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Review article

Improve predictive maintenance through the application of artificial intelligence: A systematic review

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A R T I C L E I N F O

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A B S T R A C T

Facility operations and maintenance are defined as the functions, duties, and labor required daily to operate and preserve a facility asset to ensure its original function is available for its primary use and its functions are maintained throughout the facility's life. Organizations, facility management professionals, and their stakeholders expend billions of dollars annually to perform this function in the United States. Much of the cost is on inadequate facility operations that may be avoided. Utilizing the theoretical lens of the adaptive structuration theory, this rapid evidence assessment shall review the current body of scholarly literature to identify how artificial intelligence can be used with predictive maintenance to reduce a facility operations program's operations and maintenance costs. Through an organized systematic review process, this research shall utilize peer-reviewed scholarly articles published within the last 5 years to perform a rapid evidence assessment of predictive maintenance and artificial intelligence in facility operations. Through this rapid evidence assessment, the research finds three common themes that respond to the research question. The most significant theme is artificial intelligence, once implemented in the process, provides unbiased investment and repair recommendations from the analyzed data. An unanticipated discovery of interest is that the current body of literature identifies insufficient data as the number one barrier to the full implementation of artificial intelligence within a facility operations program.

1. Introduction

A majority, 70–80 %, of the costs of a facility asset are realized during the operation and maintenance phase of the facility life cycle [1–3]. A National Institute of Standards and Technology (NIST) study in 2018 summarized that $50B is spent annually on operations and maintenance in the continental United States [4]. Operations and maintenance are defined as the functions, duties, and labor required daily to operate and preserve a facility asset to ensure its original functionality is available for its primary use and its functions are maintained throughout the life of the asset [5,6]. To meet this functionality and reduce costs, organizations and managers of facility assets are constantly on the lookout for opportunities to reduce the expense during the operations and maintenance phase of the facility life cycle. Through scholarly research, many scholars have argued that digitization of the facility management process through artificial intelligence will reduce redundancies and introduce several efficiencies that will reduce costs [6,7]. Introducing artificial intelligence (AI) into the facility operations and maintenance processes may be an avenue to reducing the continual increase in operation and maintenance costs. With this systematic review, research was conducted to respond to the research question of how AI can be used with predictive maintenance to reduce the operations and maintenance costs in facility operations. This research is beneficial to the facility management profession, organizational leaders, and stakeholders because it provides a systematic review of predictive maintenance and provides awareness of opportunities to expand the use of AI into an operation and maintenance program to save costs. Entering the research, the belief was the research will indicate AI will reduce operations and maintenance costs through work request response efficiencies, reduction in labor, and improved data analysis for informed decisions and recommendations.

2. Literature background

Over the years, facility management professionals have implemented many diverse types of maintenance strategies to make their operations and maintenance programs as effective, efficient, and responsive as possible. In the National Institute of Standards and Technology (NIST)

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report in 2018, author Douglas Thomas reports census data estimates $50B was spent on outsourcing maintenance and repair in 2016 [4]. Attractive to any business leader, in the 2018 NIST report Mr. Thomas also argues that cost savings from adopting predictive maintenance methodology are not truly defined but estimates it has the potential savings anywhere from 15 to 98 % of the total maintenance cost [4]. Kim et al. [8] report that many of the maintenance strategies benefit the response levels required to maintain an operational facility and historically the strategies have kept the facility management program active [8]. Thus, implementing the right maintenance strategy can save the organization resources to perform other organizational needs. Seeking such savings, facility management professionals have grappled with finding the correct maintenance strategy for their programs.

The typical maintenance strategies in the industry today are preventative maintenance, corrective maintenance, and predictive maintenance. Preventative maintenance (PM) is defined as work performed on a fixed interval that is based on the original equipment manufacturer (OEM) or industry-recommended schedule [9,10]. The PM work involves replacing the equipment's recommended components and protection material based on the OEM and/or industry recommendations. Corrective maintenance is repair work done to restore equipment to its original operating characteristics following a diagnostic finding or following equipment failure [9,11,12]. This type of maintenance is performed when an equipment or system failure occurs or when the equipment can no longer serve its purpose, thus, the maintenance involves performing the service necessary to restore it to operations.

Predictive maintenance (PdM) is work performed as part of a condition-based maintenance strategy that involves monitoring the operational characteristics of the equipment, analyzing operational data and/or equipment functionality, determining a problem exists, and resolving the problem before equipment failure occurs [9,12–17]. PdM is performed by technicians intimately familiar with the operational characteristics of the equipment and may or may not involve the use of diagnostic equipment. As technology changes and improves the way maintenance tasks are performed, maintenance strategies improve. Ideally, facility management leaders desire to implement PdM into their maintenance program because scholars report it introduces fewer unanticipated equipment failures and more opportunities to save on operation and maintenance costs [1,3]. As reported in the 2018 NIST report, there is a lot of waste in trying to implement new or change existing maintenance strategies [4]. Therefore, this research investigates predictive maintenance and AI identifies how cost savings may be realized and provide recommendations on proceeding forward with implementing AI into a facility operations program.

Artificial intelligence (AI) enables a machine to mimic human perception and cognition. AI is a general term used to encapsulate many different uses of predictive statistical models. Familiar AI names and functions are neuro networks, robotics, expert systems, machine learning, deep learning, or machines used to evaluate data based on weighted factors to present a functional use of the data [18]. Today, AI applications continue to expand as they range from language translation, speech recognition, robotics, data analytics, problem-solving, vision, decision recommendations, medicine, and many other analytic functions [19,20]. Athanasopoulou et al. [19] presents many different uses of AI in biomedical research and argue the medical community is expanding the application of AI. Marinaks (2020) argues employing the AI framework of machine learning and deep learning provided data analytics solutions for energy management and energy-efficient protocols in facilities. This argument supports the idea of energy conservation and improves the data collection to support analytics. Tan et al. [18]. introduce MIGRATE (machine learning for smart energy), a three-step framework to predict machine-specific load profiles by energy disaggregation, which in turn predicts activity state and production capacities (p. 1). AI is rapidly expanding into every industry but in this current rapid evidence assessment, the literature was reviewed for AI's application, use, and expansion into the facility management profession, specifically, facility operations.

2.1. Research question

Using CIMO logic researchers construct review questions, conduct design science research on the review questions, and produce synthesized evidence-based results and recommendations to influence evidence-based decisions. This research article conducts design science research to respond to the question guiding this article. See Table 1 for the CIMO table discussing the CIMO framework used to develop the research question. The research on AI shall add to the body of knowledge by taking a different approach to implement AI into the facility maintenance process. The approach shall provide the profession with an unbiased, peer-reviewed, evidence-based review of the current body of literature (within the last 5 years). The reader of this article shall depart with an understanding that AI enhances the productivity of maintenance activity, has the potential to cut costs, and will improve the facility management program. The research question backing this article is how AI can be used with predictive maintenance to reduce the operations and maintenance costs in facility operations. The theoretical lens for conducting this review is the adaptive structuration theory.

3. Theory

The adaptive structuration theory (AST) is a theory focused on the implementation and use of information and communication technologies in groups and organizations [23,24]. DeSanctis and Poole [23] theorize AST examines organizational change from two vantage points; types of structures provided by introducing modern technology and the types of structures created by actors interacting with the new technology. The concept of introducing modern technology, interacting with modern technology, and creating new structures is important to this research. The independent variables being studied are task, people, and technology. The concept elements of the theory are structures, systems, and outcomes. Aligning the theory concept elements to the study variables, we see structures are the tasks performed and the boundaries set in the performance of those tasks [24]. Systems are the relationships among the actors (people and technology) performing the tasks to obtain the overall outcome [23,24]. DeSanctis and Poole [23] further argue that as people interact with technology and become accustomed to performing tasks, they create their structures known as appropriation. This concept is the organization's members adapting to the new technological features and making the process their own. The appropriations may also be depicted as organizational members' attitudes toward modern technology [23]. This concept becomes important to the research because acceptance of the new technology is essential to achieve the overall outcome of increased production and reduction in cost.

Table 1
CIMO model.

Context	Which individuals, relationships, institutional settings, or wider systems are being studied [21]?	In this article, artificial Intelligence, Predictive Maintenance Methodology, facility management program
Intervention	The effects of what event, action, or activity are being studied [21]?	Applying artificial intelligence to the predictive maintenance methodology
Mechanism	What are the mechanisms that explain the relationship between interventions and outcomes? Under what circumstances are these mechanisms activated or not activated [21,22]?	Technology decision support system, subject matter expertise, data review from operations
Outcome	What are the effects of the intervention? How will the outcomes be measured? What are the intended and unintended effects [21,22]?	Reduction in maintenance costs.

Understanding and applying this theoretical framework to the adaptation of AI into the predictive maintenance process will provide an expanded outlook on how the maintenance is accepted and performed by the facility management community.

The AST was first introduced in 1994 by authors Gerardine DeSanctis and Marshall Scott Poole. Stemming from the structural theory by Anthony Giddens, the AST has remained unchanged. During the implementation of the AST, industries were implementing advanced communication and technology devices, so employers were looking for a management theory explaining organizational change strategies involving technology [23]. The AST is not only for technology implementation: scholars have also used the theory for organizational change, virtual teams, the evolution of standards, and the implementation of innovations [24]. Recently Olowa et al. [25], used AST to define the characteristics of a building information modeling-enabled learning environment in their article. They used the theory's concept of structures to frame how software acceptance will evolve into the desired outcomes [25]. The theory has received some criticisms as being too positive and straying away from Anthony Giddens's structural theory approach. Although heard and recognized, the criticisms have not changed the theory, and it is still valid and is widely used by scholars today.

Other theories were reviewed for consideration in this research article. The researcher considered the technology acceptance model (TAM) which focused on the individual user and their attitude toward the acceptance of the use of technology. This theory was not selected because the focus of this study is on the technology itself and the cost-saving potential. The unified theory of acceptance was considered and eliminated because, like TAM, this theory focused on individual acceptance of technology. Now, let's apply the AST to take a simplified look at how facility maintenance technicians perform predictive maintenance.

Using the AST as a theoretical lens, Fig. 1 depicts the predictive framework incorporated with the adaptive structuration theory concepts. The maintenance technician observes a facility asset in operation in the structure concept. As the system or actor, the technician determines if the facility asset is operating according to the asset's operating characteristics. If yes, the technician documents the observances according to the procedural boundary conditions. If not, the maintenance technician performs a level of maintenance to return the asset to its normal operating characteristics. This activity simplifies the current approach of analyzing an asset's operational characteristics and performing maintenance before there is a failure based on the asset's data.

The following method section shall provide the article's search strategy to locate the research articles, describe the appraisal tool used to assess the articles and provide a summary of each article's research question, method, and results.

4. Method

A rapid evidence assessment (REA) is an evidence-based management approach in which to deliver timely decision-based recommendations with limited resources [21]. Evidence-based management research has several research designs for decision-based approaches to collect scholarly, peer-reviewed evidence on a management problem, and develop scholarly evidence supporting decisions based on the soundness of the evidence. This evidence-based framework is vital for this study because it will support a decision-based approach to deliver recommendations to inform leaders of the benefits of implementing AI into their facility operations. The structure of this methodology is, in order of appearance, the discussion of the search strategy and inclusion/exclusion criteria, study selection, critical appraisal, and a description of the data set and synthesis of the evidence.

4.1. Search strategy and inclusion/exclusion criteria

The focus of the search strategy was to conduct the research required to find the articles to respond to the review question using the University of Maryland Global Campus (UMGC) online library. The article search was conducted in two online databases, as presented in Appendix A. The databases were chosen because they contain information on facility management, facility maintenance, and facility operations. The article inclusion criteria were based on whether the article's subject pertained to predictive and proactive maintenance of facility systems, the article's published date range within the last five years, whether the article has been peer-reviewed, and whether the article was written in the English language.

4.2. Study selection

The scholarly, peer-reviewed article search returned 60 articles from the two databases (see Appendix B). The 60 articles were batch downloaded from the databases by their research information systems file, into Mendeley Desktop, version 1.19.8. In Mendeley, the articles were stored, organized, reviewed, and screened for inclusion in the research.

