-informed decision-making in an electric arc furnace," *The International Journal of Advanced Manufacturing Technology*, vol. 105, no. 1, pp. 595–608, Nov. 2019, doi: 10.1007/s00170-019-04189-w.

[44] J. J. Montero Jimenez, S. Schwartz, R. Vingerhoeds, B. Grabot, and M. Salaün, "Towards multi-model approaches to predictive maintenance: A systematic literature survey on diagnostics and prognostics," *Journal of Manufacturing Systems*, vol. 56, pp. 539–557, Jul. 2020, doi: 10.1016/j.jmsy.2020.07.008.

[45] Q. Zhou, P. Yan, and Y. Xin, "Research on a knowledge modelling methodology for fault diagnosis of machine tools based on formal semantics," *Advanced Engineering Informatics*, vol. 32, pp. 92–112, Apr. 2017, doi: 10.1016/j.aei.2017.01.002.

[46] J. M. Fordal, T. I. Bernhardsen, H. Rødseth, and P. Schjølberg, "Balanced Maintenance Program with a Value Chain Perspective," in *Advanced Manufacturing and Automation IX*, Singapore, 2020, pp. 317–324.

[47] H. Panetto and A. Molina, "Enterprise integration and interoperability in manufacturing systems: Trends and issues," *Computers in Industry*, vol. 59, no. 7, pp. 641–646, Sep. 2008, doi: 10.1016/j.compind.2007.12.010.

[48] Y. Park, J. Woo, and S. Choi, "A Cloud-based Digital Twin Manufacturing System based on an Interoperable Data Schema for Smart Manufacturing," *null*, vol. 33, no. 12, pp. 1259–1276, Dec. 2020, doi: 10.1080/0951192X.2020.1815850.

[49] Phogat Sandeep and Gupta Anil Kumar, "Identification of problems in maintenance operations and comparison with manufacturing operations: A review," *Journal of Quality in Maintenance Engineering*, vol. 23, no. 2, pp. 226–238, Jan. 2017, doi: 10.1108/JQME-06-2016-0027.

[50] J. Abreu, P. V. Martins, S. Fernandes, and M. Zacarias, "Business Processes Improvement on Maintenance Management: A Case Study," *Procedia Technology*, vol. 9, pp. 320–330, Jan. 2013, doi: 10.1016/j.protcy.2013.12.036.

[51] M. A. Munir, M. A. Zaheer, M. Haider, M. Z. Rafique, M. A. Rasool, and M. S. Amjad, "Problems and Barriers Affecting Total Productive Maintenance Implementation," *Eng.*

Technol. Appl. Sci. Res., vol. 9, no. 5, pp. 4818–4823, Oct. 2019, doi: 10.48084/etasr.3082.

[52] A. K. Srivastava, G. Kumar, and P. Gupta, "Estimating maintenance budget using Monte Carlo simulation," *Life Cycle Reliability and Safety Engineering*, vol. 9, no. 1, pp. 77–89, Mar. 2020, doi: 10.1007/s41872-020-00110-7.

[53] T. Yu, C. Zhu, Q. Chang, and J. Wang, "Imperfect corrective maintenance scheduling for energy efficient manufacturing systems through online task allocation method," *Journal of Manufacturing Systems*, vol. 53, pp. 282–290, Oct. 2019, doi: 10.1016/j.jmsy.2019.11.002.

[54] S. Kłos and J. Patalas-Maliszewska, "Using a Simulation Method for Intelligent Maintenance Management," in *Intelligent Systems in Production Engineering and Maintenance – ISPEM 2017*, Cham, 2018, pp. 85–95.

[55] Portioli-Staudacher Alberto and Tantardini Marco, "Integrated maintenance and production planning: a model to include rescheduling costs," *Journal of Quality in Maintenance Engineering*, vol. 18, no. 1, pp. 42–59, Jan. 2012, doi: 10.1108/13552511211226184.

[56] E.-H. Aghezzaf, A. Khatab, and P. L. Tam, "Optimizing production and imperfect preventive maintenance planning′s integration in failure-prone manufacturing systems," *Reliability Engineering & System Safety*, vol. 145, pp. 190–198, Jan. 2016, doi: 10.1016/j.ress.2015.09.017.

[57] M. Celen and D. Djurdjanovic, "Operation-dependent maintenance scheduling in flexible manufacturing systems," *CIRP Journal of Manufacturing Science and Technology*, vol. 5, no. 4, pp. 296–308, Jan. 2012, doi: 10.1016/j.cirpj.2012.09.005.

