**Critical success factors for implementing smart maintenance in the fourth industrial revolution era: A bibliometric analysis within the built environment**

**Abstract.**

**Purpose -** The implementation of smart maintenance has greatly benefited facility managers, construction project managers, and other stakeholders within the built environment. Unfortunately, its actualisation for stakeholders in the built environment in the fourth industrial revolution era (4IR) remains a challenge. To reduce the challenge, this study conducts a bibliometric analysis to unearth the critical success factors supporting smart maintenance implementation. The future direction and practice of smart maintenance in the construction industry were also explored.

**Design/methodology/approach** – A bibliometric approach was adopted for reviewing articles extracted from the Scopus database. Keywords such as ("smart maintenance") OR ("intelligent maintenance") OR ("technological maintenance") OR ("automated maintenance") OR ("computerized maintenance") were used to extract articles from the Scopus database. The articles were restricted between 2006 and 2021 to capture the 4IR era. The initial extracted papers were 1048; however, 288 papers were selected and analysed using VOSviewer software.

**Findings** – The findings revealed that the critical success factors supporting the implementation of smart maintenance in the 4IR era are collaboration, digital twin design, energy management system, and decentralised data management system. Regarding the future practice of smart maintenance in the 4IR era, it was also revealed that smart maintenance is possible to evolve into maintenance 4.0. This will support the autonomous maintenance of infrastructures in the built environment.

**Research limitations/implications** – The use of a single database contributed to the limitation of the findings from this study.

**Practical implications** – Despite the limitations, the findings of this study contributed to practice and research by providing stakeholders in the built environment with the direction of smart maintenance practice.

**Originality/value –** Stakeholders in the built environment have clamoured to implement smart maintenance in the 4IR era. This study provided the critical success factors for adopting smart maintenance, guaranteeing the 4IR era. It also provides the research trends and direction of smart maintenance practice.

**Keyword:** sustainability, smart cities, smart maintenance, construction industry, civil engineering, smart sensors

1. **Introduction**

Maintenance entails preserving an infrastructure so that it can continue to sustain its durability and economic value. This is a critical aspect of infrastructure management because a lack of maintenance leads to heavy economic loss (Ugwu et al., 2018). In the 4th industrial revolution (4IR) era, technology must be integrated into every engineering aspect to achieve efficiency and productivity. According to Aghimien et al. (2019), technological advancement has reformed the function method of most societal activities. Furthermore, the dawn of the 4th industrial revolution (4IR) has contributed to this situation as people are becoming more aware of the benefit of adopting technology in everyday activities. Yun et al. (2013) noted that smart structural health monitoring is regarded as a procedure to monitor the performance of a structure and detect damage, which helps in improving the durability and economic value of the infrastructure, and further reduces the cost of maintenance and repairs throughout the life cycle of the infrastructure.

The concept of smart maintenance can greatly benefit several industries considering the current technological advancement, and most scheduled maintenance can be done using a smart system. In the manufacturing industry, smart maintenance can be referred to as an organizational design for managing the maintenance of manufacturing plants in environments with common digital technologies (Bokrantz et al., 2020a). Furthermore, Levrata et al. (2008) categorized e-maintenance as a concept linked to using information communication technologies to maintain engineering infrastructure. Yun et al. (2011) noted that this requires a systematic visual inspection, instrumentation, load capacity test, field measurement for design and construction verification, and long-term performance monitoring and assessment to manage infrastructure effectively. Similarly, Lundgren et al. (2020) characterized smart maintenance into four scopes: data-driven decision-making, human capital resources, and internal and external integration. These four scopes give smart maintenance a broader perspective and effects than traditional maintenance.