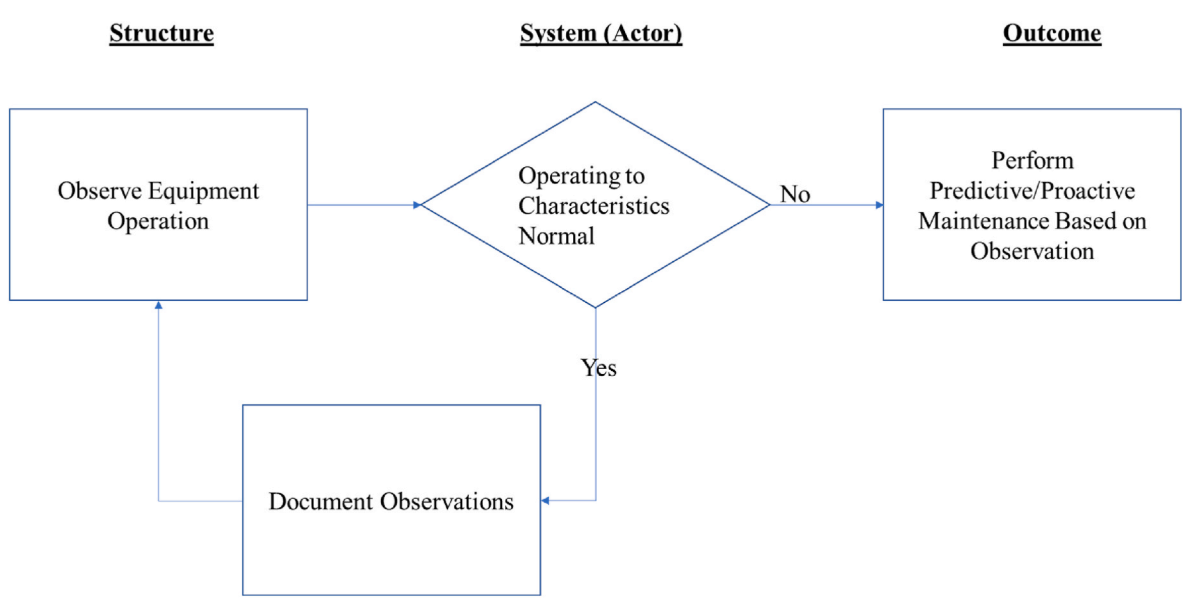


Fig. 1. Predictive maintenance framework.

Initially, Mendeley identified duplicates that were automatically removed from the Mendeley database—additional eligibility screening involved reading the article's abstract for detailed information on the articles. Appendix B contains a PRISMA diagram that provides in-depth details of how the articles were eliminated to the final 14 articles for this REA.

4.3. Critical quality appraisal

Long et al. [26] quality appraisal approach, TAPUPAS, was adopted for the appraisal of the articles. TAPUPAS has seven categories for appraising the transparency and rigor of qualitative, quantitative, or mixed methods research articles [26]. The categories of the appraisal tool are transparency, accessibility, purposivity, utility, propriety, accuracy, and specificity. For scoring each category, a scale was used of one through three, with three being the greatest level. A score of one means the article did not meet the criteria, a score of two the article meets the criteria, and a score of three is the article exceeds the criteria. The highest overall score for an article was 21 and was achieved if the article scored three in each of the seven evaluation criteria. To select the highest quality articles, articles achieving an overall score of 14 or above were considered quality articles for inclusion in the research because they met the minimum score in each of the seven categories. Any article scoring a one in any category was eliminated for not meeting the minimum criteria. For reference, Appendix D, Table D1 contains a summary listing of the scores for each article and each of the TAPUPAS evaluation criteria. Tables D2 through D18 contain the quality appraisal for each of the 17 articles screened as evidence for this rapid evidence assessment. After conducting the quality appraisal, three articles were eliminated because of their low-quality appraisal scores, leaving 14 articles included in the synthesis.

4.4. Description of data set and critical appraisal

The selection of the TAPUPAS appraisal tool was because it is a widely accepted tool by scholars, practitioners, and researchers for review of quantitative, qualitative, and mixed research method articles [21,26,27]. The quality appraisal tool has some disadvantages. Scholars have argued the appraisal tool introduces subjectivity into the scoring of articles and different researchers may produce varying results of acceptance [28]. Being this study was part of an academic setting, this criticism is a limitation of this study because the researcher is the same as the reviewer. Of the 14 selected articles, one was qualitative, one was mixed method, and 12 were quantitative articles.

4.5. Coding

A crucial process in analyzing, interpreting, and formulating recommendations from qualitative data is coding [29]. A code is a short phrase or a word the researcher assigns or associates with a portion of data [30]. In research, coding is used by a researcher to operationalize qualitative data to answer a research question [31]. Using the methodology described in this REA, 14 quality appraised peer-reviewed articles were determined to be relevant to the current management problem and review question. With this determination, the 14 articles were coded, categorized, and findings developed, and from that process, recommendations were systematically developed based on the evidence.

Descriptive coding during the first cycle coding, second cycle coding, and developing themes were applied for this REA. Descriptive coding assigns labels to passages, words, phrases, and other forms of qualitative data [30]. Both deductive and inductive coding were applied to create the descriptive codes. Atlas.TI version 23 software was used to assist the researcher with organizing the first-cycle coding, and second-cycle coding, and for developing the final themes for this research. With the use of Atlas TI, the articles' discussion and findings were reviewed and coded. The codes were sorted, structured, and reviewed to discover patterns and relationships in the data. Through these relationships, themes were developed to respond to the REA review question.

4.5.1. First cycle coding

The first cycle coding process began by reviewing the context within the CIMO model (Table 1) and the concepts of the adaptive structure theory as a lens to develop deductive codes. Within the theory, the concepts of structure, system, and outcome were used to develop the 16 deductive codes used in the first cycle (see Appendix E). Also, during the first cycle of coding the researcher developed an additional three inductive codes. In all, 19 codes were utilized to code the 14 articles.

4.5.2. Second cycle coding

Second-cycle coding was synthesizing or putting the data together into new assemblages to operationalize the data [30]. The second cycle of coding involved developing categories using the 19 codes, the quotations from the 14 articles, and a search for commonality in the information. Saldana [30] described a category code as an umbrella code or keyword that expresses the overarching concept of the other codes identified in the text. Through this process, codes were operationalized through the lens of the adaptive structuration theory and placed into categories. Initially, 6 categories were identified, but through cleaning the codes, three related categories were merged for a final three. These categories are listed in Appendix G, with the codes aligned to the categories.

4.5.3. Categories to themes

According to Saldana [30], themes are patterned responses or meanings from the data that inform the research question or framework; they are a more abstract entity that gives deeper meanings, interpretation, and integration to a context. The themes provided strong awareness of the characteristics in response to the review question, and through those characteristics, recommendations were developed for the readers of this study [21]. Utilizing the categories from the second cycle coding, the adaptive structuration theory, and the review question, themes were developed to respond to the review question. In total, three themes were developed and presented in Appendix G according to the 14 articles used to create the themes. Each of the three themes is representative of the data interpreted from the 14 articles.

5. Results

In this section, the coding results and findings shall be presented according to the evidence derived from the articles. Using the adaptive structuration theory, CIMO model context, and the review question as a lens, the following findings were developed according to the evidence and the following research question, *"How can artificial intelligence be used with predictive maintenance to reduce the operations and maintenance cost in facility operations?"*

5.1. Finding 1

Enabling artificial intelligence provides the potential for remote monitoring of facility system conditions.

The scholarly evidence from 8 of the 14 articles revealed AI, once operationalized, provides real-time monitoring and awareness of the facility systems' operational characteristics [13]. reported better monitoring leads to better facility operations in their article presenting their Industrial Data Analysis Improvement Cycle framework. The framework presented a visual representation of their test air handling unit that enables visual detection of anomalies that represent the degradation of the unit [13]. Implementation of their framework allowed direct monitoring of indoor air quality and other air transfer characteristics [32]. in their processing plant retrofitted for Industry 4.0 framework reported that once implemented, the framework provided remote monitoring, which alerted plant operators of an emergent condition even when they are separated from the plant. Although the article was focused on safety and health in the gas and oil industry [33], surmised that a proactive construction management system might be applied to monitor fault detection and diagnosis of any rotating machinery. Through the sub-networked real-time location system and virtual construction simulation system, their system provided the capability to relay alarm signals to specific tags in the location network and monitor hazardous areas for unexpected workers, equipment, and vehicles [33]. Rojek et al. [11] reported AI monitoring operations to provide real-time reports based on preprocessed data for immediate awareness of predictive suggestions for optimal settings of equipment to meet preset ranges. Also, anomaly detection within the facility systems provides effective and efficient notifications of emergent conditions during equipment failure or impeding failure [11]. Marzouk and Zaher [34] reported that exploiting AI in facility operations provides opportunities for facility managers to monitor, manipulate, and retrieve required maintenance from their cellular phones. The automated system may provide awareness of current conditions, alert of potential faults, and allow the technician to provide a certain level of manipulation [34]. Cheng et al. [35] found that remote monitoring puts the customer and the occupant at the front of facility operations. Through remote monitoring, facility managers can receive reports of conditions, and occupant discomforts, or monitor preset conditions and make immediate adjustments which provide an immediate response [35]. Artificial intelligence, once installed into a facility operation and maintenance program, offered massive opportunities to cut costs by improving facility system operation and virtually monitoring and manipulating facility system performance.

5.2. Finding 2

5.2.1. Unbiased and data-backed facility system repair, investment, and response decisions

The evidence from 10 of the 14 scholarly articles revealed artificial intelligence provides the necessary data interpretation and awareness for facility management professionals, leaders, and stakeholders to make informed decisions on investments, system repair, and data-backed responses to equipment operations [13,35–37]. AI operating in the facility operations program collects data, analyzes, and interprets the data based on learned characteristics, and makes predictions based on the interpreted data [38]. Ochella et al. [38] go on to suggest that mid-level managers and leaders will also need training to be made aware of the capabilities and to build trust in the predictions provided by AI.

Trusting and believing in the classification of repairs, facility managers have always desired a level of service with a timely response. AI can provide the automated prioritizing of work requests so that technicians may respond promptly to high-priority requirements [34]. This response and prioritization contribute to unbiased facility repairs. Additionally, Hosamo et al. [36] found that artificial neural networks, support vector networks, and decision trees are methods of choice for predicting and ranking the severity of faults in facility operations. In their occupant-focused digital twin framework, the technology provides the decision-makers with the necessary awareness of condition changes in a monitored space that allows immediate response before the occupant notices major changes [36]. In a traditional operation, facility managers are left to insert subjectivity to respond to trouble calls. However, using a data-driven predictive maintenance planning framework, the AI networks remove the subjectivity and prioritize the work and investments [35].

The remaining useful life of a facility system is critical data to have available when making an investment decision and AI enables the data to be readily available [39]. Rojek et al. [11] stressed that AI provides improved integration of production systems, data collection, and processing in key areas. The authors go on to highlight that this level of data accumulation and communication provides the decision-makers with the necessary information to make informed investment and repair decisions [11].

Regarding the safety of all involved, AI provides unbiased decision-making and awareness to protect workers, vehicles, and uninformed occupants against dangers with alerts by the proactive construction management system [33]. Sattari et al. [33] reported that conditions like fatigue or stress led to poor judgment or poor decision making which leads to mistakes. In closing, Ahern et al. [13], presented AI as useful in an analysis that led to a customer deciding to return an unnecessary part to an air handling unit because it was determined not to be required. This type of informed decision-making saved on material costs, technician labor, time, and other organizational resources that may be used in other parts of the organization.

5.3. Finding 3

5.3.1. Increase facility system online time

The evidence from 11 of 14 scholarly articles revealed that inserting AI into the facility operations technology of the facility management program has the potential to increase facility system online time [13,32,37,40]. Predictive maintenance provided the ability to detect and inspect subtle deviations in facility systems operations, remedy those situations before failure, and keep the facility operating without interruption [13]. Maintenance technicians also plan and schedule equipment downtime for nonpeak hours so as not to interrupt or disrupt ongoing operations, a benefit to predictive maintenance enabled by artificial intelligence [13,32].