[58] A. Angius, M. Colledani, and A. Yemane, "Impact of condition based maintenance policies on the service level of multi-stage manufacturing systems," *Control Engineering Practice*, vol. 76, pp. 65–78, Jul. 2018, doi: 10.1016/j.conengprac.2018.04.011.

[59] P. D. Paraschos, G. K. Koulinas, and D. E. Koulouriotis, "Reinforcement learning for combined production-maintenance and quality control of a manufacturing system with

deterioration failures," *Journal of Manufacturing Systems*, vol. 56, pp. 470–483, Jul. 2020, doi: 10.1016/j.jmsy.2020.07.004.

[60] J. Vatn, "Industry 4.0 and real-time synchronization of operation and maintenance," in *Proceedings of the 28th International European Safety and Reliability Conference*, 2018, pp. 681–686.

[61] S. Dellagi, W. Trabelsi, Z. Hajej, and N. Rezg, "Integrated maintenance/spare parts management for manufacturing system according to variable production rate impacting the system degradation," *Concurrent Engineering*, vol. 28, no. 1, pp. 72–84, Jan. 2020, doi: 10.1177/1063293X19898734.

[62] X. Gao and P. Pishdad-Bozorgi, "BIM-enabled facilities operation and maintenance: A review," *Advanced Engineering Informatics*, vol. 39, pp. 227–247, Jan. 2019, doi: 10.1016/j.aei.2019.01.005.

[63] I. Motawa and A. Almarshad, "A knowledge-based BIM system for building maintenance," *Automation in Construction*, vol. 29, pp. 173–182, Jan. 2013, doi: 10.1016/j.autcon.2012.09.008.

[64] Becerik-Gerber Burcin, Jazizadeh Farrokh, Li Nan, and Calis Gulben, "Application Areas and Data Requirements for BIM-Enabled Facilities Management," *Journal of Construction Engineering and Management*, vol. 138, no. 3, pp. 431–442, Mar. 2012, doi: 10.1061/(ASCE)CO.1943-7862.0000433.

[65] E. A. Pärn, D. J. Edwards, and M. C. P. Sing, "The building information modelling trajectory in facilities management: A review," *Automation in Construction*, vol. 75, pp. 45–55, Mar. 2017, doi: 10.1016/j.autcon.2016.12.003.

[66] S. Lee and Ö. Akin, "Augmented reality-based computational fieldwork support for equipment operations and maintenance," *Automation in Construction*, vol. 20, no. 4, pp. 338–352, Jul. 2011, doi: 10.1016/j.autcon.2010.11.004.

[67] Y.-J. Chen, Y.-S. Lai, and Y.-H. Lin, "BIM-based augmented reality inspection and maintenance of fire safety equipment," *Automation in Construction*, vol. 110, p. 103041, Feb. 2020, doi: 10.1016/j.autcon.2019.103041.

[68] C. Chen and L. Tang, "BIM-based integrated management workflow design for schedule and cost planning of building fabric maintenance," *Automation in Construction*, vol. 107, p. 102944, Nov. 2019, doi: 10.1016/j.autcon.2019.102944.

[69] A. Ghaffarianhoseini *et al.*, "Building Information Modelling (BIM) uptake: Clear benefits, understanding its implementation, risks and challenges," *Renewable and Sustainable Energy Reviews*, vol. 75, pp. 1046–1053, Aug. 2017, doi: 10.1016/j.rser.2016.11.083.

[70] Y.-C. Lin and Y.-C. Su, "Developing Mobile- and BIM-Based Integrated Visual Facility Maintenance Management System," *The Scientific World Journal*, vol. 2013, p. 124249, Oct. 2013, doi: 10.1155/2013/124249.

[71] A. Motamedi, M. M. Soltani, and A. Hammad, "Localization of RFID-equipped assets during the operation phase of facilities," *Advanced Engineering Informatics*, vol. 27, no. 4, pp. 566–579, Oct. 2013, doi: 10.1016/j.aei.2013.07.001.

[72] O. Davtalab, "Benefits of Real-Time Data Driven BIM for FM Departments in Operations Control and Maintenance," *Computing in Civil Engineering 2017*, pp. 202–210, Jun. 2017, doi: 10.1061/9780784480823.025.

[73] Yoon Jong Han, Cha Hee Sung, and Kim Jinyoung, "Three-Dimensional Location-Based O&M Data Management System for Large Commercial Office Buildings," *Journal of Performance of Constructed Facilities*, vol. 33, no. 2, p. 04019010, Apr. 2019, doi: 10.1061/(ASCE)CF.1943-5509.0001270.