AI provides maintainers with continuous awareness of the equipment's operating characteristics by training the AI to maintain boundaries for the equipment to ensure any variations in operations are minimal [32]. Marzouk et al. [34] reported that in the event of a failure, AI not only informs the facility management personnel, but it provides awareness of the device that failed, the location, and other operational features so the responding technician brings the right equipment and tools to the job. This benefit gets the equipment back into service as quickly as possible [34]. Hosamo et al. [36] expanded on the response time, noting that through AI the facility manager can prepare maintenance equipment supplies and tools in advance as an alternative to restoring them after a failure.

In a similar occurrence, Cheng et al. [35] found condition monitoring enabled facility management personnel to keep the functionality of the building in the best possible condition. Any abnormal occurrences will alert the staff to intervene, and with AI there are countless monitoring and response capabilities [35,38,41]. In their digital twin framework, Hosamo et al. [42] surmised that computer-aided design and AI together will provide an avenue for saving cost, reducing hazards, and optimizing supply chains for building materials. In a similar report on building information modeling [43], reported that the developed building information modeling system was applied to aid the operation and maintenance of mechanical, electrical, and plumbing engineering in a real project. This operation facilitated the supply chain optimization of advanced technology by providing the necessary security to the MEP and subsystems [43]. By delivering real-time awareness, and automated responses to digitally controllable technology, AI cuts costs and enables organizations to realize savings in facility operations [34].

5.4. CERQual

Confidence in the evidence from reviews of qualitative research (CERQual) provides a transparent and systematic framework for evaluating and determining the confidence level of findings in qualitative research [44–46]. Systematically measuring the confidence in findings is necessary to provide transparency and trust in the research findings' development. CERQual includes four components of grading criteria, methodological limitations, coherence, adequacy of data, and relevance [47]. Each of the CERQual terms and grading criteria is defined in Appendix H. Each of the findings for this REA was assessed based on the

CERQual criteria and the details are displayed in Appendix I.

Findings 1, 2, and 3 are all assessed as moderate CERQual levels of confidence. The overall rating applies to the level of confidence in the adequacy of the research using the context of the review question. The basis was the research conducted on artificial intelligence, facility management, and preventative or proactive maintenance of a facility asset. All 14 articles were published within the last five years, were relevant to the research question, and were peer-reviewed. Therefore, there is no concern about the confidence of these articles or the findings.

6. Discussion

Artificial intelligence (AI) is expanding into the facility management profession. However, the current review of scholarly literature contained literature on facility programs transitioning the entire facility operations program to AI. The current body of literature contained individual successes with implementing AI to control and make decisions on many singular equipment systems or programs in facility operations. As an example of how the individual equipment systems operate using the adaptive structuration theory as a theoretical lens, Fig. 2 depicts AI as the framework for monitoring and enabling the predictive maintenance program of a facility system. Shown within the diagram, the concept of “document observations”, AI utilizes deep learning to continuously monitor the operating characteristics of the facility system and recognize any anomalies. This procedure serves as a continuous feedback loop throughout the facility system operation. The updated concept of “outcome” portrays the recommendations for predictive or proactive maintenance from the analysis tool. Any observed anomalies are transmitted to a technician in the form of recommendations. If the analysis is programmed to initiate a control adjustment, the exercising of a valve or other form of adjustment may be automatically made without human interaction. These procedures and processes save the organization labor hours during the operation and maintenance phase of facility operations.

Collectively, this review argues that the current body of literature provides evidence that AI offers additional capabilities to facility management on various portions of the entire facilities program. Opportunities include such things as remote monitoring, automated control of facility systems, immediate awareness of emergent conditions, predictive maintenance instead of break fixes, and countless labor-saving opportunities that reduce staffing. AI once fully operationalized can monitor the entire facility system and will relay emergent situations to alert remote operators [11,13,32,33]. Traditionally, facility plant operators remain near the building management system to be alerted to an emergent condition. Today, remote devices connected to the building management system offer a level of separation but not to the extent that is possible with the enhanced use of AI. AI, when properly trained to monitor the facility system’s operational characteristics, connected to a remote device, and directly connected to the CMMS, may recognize problems in the facility operations before an reoccur and produce a work request to send a technician to perform proactive maintenance. Through this scenario-based immediate response, facility system operational time may be increased, downtime decreased, and additional resources saved.

AI will expand our capability to retain, analyze, make predictions, and make informed decisions from collected data. Not only helping operators to make decisions, but AI is currently performing cognitive functions traditionally reserved for humans. In the facility management profession, operationalized AI can provide unbiased repair responses and investment decisions. Full operational capability will be achieved when AI is monitoring the operational characteristics of the facility systems, records the data, analyzes the data, develops recommendations based on the data, and presents the recommendations to facility management professionals to make decisions.

In addition, data analysis through AI will make and implement automated decisions based on operational parameters by adjusting flow characteristics as required to maintain facility system set points. With AI, more data can be analyzed and better decision-making through data is possible. Also, through analysis of work requests, time shall be saved from prioritizing work requests because it is automated, reducing labor. The use of AI will increase facility system online time enabling the facility asset to be used for its intended purpose.

6.1. Recommendations for practice

6.1.1. Recommendation one

Managers should dream big about artificial intelligence in facility management but start small with implementation in targeted areas of the program. Based on the research, only portions of facility management programs have been proven to operate effectively using AI but have shown potential for cost savings. The current research on transitioning is not fully developed and indicates a strong recommendation for a full transition. The research contains strong initiatives on individual facility systems and the use of AI but nothing all-encompassing to warrant the recommendation to transition the entire program.

Also, the body of literature expressed that there are enormous challenges to implementing AI. The most consistently reported challenge is the availability of enough data to train data-driven AI algorithms. The algorithms will require an enormous amount of real-world

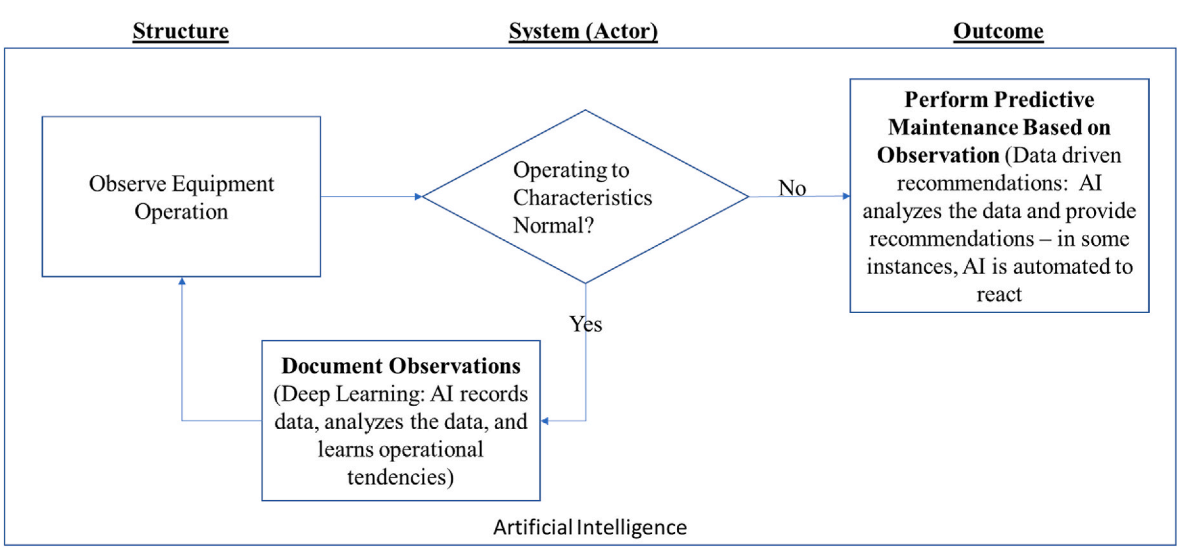


Fig. 2. Final conceptual framework of theory.

data, and a long-standing predictive maintenance program may be an avenue for accumulating the data. Expanding on the data challenge, the current research mentions the lack of equipment fault details and adequate data quality as being significant to implementation.

6.1.2. Recommendation two

Although recommendation number one is to incrementally implement AI, some initiatives are recommended to make a smooth transition to full implementation of AI once available and to take advantage of cost savings. First, strategically begin an initiative to transition from a reactive maintenance program to a predictive maintenance program. Establish a team consisting of a facility management professional, data scientist, program manager, and financial specialist to work with a facility maintenance consultant to develop a transition plan for the program. As part of the transition plan, there should be a task to perform a facility condition assessment geared toward fully automating the existing facility systems and installing total facility sensors to monitor the facility conditions. Ensuring this task is part of the transition plan will keep the team on track to implement a predictive maintenance program. In some cases, it will not be cost-effective to transition the existing facility to full automation. In these instances, a smaller level of automation may be incorporated into a sensor-driven network with a building management system to monitor operational characteristics and make recommendations based on those characteristics.

6.1.2.1. Recommendation three. Implementing AI must be an organizational initiative because every organization has its own culture and without strategic backing, the program may not materialize. Executive leaders should establish a strategic enterprise effort dedicated to backing the initiative. The enterprise's strategic effort should involve establishing a charter to guide the adoption of the new initiative. The charter should define risks, alignment with business and technology opportunities, define data governance and handling, and should define organizational competencies. A governance committee should be established to monitor progress and ensure all the needs identified along the process are documented, supported by the committee, and meet the intent of the written charter.

6.2. Future research

AI has massive opportunities in facility management as identified by the individual equipment system successes in the research. In future research, a cost basis for implementing AI is needed and therefore should be researched. To make evidence-based decisions to proceed in whole or in part with AI in a program or facility, leaders and practitioners must have and understand a cost basis for implementation. Also documented in the re-research, there needs to be a solution researched to solve the multi-operational system communication for facility support systems. Currently, building management systems, computerized maintenance management systems, direct digital control systems, and various individual equipment systems do not have one standardized communication language that allows AI to monitor the activity. Research should respond with one common communication standard for all facility systems to operate. Checklists should be created for organizations seeking to transition from a reactive-based maintenance framework to a condition-based framework. The research and checklists should identify characteristics of the necessary data requirements, training of technicians, leaders, and stakeholder requirements.

6.3. Limitations

This study was conducted by a doctoral student in an academic setting with adequate professor oversight. The student research abilities are still developing, and the skill of qualitative data analysis is fragile. Also, following the documented guidelines for conducting a rapid evidence assessment keeps the research project organized and within the boundaries of qualitative research.

The quality appraisal of the articles was conducted by one reviewer and the reviewer is the same as the author and researcher of this article. As noted in the methodology section this is a criticism of the TAPUPAS quality appraisal tool but with this being a rapid evidence assessment no other reviewer is warranted.

The researcher is a facility management professional with over 30 years of experience working in the United States federal government. This experience introduced professional bias, but the researcher took precautions. Every step of the research was conducted according to CEMBa Guideline for Rapid Evidence Assessment in Management and Organizations to avoid any conditions of bias [48]. As for bias during the analysis and synthesis, the researcher coded the articles through the adaptive structuration theory lens, used Atlas TI to store the codes, and synthesized the coded data to develop the findings. Recommendations were developed from the articles selected as part of the research.

7. Conclusion

This research responds to the management question of how artificial intelligence can be used with predictive maintenance to reduce the operations and maintenance costs in facility operations. This research investigated the scholarly literature through the adaptive structuration theory lens for recommendations to assist facility management leaders with their decisions to transition to AI. This research reviewed the latest literature about predictive maintenance and found evidence that implementing AI with predictive maintenance in a facility operations program will save on labor hours, and time spent on analysis, and will provide unbiased predictive maintenance and investment recommendations. Additional research is required to determine the process to obtain and maintain full operational capability with AI. Equally important, real-life examples of AI operating in a facility management program must be analyzed and reported for future research projects. At this time, AI was found to save facility operations costs, and this research presented opportunities for increased implementation. Future research will need to determine additional implications of AI implementation. One final point the scholarship review stresses is that AI is a new paradigm with massive benefits, expanding to all industries.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

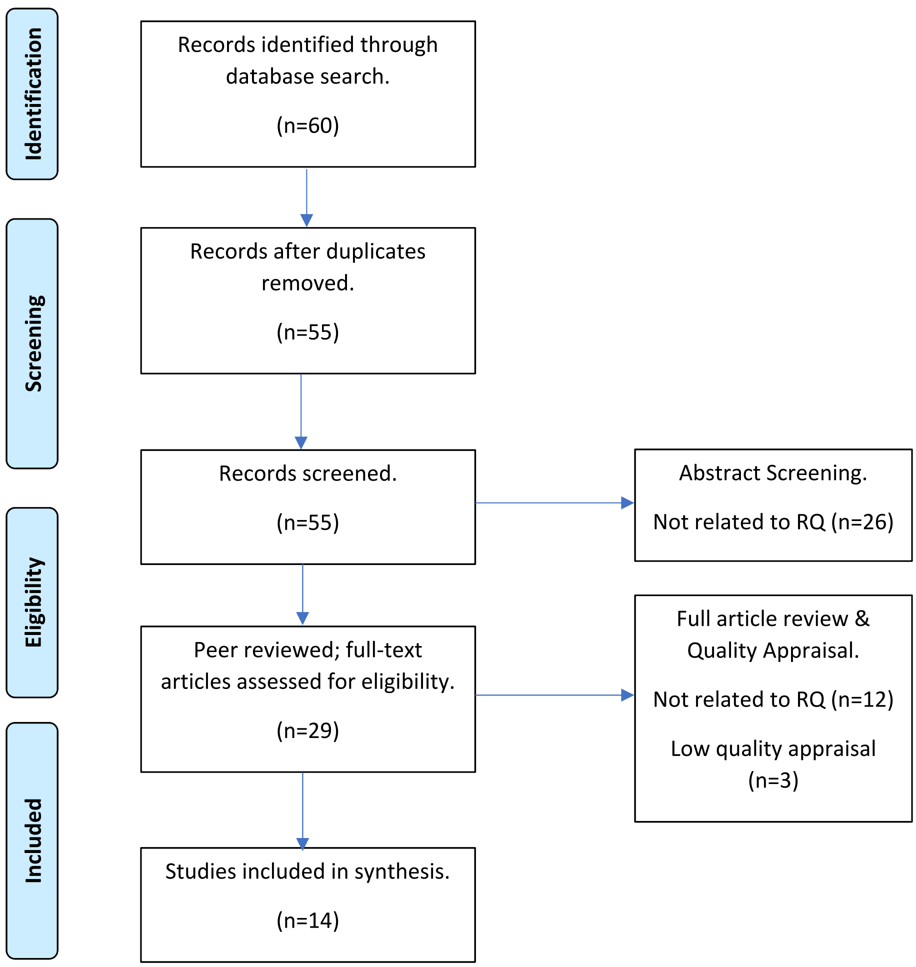
Appendix A. Listing of Databases Searched

Database Search Strings and Results

Database	String	Inclusion/Exclusion Criteria	Initial Results	Results
ScienceDirect	("predictive maintenance" OR "proactive maintenance") AND ("artificial intelligence" OR "machine learning" OR "robotics" OR "development of 'thinking' computer systems" OR "expert system" OR "intelligent retrieval") AND "facility management"	Inclusions • Predictive or Proactive maintenance	50	50
OneSearch	("predictive maintenance" OR "proactive maintenance") AND ("artificial intelligence" OR "machine learning" OR "robotics" OR "development of 'thinking' computer systems" OR "expert system" OR "intelligent retrieval") AND "facility management"•	• Published in the last 5 years. • Peer-reviewed. • English language.	10	10

Note: Downloaded article's RIS file to Mendeley software, removed duplicates, and removed articles not related to predictive maintenance and artificial intelligence amongst the aggregated downloads. The resultant articles were 29 articles for additional review. Following the review of the abstract, 18 articles were retained for a quality appraisal.

Appendix B



PRISMA Flow Diagram. Note. Adapted from "Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement," by D. Moher, A. Liberati, J. Tetzlaff, and D. Altman, 2009, *BMJ, 339*(7716) pp. 332–336 (https://doi.org/10.1136/bmj.b2535). Copyright 2009 BMJ.

Appendix C. Article Listing

Title, Author(s), Year	Research Question	Phenomenon/a Studied	Type of Research Method	Description of Sample	Results of the Study
A Digital Twin predictive maintenance framework of air handling units based on automatic fault detection and diagnostics. Hosamo, Haidar Hosamo, Svennevig, Paul	Proposes a Digital Twin predictive maintenance framework of AHU to overcome the limitations of facility maintenance	Heating, ventilation, and air conditioning systems (HVAC) Facility maintenance	Quantitative	The framework was tested in a real-world case study with data between August 2019 and October 2021 for an educational building in Norway to validate that the method was feasible.	Results demonstrate that the continually updated data combined with APAR and machine learning algorithms can detect faults and predict the future state of Air Handling Unit

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Title, Author(s), Year	Research Question	Phenomenon/a Studied	Type of Research Method	Description of Sample	Results of the Study
Ragnar, Svidt, Kjeld, Han, Daguang, Nielsen, Henrik Kofoed. 2022	management (FMM) systems now in use in buildings.	management Artificial intelligence			(AHU) components, which may assist in maintenance scheduling. Removing the detected operating faults resulted in annual energy savings of several thousand dollars due to eliminating the identified operating faults.
A novel Neutrosophic-based machine learning approach for maintenance prioritization in healthcare facilities. Ahmed, Reem, Nasiri, Fuzhan, Zayed, Tarek. 2021	The authors utilize a combination of Neutrosophic logic, Analytic Network Process (ANP), and Multi-Attribute Utility Theory (MAUT) reduce the subjectivity of expert-driven decisions and produce a reliable ranking of hospital building assets based on their variable criticality levels and performance deficiencies.	Healthcare work request priority Machine learning algorithms	Quantitative	Experts involved in the current study add up to a total of 31 sharing similar professional backgrounds relevant to the healthcare facility management fields including hospital operation and maintenance management personnel (30 %), maintenance engineers (60 %), as well as government officials involved with the planning, auditing and, prioritization of infrastructure needs and investments (10 %).	The developed model was applied to Canadian healthcare facilities, and its corresponding predictive performance was validated using comparison against a previously established model, and its excelling capability was rated.
A predictive maintenance model for k-out-of-n:F continuously deteriorating systems subject to stochastic and economic dependencies. Huynh, K T. Vu, H C. Nguyen, T D. Ho, A C. 2022.	Develop a high-performance opportunistic predictive maintenance model for k-out-of-n:F continuously deteriorating systems subject to stochastic and economic dependencies among units.	Cost model Equipment maintenance Life cycle Bayesian rule Stochastic dependency theory	Mixed Method	Developed a high-performance predictive maintenance model.	The authors developed the predictive model and in future studies will report on the real-time testing of the model.
A process plant retrofitting framework in Industry 4.0 perspective. Carlo, Fabio Di, Mazzuto, Giovanni, Bevilacqua, Maurizio, Ciarapica, Filippo Emanuele, Ortenzi, Marco, Donato, Luciano Di, Ferraro, Alessandra, Pirozzi, Marco. 2021.	The authors aim to smart retrofit by implementing all the tools necessary for IoT 4.0.	IoT 4.0 Processing Plant Retrofit	Mixed Method	Old processing plant and a literature review of 56 scholarly documents found in SCOPUS. After review, 30 documents were found relevant.	The authors proposed a general framework to guide the transition process of implementing IoT in a processing plant.
A remote laboratory for maintenance 4.0 training and education. Kans, Mirka, Campos, Jaime, Håkansson, Lars. 2020.	The authors set to describe essential competence requirements within maintenance engineering, with a focus on Maintenance 4.0, and how these could be given and trained at higher education level using modern digital and automation technologies.	Remote laboratory Industry 4.0 Information and Communication Technology Open System Architecture-Condition Based Maintenance	Quantitative	The research set up a mock classroom for remote testing and diagnosis of laboratory equipment.	The results indicate the authors were able to identify competencies needed for future engineering programs.
A theoretical framework for data-driven artificial intelligence decision-making for enhancing the asset integrity management system in the oil & gas sector. Sattari, Fereshteh, Lefsrud, Lianne. Kurian, Daniel. Macciotta, Renato. 2022.	The current study extends this research to determine the most influential element(s) of Asset Integrity Management by using a probabilistic approach.	Safety incidents Maintenance failures Predictive maintenance Machine learning	Quantitative	To save time and resources, we randomly selected 764 incidents (10 % of the data) to classify manually. These 764 incidents are then further divided into training data (535 incidents or 70 %) and test data (229 incidents or 30 %) using the train test split feature from Python's sci-kit-learn library.	The practical testing of the research answered the research intent. Application of this framework in the field will provide awareness of success for the practical application.
An artificial intelligence approach for improving maintenance to supervise machine failures and support their repair. Rojek, Izabela, Jasiulewicz-Kaczmarek, Małgorzata Piechowski, Mariusz Mikołajewski, Dariusz. 2023.	The article's author aims to discuss using AI methods and techniques to anticipate failures and respond to them in advance by doing maintenance activities in an appropriate and timely manner.	Artificial intelligence Analysis of dataset	Quantitative	Computational analysis and simulation based on the real industrial data set. Data included 29,115 records. A set of 20,381 (70 % of 29,115) was used for training.	Results show that the effective use of preventive maintenance requires substantial amounts of reliable annotated sensor data and well-trained machine-learning algorithms.
Artificial intelligence exploitation in facility management using deep learning. Marzouk, Mohamed. Zaher, Mohamed. 2020.	The authors aim to apply a methodology that can classify and localize mechanical, electrical, and plumbing (MEP) elements to assist facility managers.	Deep learning Mechanical, electrical, and plumbing systems Neural networks	Quantitative	Three fire protection systems, Class 3, using 81 images as a data set to perform transfer learning to the AlexNet network.	The proposed system aids facility managers in their tasks and decreases the maintenance costs of facilities by maintaining, upgrading, and