[74] E. W. East, "Construction operations building information exchange (COBie)," ENGINEER RESEARCH AND DEVELOPMENT CENTER CHAMPAIGN IL CONSTRUCTION …, 2007.

[75] P. Teicholz, *BIM for facility managers*. John Wiley & Sons, 2013.

[76] H.-M. Chen and Y.-H. Wang, "A 3-dimensional visualized approach for maintenance and management of facilities," *Proceedings of ISARC09*, pp. 468–475, 2009.

[77] C. K. Cogima, P. V. V. Paiva, E. Dezen-Kempter, M. A. G. Carvalho, and L. Soibelman, "The Role of Knowledge-Based Information on BIM for Built Heritage," in

Advances in Informatics and Computing in Civil and Construction Engineering, Cham, 2019, pp. 27–34.

[78] A. Akcamete, B. Akinci, and J. H. Garrett, "Potential utilization of building information models for planning maintenance activities," in *In Proceedings of the international conference on computing in civil and building engineering*, Jun. 2010, pp. 151–157.

[79] Yang Xue and Ergan Semiha, "Leveraging BIM to Provide Automated Support for Efficient Troubleshooting of HVAC-Related Problems," *Journal of Computing in Civil Engineering*, vol. 30, no. 2, p. 04015023, Mar. 2016, doi: 10.1061/(ASCE)CP.1943-5487.0000492.

[80] A. Motamedi, A. Hammad, and Y. Asen, "Knowledge-assisted BIM-based visual analytics for failure root cause detection in facilities management," *Automation in Construction*, vol. 43, pp. 73–83, Jul. 2014, doi: 10.1016/j.autcon.2014.03.012.

[81] J. J. McArthur, N. Shahbazi, R. Fok, C. Raghubar, B. Bortoluzzi, and A. An, "Machine learning and BIM visualization for maintenance issue classification and enhanced data collection," *Advanced Engineering Informatics*, vol. 38, pp. 101–112, Oct. 2018, doi: 10.1016/j.aei.2018.06.007.

[82] K. El Ammari and A. Hammad, "Remote interactive collaboration in facilities management using BIM-based mixed reality," *Automation in Construction*, vol. 107, p. 102940, Nov. 2019, doi: 10.1016/j.autcon.2019.102940.

[83] W. Chen, K. Chen, J. C. P. Cheng, Q. Wang, and V. J. L. Gan, "BIM-based framework for automatic scheduling of facility maintenance work orders," *Automation in Construction*, vol. 91, pp. 15–30, Jul. 2018, doi: 10.1016/j.autcon.2018.03.007.

[84] X. Yin, H. Liu, Y. Chen, Y. Wang, and M. Al-Hussein, "A BIM-based framework for operation and maintenance of utility tunnels," *Tunnelling and Underground Space Technology*, vol. 97, p. 103252, Mar. 2020, doi: 10.1016/j.tust.2019.103252.

[85] E. Alreshidi, M. Mourshed, and Y. Rezgui, "Requirements for cloud-based BIM governance solutions to facilitate team collaboration in construction projects," *Requirements Engineering*, vol. 23, no. 1, pp. 1–31, Mar. 2018, doi: 10.1007/s00766-016-0254-6.

[86] T.-W. Kang and H.-S. Choi, "BIM perspective definition metadata for interworking facility management data," *Advanced Engineering Informatics*, vol. 29, no. 4, pp. 958–970, Oct. 2015, doi: 10.1016/j.aei.2015.09.004.

[87] J. G. Lee, H.-S. Lee, M. Park, and W. Kim, "An Interoperable Coordination Method for Sharing Communication Information Using BCF (BIM Collaboration Format)," in *Construction Research Congress 2016*, pp. 2443–2452.

[88] A. Alvanchi and A. Seyrfar, "Improving facility management of public hospitals in Iran using building information modeling," *Scientia Iranica*, vol. 27, no. 6, pp. 2817–2829, 2020, doi: 10.24200/sci.2019.50186.1562.

[89] Y. Zou, A. Kiviniemi, and S. W. Jones, "A review of risk management through BIM and BIM-related technologies," *Safety Science*, vol. 97, pp. 88–98, 2017, doi: https://doi.org/10.1016/j.ssci.2015.12.027.

[90] M. A. Mohammed and M. A. Hassanain, "Towards improvement in facilities operation and maintenance through feedback to the design team," *The Built & Human Environment Review*, vol. 3, pp. 72–87, 2010.