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Title, Author(s), Year	Research Question	Phenomenon/a Studied	Type of Research Method	Description of Sample	Results of the Study
		Support vector machine			operating assets cost-effectively using the proposed system.
Artificial intelligence in prognostics and health management of engineering systems. Ochella, Sunday. Shafiee, Mahmood. Dinmohammadi, Fateme. 2022.	A thorough state-of-the-art review of the AI techniques adopted for prognostics and health management (PHM) of engineering systems is conducted.	PHM Predictive maintenance Artificial intelligence	Qualitative	Review of over 200 publications, with a particular focus on 178 publications comprising 86 journal papers (48 %) and 92 conference papers (∼52 %), highlighting different approaches for the use of AI in PHM of engineering systems.	The review concludes the current systems and methodologies for maintenance will inevitably become incompatible with future designs and systems; as such, continued research into AI-driven prognostics systems is expedient as it offers the best promise of bridging the potential gap.
'Cognitive facility management': Definition, system architecture, and example scenario. Xu, Jinying, Lu, Weisheng Xue, Fan, Chen, Ke. 2019.	The authors aim to take the very first step to define a new concept, cognitive facility management, which empowers cognitive capability in traditional facilities and their management. Research questions: (1) What is cognitive FM? (2) What are its key characteristics? (3) What is its system architecture? (4) How does it influence FM?	Cognitive Facility Management Eight-layer facility management system	Qualitative	This paper put forward a bold proposition – cognitive FM – in the inert body of FM literature. It provided the working definition of cognitive FM and articulated its three key definitional characteristics, i.e., perception, learning, and action, and their interrelationships.	Development and implementation of cognitive FM are determined by the changing the dyadic relationship between ourselves and the facilities we built.
Data-driven predictive maintenance planning framework for MEP components based on BIM and IoT using machine learning algorithms. Cheng, Jack C P., Chen, Weiwei, Chen, Keyu Wang, Qian. 2020.	This study aims to apply a predictive maintenance strategy with advanced technologies to overcome the limitations of the inability to predict failures.	Artificial Intelligence Building monitoring Maintenance Building Information Modeling	Quantitative	Data collection and data integration among the BIM models, FM system, and IoT network are undertaken in the information layer, while the application layer contains four modules to achieve predictive maintenance, namely: (1) condition monitoring and fault alarming module, (2) condition assessment module, (3) condition prediction module, and (4) maintenance planning module. Machine learning algorithms, ANN and SVM, are used to predict the future condition of MEP components.	The results show that the constantly updated data obtained from the information layer together with the machine learning algorithms in the application layer can efficiently predict the future condition of MEP components for maintenance planning.
Digital twin framework for automated fault source detection and prediction for comfort performance evaluation of existing non-residential Norwegian buildings. Hosamo, Haidar Hosamo, Nielsen, Henrik Kofoed, Kraniotis, Dimitrios, Svennevig, Paul Ragnar, Svidt, Kjeld. 2023.	Proposes a novel Digital Twin approach for incorporating building information modeling (BIM) with real-time sensor data, occupants' feedback, a probabilistic model of occupants' comfort, and HVAC faults detection and prediction that may affect occupants' comfort.	Air Handling Unit Building Information Modeling Bayesian Networks (BN) Computerized Maintenance Monitoring System	Quantitative	I4Helse and Tvedestrand upper secondary school are the buildings used in this study to verify the proposed Digital Twin framework. Both buildings follow Norwegian TEK10 and NS3701 standards. I4Helse was built in Grimstad, Norway, in 2017 with 1600 m (about 5249.34 ft)2 (about half the area of a large mansion) floor area, while Tvedestrand school was built in Tvedestrand, Norway, in 2020 with 14,500 m (about 9.01 mi)2 (about half the area of the Lincoln Memorial Reflecting Pool) floor area.	The suggested BN may describe comfort in a building as a probabilistic process rather than a deterministic one and provide comfort performance levels in the form of probability distributions. Although the BN model may identify the causes of occupant discomfort, it is incompatible with BIM software, making the resulting data inaccessible and difficult to interpret.
Does historical data still count? Exploring the applicability of smart building applications in the post-pandemic period. Xie, Xiang, Lu, Qiuchen, Herrera, Manuel, Yu, Qiaojun Parlikad, Ajith Kumar Schooling, Jennifer Mary. 2021.	Investigates the bidirectional interaction between humans and buildings that leads to a dramatic change in building performance data distributions post-pandemic and evaluates the applicability of typical facility management and energy management applications against these changes.	Artificial intelligence Historical data	Quantitative	The Alan Reece building is a three-story building standing over a 40,000-square-foot comprehensive area. It includes spaces with diverse uses, such as teaching, office, research, laboratory, canteen, etc. The electricity consumption (kWh per half an hour) and local ambient temperature of the Alan Reece building from October 13, 2018 to October 11, 2020 is used.	Data accumulation approaches have suffered from the changed interactive pattern between humans and buildings during the pandemic, including variations in occupancy and occupants' behavior. As a result, current smart building applications, which heavily rely on a certain volume of pre-pandemic data to feed into machine learning algorithms, might fail.

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Title, Author(s), Year	Research Question	Phenomenon/a Studied	Type of Research Method	Description of Sample	Results of the Study
Implementation of the IDAIC framework on an air handling unit to transition to proactive maintenance. Ahern, Michael. O'Sullivan, Dominic T J. Bruton, Ken. 2023.	Implement the Industrial Data Analysis Improvement Cycle framework on an Air Handling Unit (AHU) in a real industrial facility to address the lack of practical and reproducible real-world analysis.	AHU Artificial Intelligence Bayesian Networks	Quantitative	AHU is over twenty years old, operates 24/7, and is one of four similar AHUs which contribute to its selection. This AHU is a return air unit and serves an open production floor from thermal comfort and an adequate supply of fresh air perspectives only.	This approach enabled the development of data-driven analysis that visualizes the effect of the different modes of operation on the energy consumption of the AHU, which allow the onsite facilities team to make more informed decisions regarding the maintenance of this AHU.
Integrated framework for estimating remaining useful lifetime through a deep neural network. Son, Seho. Oh, Ki-Yong. 2022.	Proposes an integrated framework for a deep neural network to estimate the remaining useful life (RUL) to ensure the reliability and safety of complex mechanical systems and enable proactive maintenance for intelligent operation.	Condition monitoring Maintenance Artificial Intelligence	Quantitative	The C-MAPSS comprises four sub-datasets: FD001, FD002, FD003, and FD004. Each sub-dataset comprises training, testing, and actual RUL sets for validation. Specifically, these datasets consist of multivariate time-series data measured using 21 sensors and three operational conditions of each engine unit.	Results show the proposed integrated framework outperformed other state-of-the-art machine learning and deep learning methods under different operational conditions, suggesting that efficient feature preprocessing and hyperparameter optimization significantly improve the prediction accuracy and robustness of RUL for data-driven prognostics and health management.
Predicting the presence of hazardous materials in buildings using machine learning. Wu, Pei-Yu, Sandels, Claes, Mjörnell, Kristina, Mangold, Mikael, Johansson, Tim. 2022.	Investigate the potential of machine learning techniques with hazardous waste inventories and building registers as input data. RQ1: Which machine learning classifier provides the best results for the task? RQ2: How many training examples are needed to obtain sufficient prediction results? RQ3: What are the influential factors for predicting the target hazardous materials in specific building classes?	Machine learning Hazardous waste Multifamily housing	Quantitative	A hazardous material dataset consisting of 906 detection records and national building registers was compiled to study the presence of hazardous materials in the Swedish building stock. The detection records encompass hazardous waste inventories of demolished and renovated buildings between 2010 and 2020 retrieved from the Gothenburg and the Stockholm City Archives. Buildings built before 1990 are especially of interest as asbestos and PCB-containing materials were used extensively in construction. Detailed inventories, such as reports and protocols, accounted for most of the acquired documents with specifications of the detected hazardous materials and investigated buildings.	According to the learning curves, high validation accuracies, namely 75–85 %, were obtained for the three–ensembled classifiers after training on a minimum of 50 data points. Construction year, floor area, renovation year, and the number of stairwells and apartments were vital features for predicting the presence of asbestos pipe insulation in multifamily houses with optimal average accuracy and recall rates of 74 % and 83 %. In comparison, average accuracy, and recall rates of 78 % and 83 % were obtained for predicting PCB joints or sealants in school buildings with construction year, balanced ventilation, floor area, and balanced ventilation with heat exchanger.
Two-Stage predictive maintenance planning for hospital buildings: A multiple-objective optimization-based clustering approach. Ahmed, Reem, Nasiri, Fuzhan, Zayed, Tarek. 2022.	An objective methodology is developed to select the most suitable interventions and accordingly group the different actions. This is expected to minimize the overall downtime and disruption caused by the maintenance and rehabilitation works in healthcare facilities.	Maintenance scheduling Artificial intelligence Critical facilities	Quantitative	Not clear	The multi-objective optimization model resulted in the selection of the type and timing of interventions in each year of the planning horizon.

Appendix D

Table D1
Quality Appraisal Summary

Title, Author, Year (* denote articles selected for study)	T	A	P	U	P	A	S	∑
*A Digital Twin predictive maintenance framework of air handling units based on automatic fault detection and diagnostics. Hosamo, Haidar Hosamo, Svennevig, Paul Ragnar, Svidt, Kjeld, Han, Daguang, Nielsen, Henrik Kofoed. 2022	3	2	3	2	2	3	3	18
*A novel Neutrosophic-based machine learning approach for maintenance prioritization in healthcare facilities. Ahmed, Reem, Nasiri, Fuzhan, Zayed, Tarek. 2021	3	3	3	3	3	3	3	21

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Table D1 (*continued*)

Title, Author, Year (* denote articles selected for study)	T	A	P	U	P	A	S	∑
A predictive maintenance model for k-out-of-n:F continuously deteriorating systems subject to stochastic and economic dependencies. Huynh, K T. Vu, H C. Nguyen, T D. Ho, A C. 2022.	2	2	2	1	1	1	1	10
*A process plant retrofitting framework from an Industry 4.0 perspective. Carlo, Fabio Di, Mazzuto, Giovanni, Bevilacqua, Maurizio, Ciarapica, Filippo Emanuele, Ortenzi, Marco, Donato, Luciano Di, Ferraro, Alessandra, Pirozzi, Marco. 2021.	2	2	3	3	1	2	1	14
A remote laboratory for maintenance 4.0 training and education. Kans, Mirka, Campos, Jaime, Håkansson, Lars. 2020.	2	2	1	2	1	2	2	12
*A theoretical framework for data-driven artificial intelligence decision-making for enhancing the asset integrity management system in the oil & gas sector. Sattari, Fereshteh, Lefsrud, Lianne. Kurian, Daniel. Macciotta, Renato. 2022.	3	3	3	3	3	3	3	21
*An artificial intelligence approach for improving maintenance to supervise machine failures and support their repair. Rojek, Izabela, Jasiulewicz-Kaczmarek, Małgorzata, Piechowski, Mariusz, Mikołajewski, Dariusz. 2023.	2	2	2	2	2	2	2	14
*Artificial intelligence exploitation in facility management using deep learning. Marzouk, Mohamed. Zaher, Mohamed. 2020.	3	3	3	3	3	3	3	21
*Artificial intelligence in prognostics and health management of engineering systems. Ochella, Sunday. Shafiee, Mahmood. Dinmohammadi, Fateme. 2022.	3	3	3	3	3	3	3	21
*'Cognitive facility management': Definition, system architecture, and example scenario. Xu, Jinying, Lu, Weisheng, Xue, Fan, Chen, Ke. 2019.	3	3	3	3	2	2	3	19
*Data-driven predictive maintenance planning framework for MEP components based on BIM and IoT using machine learning algorithms. Cheng, Jack C P., Chen, Weiwei, Chen, Keyu, Wang, Qian. 2020.	3	3	3	3	3	3	3	21
*Digital twin framework for automated fault source detection and prediction for comfort performance evaluation of existing non-residential Norwegian buildings. Hosamo, Haidar Hosamo, Nielsen, Henrik Kofoed, Kraniotis, Dimitrios, Svennevig, Paul Ragnar, Svidt, Kjeld. 2023.	3	3	3	2	3	3	3	20
*Does historical data still count? Exploring the applicability of smart building applications in the post-pandemic period. Xie, Xiang, Lu, Qiuchen, Herrera, Manuel, Yu, Qiaojun, Parlikad, Ajith Kumar, Schooling, Jennifer Mary. 2021.	3	2	3	2	2	2	3	17
*Implementation of the IDAIC framework on an air handling unit to transition to proactive maintenance. Ahern, Michael. O'Sullivan, Dominic T J. Bruton, Ken. 2023.	3	3	3	3	3	3	3	21
*Integrated framework for estimating remaining useful lifetime through a deep neural network. Son, Seho. Oh, Ki-Yong. 2022.	2	3	3	3	3	2	2	17
*Predicting the presence of hazardous materials in buildings using machine learning. Wu, Pei-Yu, Sandels, Claes, Mjörnell, Kristina, Mangold, Mikael, Johansson, Tim. 2022.	3	3	3	2	2	3	3	19
Two-Stage predictive maintenance planning for hospital buildings: A multiple-objective optimization-based clustering approach. Ahmed, Reem, Nasiri, Fuzhan, Zayed, Tarek. 2022.	1	2	2	2	3	2	2	14

Table D2
Quality Assessment of Hosamo et al. [42] Article

Factor	Factor Defined	Score	Score Evidence	Evidence Page
Transparency	Is the process of generating knowledge explicit and clear?	3	The authors identify the literature gap and describe the study's intent as the deployment of a framework helping decision-makers be environmentally aware in the maintenance of cyber-physical systems.	Page 12
Accessibility	Does it meet the needs of those seeking knowledge?	2	The authors guided practitioners and leaders seeking to obtain awareness of the maintenance framework the author proposed.	Page 21
Purpositivity	Does the author achieve the aims and objectives of the research?	3	The study's purpose is to provide a framework for sustainable condition-based maintenance, and the authors meet the purpose.	Page 21
Utility	Is the research appropriate to the decision-making setting? Does it provide answers to practical questions?	2	The research is appropriate and answers critical questions, although it stops short of providing a real-time scenario.	Page 21
Propriety	Did the researchers obtain approval from the organization to conduct the study?	2	No approval is required because the study was conducted in theory only.	N/A
Accuracy	Claims made by researchers should be based on the participants' data. Are the claims made based on the collected data?	3	The claims made in the research were made using the data collected by the authors. In detail, the authors provided their methods, measures, and analysis techniques. In the end, the authors summarized their results and provided how to apply the results in practice.	Pages 14-17
Specificity	Does the research generated consider and apply source-specific standards?	3	The research provides a framework for future implementation of the maintenance awareness policy.	Page 21
Total Score		18		

Note. Adapted from "Philosophy and quality? TAPUPASM as an approach to rigour in critical realist research," by G. Ryan and J. Rutty, 2019, *Nurse Researcher, 27*(1) pp. 4–5 (https://doi.org/10.7748/nr.2019.e1590). Copyright 2019 RCN Publishing Company Limited.

Table D3
Quality Assessment of Ahmed et al. [49] Article

Factor	Factor Defined	Score	Score Evidence	Evidence Page
Transparency	Is the process of generating knowledge explicit and clear?	3	The authors introduced the problem in the current methods of prioritizing work requests.	Pages 4-11
Accessibility	Does it meet the needs of those seeking knowledge?	3	The authors presented a case study that can be overlayed in other practical cases and the results may be utilized to make decisions.	Page 11
Purpositivity	Does the author achieve the aims and objectives of the research?	3	The purpose of the study was met.	Page 1 and 10
Utility	Is the research appropriate to the decision-making setting? Does it provide answers to practical questions?	3	The research provides an unbiased approach to managing facility management work requests that may be implemented immediately.	Page 10

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Table D3 (*continued*)

Factor	Factor Defined	Score	Score Evidence	Evidence Page
Propriety	Did the researchers obtain approval from the organization to conduct the study?	3	The study was conducted at a museum in China. The researchers obtained approval to conduct the research.	Page 3
Accuracy	Claims made by researchers should be based on the participants' data. Are the claims made based on the collected data?	3	The authors used literature reviews to develop the problem, surveys to validate the concerns, and work requests to test the results.	Pages 4 - 11
Specificity	Does the research generated consider and apply source-specific standards?	3	The research applied and related to standard-specific information and material. As for the source, the standards were applied to the source material obtained.	Page 6
Total Score		21		

Note. Adapted from "Philosophy and quality? TAPUPASM as an approach to rigour in critical realist research," by G. Ryan and J. Rutty, 2019, *Nurse Researcher, 27*(1) pp. 4–5 (https://doi.org/10.7748/nr.2019.e1590).

Table D4
Quality Assessment of [10] Article

Factor	Factor Defined	Score	Score Evidence	Evidence Page
Transparency	Is the process of generating knowledge explicit and clear?	2	The author provides a predictive maintenance model	Page 16
Accessibility	Does it meet the needs of those seeking knowledge?	2	The author guided guidance for conducting the test and the procedure is repeatable.	Pages 3-14
Purpositivity	Does the author achieve the aims and objectives of the research?	2	The purpose of the study was to present the framework to overcome challenges with the implementation of BIM and the purpose was met.	Page 1110
Utility	Is the research appropriate to the decision-making setting? Does it provide answers to practical questions?	1	The research is a theory and requires more testing to answer this question.	Pages 16
Propriety	Did the researchers obtain approval from the organization to conduct the study?	1	The research is testing theory to develop a new method for predictive maintenance. The researchers did not need approval.	Page 16
Accuracy	Claims made by researchers should be based on the participants' data. Are the claims made based on the collected data?	1	The claims made by the author were backed by theory.	Pages 12
Specificity	Does the research generated consider and apply source-specific standards?	1	Not clear.	N/A
Total Score		10		

Note. Adapted from "Philosophy and quality? TAPUPASM as an approach to rigour in critical realist research," by G. Ryan and J. Rutty, 2019, *Nurse Researcher, 27*(1) pp. 4–5 (https://doi.org/10.7748/nr.2019.e1590).

Table D5
Quality Assessment of Carlo et al. [32] Article

Factor	Factor Defined	Score	Score Evidence	Evidence Page
Transparency	Is the process of generating knowledge explicit and clear?	2	The author contributed to the literature by providing a framework for implementing IoT 4.0 into an existing mixing plant.	Pages 72
Accessibility	Does it meet the needs of those seeking knowledge?	2	The research conducted provides the framework for implementing alternate solutions. Managers and leaders can benefit from the findings because these are practical solutions that can be implemented.	Pages 70
Purpositivity	Does the author achieve the aims and objectives of the research?	3	The authors set out to present a solution that, once implemented, will allow managers and leaders to make informed and quicker decisions about the efficiency of the processing plant.	Pages 72
Utility	Is the research appropriate to the decision-making setting? Does it provide answers to practical questions?	3	The research does provide answers to implementing or retrofitting a processing plant. This same framework may be beneficial to other treatment plants.	Page 71
Propriety	Did the researchers obtain approval from the organization to conduct the study?	1	Not forthcoming in the article.	N/A
Accuracy	Claims made by researchers should be based on the participants' data. Are the claims made based on the collected data?	2	The claims made by the study reflect the documentation obtained about the asset. The process of implementing the corrective actions was accounted for by evaluating the documentation.	Pages 71
Specificity	Does the research generated consider and apply source-specific standards?	1	The research generalizes the data and applies source-specific standards.	Page 72
Total Score		14		

Note. Adapted from "Philosophy and quality? TAPUPASM as an approach to rigour in critical realist research," by G. Ryan and J. Rutty, 2019, *Nurse Researcher, 27*(1) pp. 4–5 (https://doi.org/10.7748/nr.2019.e1590).

Table D6
Quality Assessment of Kans et al. [50] Article

Factor	Factor Defined	Score	Score Evidence	Evidence Page
Transparency	Is the process of generating knowledge explicit and clear?	2	The author contributed to the literature by expressing a case for competencies regarding maintenance 4.0 from a distance and broad perspective.	Page 103
Accessibility	Does it meet the needs of those seeking knowledge?	2	The research conducted provides the framework for implementing alternate solutions. Managers and leaders can benefit from the findings because these are practical solutions that can be implemented.	Page 105
Purpositivity	Does the author achieve the aims and objectives of the research?	1	The authors set out to present a solution that, once implemented, will allow managers and leaders to make informed and quicker decisions about maintenance. This was achieved through overcoming challenges.	Page 103
Utility	Is the research appropriate to the decision-making setting? Does it provide answers to practical questions?	2	The research provides managers and leaders with the necessary cost savings information to make decisions. The research identifies a cost-benefit analysis as a problem because BIM and SIM have not been widely implemented so a return on investment cannot be obtained.	Page 102
Propriety	Did the researchers obtain approval from the organization to conduct the study?	1	The authors obtained the information to conduct the analysis, so it is assumed permissions were granted.	Page 103
Accuracy	Claims made by researchers should be based on the participants' data. Are the claims made based on the collected data?	2	The claims made by the study reflect the documentation obtained about the asset. The process of implementing the corrective actions was accounted for by evaluating the documentation.	Page 102
Specificity	Does the research generated consider and apply source-specific standards?	2	The research generalizes the data and applies source-specific standards.	Page 102
Total Score		12		

Note. Adapted from "Philosophy and quality? TAPUPASM as an approach to rigour in critical realist research," by G. Ryan and J. Rutty, 2019, *Nurse Researcher, 27*(1) pp. 4–5 (https://doi.org/10.7748/nr.2019.e1590). Copyright 2019 RCN Publishing Company Limited.

Table D7
Quality Assessment of Sattari et al. [33] Article

Factor	Factor Defined	Score	Score Evidence	Evidence Page
Transparency	Is the process of generating knowledge explicit and clear?	3	The authors clearly state their intent and present their results.	Page 15
Accessibility	Does it meet the needs of those seeking knowledge?	3	The study responds to the need for a framework to predict incidents within the industry.	Page 15
Purpositivity	Does the author achieve the aims and objectives of the research?	3	The research purpose is to use the dynamic and intelligent approach based on the BIM for the management of Health and Safety. The research finding could not support the implementation for that purpose.	Page 14-15
Utility	Is the research appropriate to the decision-making setting? Does it provide answers to practical questions?	3	The research provides insight to leaders and managers seeking implementation information for health and safety.	Page 15
Propriety	Did the researchers obtain approval from the organization to conduct the study?	3	The authors obtained approval and documentation from the organization.	Page 16
Accuracy	Claims made by researchers should be based on the participants' data. Are the claims made based on the collected data?	3	The claims made in the research were based on the data collected as part of this research.	Page 13
Specificity	Does the research generated consider and apply source-specific standards?	3	The author tested the use of BIM in developing health and safety protocols.	Page 12
Total Score		21		

Note. Adapted from "Philosophy and quality? TAPUPASM as an approach to rigour in critical realist research," by G. Ryan and J. Rutty, 2019, *Nurse Researcher, 27*(1) pp. 4–5 (https://doi.org/10.7748/nr.2019.e1590). Copyright 2019 RCN Publishing Company Limited.

Table D8
Quality Assessment of Rojek et al. [11] Article

Factor	Factor Defined	Score	Score Evidence	Evidence Page
Transparency	Is the process of generating knowledge explicit and clear?	2	The authors have a clear purpose for the study, but the knowledge generated is vague and left to the reader to interpret.	Page 1
Accessibility	Does it meet the needs of those seeking knowledge?	2	The author's research provides challenges and barriers to implementing BIM and provides leaders with additional information.	Pages 11
Purpositivity	Does the author achieve the aims and objectives of the research?	2	The authors where the objective is met, although their findings point to most participants being happy with the results.	Page 11
Utility	Is the research appropriate to the decision-making setting? Does it provide answers to practical questions?	2	The authors provided answers to some questions surrounding their research but left a lot of questions open for the reader to interpret.	Page 10
Propriety	Did the researchers obtain approval from the organization to conduct the study?	3	The researchers obtained the necessary approvals to conduct the research, interview the participants, and collect the data necessary for the research.	Page 11
Accuracy	Claims made by researchers should be based on the participants' data. Are the claims made based on the collected data?	2	Claims made by the researchers were based on data and a computerized framework.	Page 6

(*continued on next page*)

Table D8 (*continued*)

Factor	Factor Defined	Score	Score Evidence	Evidence Page
Specificity	Does the research generated consider and apply source-specific standards?	2	The authors introduced bias by selecting the sample for the methodology. The data selected was good.	Page 3
Total Score		14		

Note. Adapted from "Philosophy and quality? TAPUPASM as an approach to rigour in critical realist research," by G. Ryan and J. Rutty, 2019, *Nurse Researcher, 27*(1) pp. 4–5 (https://doi.org/10.7748/nr.2019.e1590). Copyright 2019 RCN Publishing Company Limited.

Table D9
Quality Assessment of Marzouk and Zaher [34] Article

Factor	Factor Defined	Score	Score Evidence	Evidence Page
Transparency	Is the process of generating knowledge explicit and clear?	3	The author set to decrease the lack of knowledge of the required maintenance to MEP elements that leads to a lower life cycle cost. These.	Pages 609
Accessibility	Does it meet the needs of those seeking knowledge?	3	The research conducted provides the framework for implementing alternate solutions. Managers and leaders can benefit from the findings because these are practical solutions that can be implemented.	Page 609
Purpositivity	Does the author achieve the aims and objectives of the research?	3	The authors set out to present a solution that, once implemented, will allow managers and leaders to make informed and quicker decisions about maintenance. This was achieved through overcoming challenges.	Page 609
Utility	Is the research appropriate to the decision-making setting? Does it provide answers to practical questions?	3	The research provides managers and leaders with the necessary cost savings information to make decisions.	Page 609
Propriety	Did the researchers obtain approval from the organization to conduct the study?	3	The authors obtained the information to conduct the analysis, so it is assumed permissions were granted.	Page 621
Accuracy	Claims made by researchers should be based on the participants' data. Are the claims made based on the collected data?	3	The claims made by the study reflect the documentation obtained about the asset. The process of implementing the corrective actions was accounted for by evaluating the documentation.	Page 620
Specificity	Does the research generated consider and apply source-specific standards?	3	The research generalizes the data and applies source-specific standards.	Page 620
Total Score		21		

Note. Adapted from "Philosophy and quality? TAPUPASM as an approach to rigour in critical realist research," by G. Ryan and J. Rutty, 2019, *Nurse Researcher, 27*(1) pp. 4–5 (https://doi.org/10.7748/nr.2019.e1590). Copyright 2019 RCN Publishing Company Limited.