[91] Parn Erika A., Edwards David, Riaz Zainab, Mehmood Fahad, and Lai Joseph, "Engineering-out hazards: digitising the management working safety in confined spaces," *Facilities*, vol. 37, no. 3/4, pp. 196–215, Jan. 2019, doi: 10.1108/F-03-2018-0039.

[92] I. ISO, "16739-1: 2018: Industry Foundation Classes (IFC) for Data Sharing in the Construction and Facility Management Industries—Part 1: Data Schema," *International Organisation for Standardisation: Geneva, Switzerland*, 2018.

[93] W. Shen, Q. Hao, and Y. Xue, "A loosely coupled system integration approach for decision support in facility management and maintenance," *Automation in Construction*, vol. 25, pp. 41–48, Aug. 2012, doi: 10.1016/j.autcon.2012.04.003.

[94] Shalabi Firas and Turkan Yelda, "IFC BIM-Based Facility Management Approach to Optimize Data Collection for Corrective Maintenance," *Journal of Performance of Constructed Facilities*, vol. 31, no. 1, p. 04016081, Feb. 2017, doi: 10.1061/(ASCE)CF.1943-5509.0000941.

[95] J. Heaton, A. K. Parlikad, and J. Schooling, "Design and development of BIM models to support operations and maintenance," *Computers in Industry*, vol. 111, pp. 172–186, Oct. 2019, doi: 10.1016/j.compind.2019.08.001.

[96] E. T. Santos, "Building Information Modeling and Interoperability," Sao Paulo, Brazil, Nov. 2009, Accessed: Feb. 11, 2021. [Online]. Available: http://papers.cumincad.org/cgi-bin/works/Show?sigradi2009_1089.

[97] S. Tang, D. R. Shelden, C. M. Eastman, P. Pishdad-Bozorgi, and X. Gao, "A review of building information modeling (BIM) and the internet of things (IoT) devices integration: Present status and future trends," *Automation in Construction*, vol. 101, pp. 127–139, May 2019, doi: 10.1016/j.autcon.2019.01.020.

[98] R. Santos, A. A. Costa, J. D. Silvestre, and L. Pyl, "Integration of LCA and LCC analysis within a BIM-based environment," *Automation in Construction*, vol. 103, pp. 127–149, Jul. 2019, doi: 10.1016/j.autcon.2019.02.011.

[99] A. Ahmed, N. E. Korres, J. Ploennigs, H. Elhadi, and K. Menzel, "Mining building performance data for energy-efficient operation," *Advanced Engineering Informatics*, vol. 25, no. 2, pp. 341–354, Apr. 2011, doi: 10.1016/j.aei.2010.10.002.

[100] P. Singh and A. Sadhu, "Multicomponent energy assessment of buildings using building information modeling," *Sustainable Cities and Society*, vol. 49, p. 101603, Aug. 2019, doi: 10.1016/j.scs.2019.101603.

[101] X. Gao and P. Pishdad-Bozorgi, "A framework of developing machine learning models for facility lifecycle cost analysis," *null*, vol. 48, no. 5, pp. 501–525, Jul. 2020, doi: 10.1080/09613218.2019.1691488.

[102] A. TohidiFar, M. Mousavi, and A. Alvanchi, "A hybrid BIM and BN-based model to improve the resiliency of hospitals' utility systems in disasters," *International Journal of Disaster Risk Reduction*, vol. 57, p. 102176, Apr. 2021, doi: 10.1016/j.ijdrr.2021.102176.

[103] C.-H. Lee, M.-H. Tsai, and S.-C. Kang, "A visual tool for accessibility study of pipeline maintenance during design," *Visualization in Engineering*, vol. 2, no. 1, p. 6, Sep. 2014, doi: 10.1186/s40327-014-0006-y.

[104] E. M. Wetzel and W. Y. Thabet, "The use of a BIM-based framework to support safe facility management processes," *Automation in Construction*, vol. 60, pp. 12–24, Dec. 2015, doi: 10.1016/j.autcon.2015.09.004.

[105] J. Beetz, L. van Berlo, R. de Laat, and P. van den Helm, "BIMserver. org–An open source IFC model server," in *Proceedings of the CIP W78 conference*, Cairo, Egypt, Nov. 2010, p. 8.

[106] T. Bray, "The javascript object notation (json) data interchange format (No. RFC 8259)," Technical Report, Dec. 2017. [Online]. Available: https://rfc-editor.org/rfc/rfc8259.txt.

[107] J. D. Brown, "Likert items and scales of measurement," *Statistics*, vol. 15, no. 1, pp. 10–14, Mar. 2011.