Table D10
Quality Assessment of Ochella et al. [38] Article

Factor	Factor Defined	Score	Score Evidence	Evidence Page
Transparency	Is the process of generating knowledge explicit and clear?	3	The authors provide a clear objective of the research, and they provide thorough findings.	Page 3
Accessibility	Does it meet the needs of those seeking knowledge?	3	The research meets the needs of managers, practitioners, and leaders seeking to implement BIM into their space management process.	Page 3
Purpositivity	Does the author achieve the aims and objectives of the research?	3	The authors meet the objectives of their research by providing a clear research purpose and clear findings/explanations in the conclusion.	Pages 6
Utility	Is the research appropriate to the decision-making setting? Does it provide answers to practical questions?	3	The research is conducive to the setting although a larger facility and more explanation of the facility would have provided more details.	Page 13
Propriety	Did the researchers obtain approval from the organization to conduct the study?	3	The researchers obtained approval from the facility owners and provided the owners and their customers with the results.	Page 13
Accuracy	Claims made by researchers should be based on the participants' data. Are the claims made based on the collected data?	3	The claims made by the researchers were a direct result of the participant data. The results spoke to the appreciation of the participants for the researchers providing the level of input into the research.	Pages 11
Specificity	Does the research generated consider and apply source-specific standards?	3	The research applies source-specific standards in the analysis, methodology, and discussion of the findings.	Pages 12
Total Score		21		

Note. Adapted from "Philosophy and quality? TAPUPASM as an approach to rigour in critical realist research," by G. Ryan and J. Rutty, 2019, *Nurse Researcher, 27*(1) pp. 4–5 (https://doi.org/10.7748/nr.2019.e1590). Copyright 2019 RCN Publishing Company Limited.

Table D11
Quality Assessment of Xu et al. [51] Article

Factor	Factor Defined	Score	Score Evidence	Evidence Page
Transparency	Is the process of generating knowledge explicit and clear?	3	The author contributed to the literature by advancing the stagnant FM discourses defined and subsequently confined by the smart/intelligent building language three decades ago.	Pages 1, 3, 5
Accessibility	Does it meet the needs of those seeking knowledge?	3	The research conducted provides the framework for implementing alternate solutions. Managers and leaders can benefit from the findings because these are practical solutions that can be implemented.	Page 9

(*continued on next page*)

Table D11 (*continued*)

Factor	Factor Defined	Score	Score Evidence	Evidence Page
Purpositivity	Does the author achieve the aims and objectives of the research?	3	The authors set out to present a solution that, once implemented, will allow managers and leaders to make informed and quicker decisions about maintenance. This was achieved through overcoming challenges.	Page 9
Utility	Is the research appropriate to the decision-making setting? Does it provide answers to practical questions?	3	The research provides managers and leaders with the necessary cost savings information to make decisions.	Page 9
Propriety	Did the researchers obtain approval from the organization to conduct the study?	2	The authors obtained the information to conduct the analysis, so it is assumed permissions were granted.	Page 8
Accuracy	Claims made by researchers should be based on the participants' data. Are the claims made based on the collected data?	2	The claims made by the study reflect the documentation obtained about the asset. The process of implementing the corrective actions was accounted for by evaluating the documentation.	Page 5 - 9
Specificity	Does the research generated consider and apply source-specific standards?	3	The research generalizes the data and applies source-specific standards.	Page 10
Total Score		19		

Note. Adapted from "Philosophy and quality? TAPUPASM as an approach to rigour in critical realist research," by G. Ryan and J. Rutty, 2019, *Nurse Researcher, 27*(1) pp. 4–5 (https://doi.org/10.7748/nr.2019.e1590). Copyright 2019 RCN Publishing Company Limited.

Table D12
Quality Assessment of Cheng et al. [35] Article

Factor	Factor Defined	Score	Score Evidence	Evidence Page
Transparency	Is the process of generating knowledge explicit and clear?	3	The author contributed to the literature by providing a comparative example of an alternate solution to BIM and overcoming the challenges currently identified in facility management.	Pages 1, 3, 5
Accessibility	Does it meet the needs of those seeking knowledge?	3	The research conducted provides the framework for implementing alternate solutions. Managers and leaders can benefit from the findings because these are practical solutions that can be implemented.	Page 9 - 14
Purpositivity	Does the author achieve the aims and objectives of the research?	3	The authors set out to present a solution that, once implemented, will allow managers and leaders to make informed and quicker decisions about maintenance. This was achieved through overcoming challenges.	Page 14
Utility	Is the research appropriate to the decision-making setting? Does it provide answers to practical questions?	3	The research provides managers and leaders with the necessary cost savings information to make decisions.	Page 9 - 14
Propriety	Did the researchers obtain approval from the organization to conduct the study?	3	The authors obtained the information to conduct the analysis, so it is assumed permissions were granted.	Page 8
Accuracy	Claims made by researchers should be based on the participants' data. Are the claims made based on the collected data?	3	The claims made by the study reflect the documentation obtained about the asset. The process of implementing the corrective actions was accounted for by evaluating the documentation.	Page 5 - 9
Specificity	Does the research generated consider and apply source-specific standards?	3	The research generalizes the data and applies source-specific standards.	Page 10
Total Score		21		

Note. Adapted from "Philosophy and quality? TAPUPASM as an approach to rigour in critical realist research," by G. Ryan and J. Rutty, 2019, *Nurse Researcher, 27*(1) pp. 4–5 (https://doi.org/10.7748/nr.2019.e1590). Copyright 2019 RCN Publishing Company Limited.

Table D13
Quality Assessment of Hosamo et al. [36] Article

Factor	Factor Defined	Score	Score Evidence	Evidence Page
Transparency	Is the process of generating knowledge explicit and clear?	3	The author contributed to the literature by providing a comparative example of an alternate solution to preventive and corrective maintenance.	Pages 21
Accessibility	Does it meet the needs of those seeking knowledge?	3	The research conducted provides the framework for implementing alternate solutions. Facility Managers and leaders can benefit from the finding because these are practical solutions that can be implemented.	Page 9 - 14
Purpositivity	Does the author achieve the aims and objectives of the research?	3	The authors set out to present a solution that, once implemented, will allow managers and leaders to make informed and quicker decisions about maintenance. This was achieved through overcoming challenges.	Page 21
Utility	Is the research appropriate to the decision-making setting? Does it provide answers to practical questions?	2	The research provides managers and leaders with the necessary information to make decisions.	Page 21
Propriety	Did the researchers obtain approval from the organization to conduct the study?	3	The authors obtained the information to conduct the analysis, so it is assumed permissions were granted.	Page 6
Accuracy	Claims made by researchers should be based on the participants' data. Are the claims made based on the collected data?	3	The claims made by the study reflect the documentation obtained about the asset. The process of implementing the corrective actions was accounted for by evaluating the documentation.	Page 5 - 9
Specificity	Does the research generated consider and apply source-specific standards?	3	The research generalizes the data and applies source-specific standards.	Page 1
Total Score		20		

Note. Adapted from "Philosophy and quality? TAPUPASM as an approach to rigour in critical realist research," by G. Ryan and J. Rutty, 2019, *Nurse Researcher, 27*(1) pp. 4–5 (https://doi.org/10.7748/nr.2019.e1590). Copyright 2019 RCN Publishing Company Limited.

Table D14
Quality Assessment of Xie et al. [37] Article

Factor	Factor Defined	Score	Score Evidence	Evidence Page
Transparency	Is the process of generating knowledge explicit and clear?	3	The author contributed to the literature by providing a comparative example of an alternate solution to BIM and overcoming the challenges currently identified in facility management.	Pages 1, 3, 5
Accessibility	Does it meet the needs of those seeking knowledge?	2	The research conducted provides the framework for implementing alternate solutions. Managers and leaders can benefit from the findings because these are practical solutions that can be implemented.	Page 9 - 14
Purpositivity	Does the author achieve the aims and objectives of the research?	3	The authors set out to present a solution that, once implemented, will allow managers and leaders to make informed and quicker decisions about maintenance. This was achieved through overcoming challenges.	Page 14
Utility	Is the research appropriate to the decision-making setting? Does it provide answers to practical questions?	2	The research provides managers and leaders with the necessary cost savings information to make decisions. The research identifies a cost-benefit analysis as a problem because BIM and SIM have not been widely implemented so a return on investment cannot be obtained.	Page 9 - 14
Propriety	Did the researchers obtain approval from the organization to conduct the study?	2	The authors obtained the information to conduct the analysis, so it is assumed permissions were granted.	Page 8
Accuracy	Claims made by researchers should be based on the participants' data. Are the claims made based on the collected data?	2	The claims made by the study reflect the documentation obtained about the asset. The process of implementing the corrective actions was accounted for by evaluating the documentation.	Page 5 - 9
Specificity	Does the research generated consider and apply source-specific standards?	3	The research generalizes the data and applies source-specific standards.	Page 10
Total Score		17		

Note. Adapted from "Philosophy and quality? TAPUPASM as an approach to rigour in critical realist research," by G. Ryan and J. Rutty, 2019, *Nurse Researcher, 27*(1) pp. 4–5 (https://doi.org/10.7748/nr.2019.e1590). Copyright 2019 RCN Publishing Company Limited.

Table D15
Quality Assessment of Ahern et al. [13] Article

Factor	Factor Defined	Score	Score Evidence	Evidence Page
Transparency	Is the process of generating knowledge explicit and clear?	3	The author contributed to the literature by providing a framework and successfully performing realistic testing on the framework.	Pages 1, 14
Accessibility	Does it meet the needs of those seeking knowledge?	3	The research conducted provides the framework for implementing alternate solutions. Managers and leaders can benefit from the findings because these are practical solutions that can be implemented.	Page 9 - 14
Purpositivity	Does the author achieve the aims and objectives of the research?	3	The authors set out to present a solution that, once implemented, will allow managers and leaders to make informed and quicker decisions about maintenance. This was achieved through overcoming challenges.	Page 14
Utility	Is the research appropriate to the decision-making setting? Does it provide answers to practical questions?	3	The research provides managers and leaders with the awareness necessary to implement an AI-driven solution to potential cost savings information to make decisions.	Page 16
Propriety	Did the researchers obtain approval from the organization to conduct the study?	3	The authors obtained the information to conduct the analysis, so it is assumed permissions were granted.	Page 8
Accuracy	Claims made by researchers should be based on the participants' data. Are the claims made based on the collected data?	3	The claims made by the study reflect the documentation obtained about the asset. The process of implementing the corrective actions was accounted for by evaluating the documentation.	Page 5 - 9
Specificity	Does the research generated consider and apply source-specific standards?	3	The research generalizes the data and applies source-specific standards.	Page 10
Total Score		21		

Note. Adapted from "Philosophy and quality? TAPUPASM as an approach to rigour in critical realist research," by G. Ryan and J. Rutty, 2019, *Nurse Researcher, 27*(1) pp. 4–5 (https://doi.org/10.7748/nr.2019.e1590). Copyright 2019 RCN Publishing Company Limited.

Table D16
Quality Assessment of Son and Oh [39] Article

Factor	Factor Defined	Score	Score Evidence	Evidence Page
Transparency	Is the process of generating knowledge explicit and clear?	2	The author contributed to the literature by providing a framework for deep neural networks to estimate the remaining useful life.	Pages 1, 13
Accessibility	Does it meet the needs of those seeking knowledge?	3	The research conducted provides the framework for implementing other state-of-the-art solutions. Facility management managers and leaders can benefit from the findings because these are practical solutions that can be implemented.	Page 13
Purpositivity	Does the author achieve the aims and objectives of the research?	3	The authors set out to present a solution that, once implemented, will allow managers and leaders to make informed and quicker decisions about maintenance. This was achieved through overcoming challenges.	Page 12
Utility	Is the research appropriate to the decision-making setting? Does it provide answers to practical questions?	3	The research provides managers and leaders with the necessary information to make decisions. The research identifies a cost-benefit analysis as a problem because BIM and SIM have not been widely implemented so a return on investment cannot be obtained.	Page 12 - 13

(*continued on next page*)

Table D16 (*continued*)

Factor	Factor Defined	Score	Score Evidence	Evidence Page
Propriety	Did the researchers obtain approval from the organization to conduct the study?	2	The authors obtained the information to conduct the analysis, so it is assumed permissions were granted.	Page 8
Accuracy	Claims made by researchers should be based on the participants' data. Are the claims made based on the collected data?	2	The claims made by the study reflect the documentation obtained about the asset. The process of implementing the corrective actions was accounted for by evaluating the documentation.	Page 5 - 9
Specificity	Does the research generated consider and apply source-specific standards?	2	The research generalizes the data and applies source-specific standards.	Page 10
Total Score		17		

Note. Adapted from "Philosophy and quality? TAPUPASM as an approach to rigour in critical realist research," by G. Ryan and J. Rutty, 2019, *Nurse Researcher, 27*(1) pp. 4–5 (https://doi.org/10.7748/nr.2019.e1590). Copyright 2019 RCN Publishing Company Limited.

Table D17
Quality Assessment of Wu et al. [40] Article.

Factor	Factor Defined	Score	Score Evidence	Evidence Page
Transparency	Is the process of generating knowledge explicit and clear?	3	The authors contributed to the literature by providing a detailed testing framework of machine learning to predict hazardous material presence in multifamily housing. This framework provides a mechanism for future predictions using machine language.	Page 13
Accessibility	Does it meet the needs of those seeking knowledge?	3	Managers and leaders can benefit from the findings because these are practical solutions that can be implemented.	Pages 9 - 14
Purpositivity	Does the author achieve the aims and objectives of the research?	3	The authors set out to investigate the prediction potential of machine learning techniques with hazardous waste inventories and building registers as input data.	Page 13
Utility	Is the research appropriate to the decision-making setting? Does it provide answers to practical questions?	2	The research provides managers and leaders with the necessary information to make decisions. The research identifies a predictive potential of hazardous material using machine language. This information may be used to estimate demolition costs.	Page 9 - 14
Propriety	Did the researchers obtain approval from the organization to conduct the study?	2	The authors obtained the information to conduct the analysis, so it is assumed permissions were granted.	Page 14
Accuracy	Claims made by researchers should be based on the participants' data. Are the claims made based on the collected data?	3	The claims made by the study reflect the documentation obtained about the research.	Page 14
Specificity	Does the research generated consider and apply source-specific standards?	3	The research generalizes the data and applies source-specific standards.	Page 10
Total Score		19		

Note. Adapted from "Philosophy and quality? TAPUPASM as an approach to rigour in critical realist research," by G. Ryan and J. Rutty, 2019, *Nurse Researcher, 27*(1) pp. 4–5 (https://doi.org/10.7748/nr.2019.e1590). Copyright 2019 RCN Publishing Company Limited.

Table D18
Quality Assessment of Ahmed et al. [52] Article

Factor	Factor Defined	Score	Score Evidence	Evidence Page
Transparency	Is the process of generating knowledge explicit and clear?	1	The author conducted testing on a model, but the creation of knowledge is not clear.	N/A
Accessibility	Does it meet the needs of those seeking knowledge?	2	The research conducted provides the framework for implementing alternate solutions. Managers and leaders may benefit from the findings because these are practical solutions that can be implemented.	Page 9
Purpositivity	Does the author achieve the aims and objectives of the research?	2	The authors set out to present a solution that, once implemented, will allow managers and leaders to make informed and quicker decisions about maintenance. This was achieved through overcoming challenges.	Page 9
Utility	Is the research appropriate to the decision-making setting? Does it provide answers to practical questions?	2	The research provides managers and leaders with the necessary cost savings information to make decisions. The research identifies a cost-benefit analysis as a problem because BIM and SIM have not been widely implemented so a return on investment cannot be obtained.	Page 9
Propriety	Did the researchers obtain approval from the organization to conduct the study?	3	The authors obtained the information to conduct the analysis, so it is assumed permissions were granted.	Page 10
Accuracy	Claims made by researchers should be based on the participants' data. Are the claims made based on the collected data?	2	The claims made by the study reflect the documentation obtained about the asset. The process of implementing the corrective actions was accounted for by evaluating the documentation.	Page 5
Specificity	Does the research generated consider and apply source-specific standards?	2	The research generalizes the data and applies source-specific standards.	Page 4
Total Score		14		

Note. Adapted from "Philosophy and quality? TAPUPASM as an approach to rigour in critical realist research," by G. Ryan and J. Rutty, 2019, *Nurse Researcher, 27*(1) pp. 4–5 (https://doi.org/10.7748/nr.2019.e1590). Copyright 2019 RCN Publishing Company Limited.

Appendix E. First Cycle Codes

Deductive Codes:	
Set boundary	Task performance
Technician	Manager
Leader	Stakeholder
Cost	Online time
Time	Downtime
Appropriation	Adaptation
Monitor	Record
Schedule	Occupant
Inductive Codes:	
Data limitations	Analyze
Unbiased outcome	

Appendix F. Codes Aligned Under Categories

Actors	Task	Outcome
Leader	Adaptation	Cost improvement
Manager	Analyze	Downtime
Monitor	Appropriation	Online Time
Occupant	Facility System Adaptability	Time (labor)
Stakeholder	Record	
Technician	Schedule	
	Set Boundary	
	Task performance	

Appendix G. Themes Aligned by Articles

	Remote monitoring of facility system conditions.	Unbiased and data-backed repair, investment, and responsible decisions.	Increase facility system online time.
*A Digital Twin predictive maintenance framework of air handling units based on automatic fault detection and diagnostics. Hosamo, Haidar Hosamo, Svennevig, Paul Ragnar, Svidt, Kjeld, Han, Daguang, Nielsen, Henrik Kofoed. 2022			X
*A novel Neutrosophic-based machine learning approach for maintenance prioritization in healthcare facilities. Ahmed, Reem, Nasiri, Fuzhan, Zayed, Tarek. 2021	X	X	X
*A process plant retrofitting framework from an Industry 4.0 perspective. Carlo, Fabio Di, Mazzuto, Giovanni, Bevilacqua, Maurizio, Ciarapica, Filippo Emanuele, Ortenzi, Marco, Donato, Luciano Di, Ferraro, Alessandra, Pirozzi, Marco. 2021.	X		X
*A theoretical framework for data-driven artificial intelligence decision-making for enhancing the asset integrity management system in the oil & gas sector. Sattari, Fereshteh, Lefsrud, Lianne. Kurian, Daniel. Macciotta, Renato. 2022.	X	X	X
*An artificial intelligence approach for improving maintenance to supervise machine failures and support their repair. Rojek, Izabela, Jasiulewicz-Kaczmarek, Małgorzata, Piechowski, Mariusz, Mikołajewski, Dariusz. 2023.	X	X	X
*Artificial intelligence exploitation in facility management using deep learning. Marzouk, Mohamed. Zaher, Mohamed. 2020.	X	X	X
*Artificial intelligence in prognostics and health managemen t of engineering systems. Ochella, Sunday. Shafiee, Mahmood. Dinmohammadi, Fateme. 2022.		X	
*'Cognitive facility management': Definition, system architecture, and example scenario. Xu, Jinying, Lu, Weisheng, Xue, Fan, Chen, Ke. 2019.			
*Data-driven predictive maintenance planning framework for MEP components based on BIM and IoT using machine learning algorithms. Cheng, Jack C P., Chen, Weiwei, Chen, Keyu, Wang, Qian. 2020.	X	X	X
*Digital twin framework for automated fault source detection and prediction for comfort performance evaluation of existing non-residential Norwegian buildings. Hosamo, Haidar Hosamo, Nielsen, Henrik Kofoed, Kraniotis, Dimitrios, Svennevig, Paul Ragnar, Svidt, Kjeld. 2023.	X	X	X
*Does historical data still count? Exploring the applicability of smart building applications in the post-pandemic period. Xie, Xiang, Lu, Qiuchen, Herrera, Manuel, Yu, Qiaojun, Parlikad, Ajith Kumar, Schooling, Jennifer Mary. 2021.		X	X
*Implementation of the IDAIC framework on an air handling unit to transition to proactive maintenance. Ahern, Michael. O'Sullivan, Dominic T J. Bruton, Ken. 2023.	X	X	X
*Integrated framework for estimating remaining useful lifetime through a deep neural network. Son, Seho. Oh, Ki-Yong. 2022.		X	
*Predicting the presence of hazardous materials in buildings using machine learning. Wu, Pei-Yu, Sandels, Claes, Mjörnell, Kristina, Mangold, Mikael, Johansson, Tim. 2022.			X

Appendix H. Descriptions of CERQual levels of confidence

Level	Definition
High confidence	The review finding is highly likely a reasonable representation of the phenomenon of interest
Moderate confidence	It is likely that the review finding is a reasonable representation of the phenomenon of interest
Low confidence	It is possible that the review finding is a reasonable representation of the phenomenon of interest
Very low confidence	It is not clear whether the review finding is a reasonable representation of the phenomenon of interest

Note. Adapted from "Applying GRADE-CERQual to qualitative evidence synthesis findings: Introduction to the series.," by S. Lewin, M. Bohren, A. Rashidian, H. Munthe-Kaas, C. Glenton, C. Colvin, R. Garside, J. Noyes, A. Booth, O. Tunçalp, M. Wainwright, S. Flottorp, and J. Tucker. 2018. *Implementation Science*. (https://doi.org/10.1186/s13012-017-0689-2).

Appendix I. CERQual Qualitative Evidence Profile

Summary of review findings	Studies contributing to the review finding	Methodological limitations	Coherence	Adequacy	Relevance	CERQual assessment of confidence	Explanation of CERQual assessment
1. Remote monitoring of facility system conditions.	[11,13,33–36,42,49],	Minor methodological limitations (all 8 of the studies with no or very minor concerns)	No minor coherence concerns (all 8 studies have no minor coherence concerns)	Minor concerns about the adequacy	Minor to no concern about relevance (although one study was on the oil and gas industry it involved artificial intelligence preventive and proactive maintenance)	Moderate confidence	Minor to no concern on all factors although one study on the oil and gas industry involved predictive maintenance
2. Unbiased and data-backed repair, investment, and response decisions.	[11,13,32–36,38,42,49],	No to minor methodological limitations (all 10 studies have no to minor concerns)	No to minor coherence concerns (all 10 studies have no to minor coherence concerns)	No to minor concerns about the adequacy	No concern about the relevance	High Confidence	High confidence because of no to minor concern concerning relevance, methodological, coherence, and adequacy
3. Increase facility system online time.	[11,13,33–36,42,49],	No to minor methodological limitations (all 8 studies have no to minor concerns)	No to minor coherence concerns (all 8 studies have no to minor coherence concerns)	Minor concerns about the adequacy	Minor to no concern about relevance (although one study was on the oil and gas industry it involved artificial intelligence preventive and proactive maintenance)	Moderate confidence	Minor to no concern on all factors although one study on the oil and gas industry involved predictive maintenance

Note. Adapted from "Applying GRADE-CERQual to qualitative evidence synthesis findings paper 2: How to make an overall CERQual assessment of confidence and create a summary of qualitative findings table", by S. Lewin, M. Bohren, A. Rashidian, H. Munthe-Kaas, C. Glenton, C. Colvin, R. Garside, J. Noyes, A. Booth, O. Tunçalp, M. Wainwright, S. Flottorp, and J. Tucker. 2018. *Implementation Science*. (https://doi.org/10.1186/s13012-017-0689-2).

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