Among the four scopes, data-driven decision-making was noted to make maintenance activities predictable and plannable, thereby reducing the chances of any unwanted circumstances occurring. Data-driven decision-making is based on gathering data as the infrastructure continues to function; this offers better insight into the infrastructure than the old time-based preventive maintenance plans. Furthermore, maintenance decisions are based on the real conditions of the infrastructure (Bokrantz et al. 2020a). Hence, maintenance decisions can be based on data, not experience and intuition (Bokrantz et al., 2017). The human capital resources scope is based on maintenance workers' personal knowledge, skills, abilities, and other characteristics, which are changing due to technological advancement. Maintenance workers must now have generic skills, specifically in data analysis (Akkermans et al., 2016; Roda et al., 2018; Bokrantz et al., 2020a). Internal integration deals with data sharing, information, and knowledge; generically, it deals with collaboration between maintenance functions and the plant organization.

 External integration establishes maintenance links with external parties, such as strategic partnerships and networks. These links permit sharing of equipment data between parties, allowing knowledge resources to be consolidated (Bokrantz et al., 2020a). Lundgren et al. (2020) categorizing smart maintenance seems specific to the manufacturing industry. Aghimien et al. (2018a), Castagnino et al. (2016), and Osunsanmi et al. (2018) opined that the manufacturing and retailing industry is more open to adopting modern technologies in other to boost their production. Furthermore, the construction industry is still very reluctant to adopt several innovative technologies, which affects the use of modern technologies to perform maintenance activities in the Construction and facility management industry (Aghimien et al. 2018a, Castagnino et al. 2016 and Osunsanmi et al. 2018). Considering that maintenance improves the economic value and durability of infrastructure, it has become imperative to promote technology in infrastructure maintenance aimed at giving the stakeholders within the construction industry a competitive advantage (Ugwu et al. 2018). Despite the promotion of technology for maintenance, also known as smart maintenance, its actualisation for stakeholders in the built environment in the fourth industrial revolution era remains challenging. Although Bokrantz et al. (2020) and Turner et al. (2019) conducted a similar study on smart maintenance, their study was done in the manufacturing industry. Another similar study was conducted by Silverio-Fernandez (2019), but they only identified the critical success factors for implementing smart devices in the construction industry while neglecting maintenance. This, therefore, created a gap in the literature and practice regarding the critical success factors of smart maintenance

 To fill the gap, this study had three major objectives. Firstly, to determine the future direction of smart maintenance research and practice concerning the stakeholders in the built environment. Secondly, to identify areas from which the concept of smart maintenance can be built upon both in research and practice. Thirdly, to compose critical success factors necessary for achieving smart maintenance for stakeholders in the built environment in the fourth industrial revolution era. This study promotes research in smart maintenance and the adoption of technologies in performing maintenance activities in the built environment. It is hoped that adopting the findings will help the construction industry in its quest for technological transformation and further create a robust foundation for a collaborative partnership between the construction industry and the technology Industry. Furthermore, the findings will generate a knowledge path for future research on smart maintenance within the built environment.

1. **Smart maintenance of infrastructure in the built environment**

The built environment in this study is made up of the activities performed by stakeholders in the engineering and construction industry. Shia et al. (2020) submitted that stakeholders in this Industry (engineering and construction) are experiencing a swift digital revolution in all aspects of practice. In this era of the 4th industrial revolution, adopting digital technologies in every engineering construction stage should be the priority for the construction industry (UK construction report 2025, 2019). Tarimoa et al. (2017) stated that roads could offer quality satisfaction to users if the correct maintenance plan is implemented. According to Cortés-Pérez et al. (2020), studies have revealed that building information modelling can enhance the working condition in construction sites and improve maintenance activities. According to Yokoyama (2015), the information revolution of the 20th century has allowed railway operators to discover innovative ways of railway maintenance. Yokoyama (2015) further noted that asset management and maintenance work aided by artificial intelligence makes decision-making in the maintenance of bridges, roads, tunnels, and other civil infrastructure smart.

Additionally, artificial intelligence-aided maintenance work still has a significant barrier to overcome. However, overcoming these challenges will yield great benefits (Yokoyama 2015). Several maintenance concepts are found to be in line with the current digitalization process, specifically in the manufacturing industry Lundgren et al., (2020), which are e-maintenance Lee et al., 2006 and Muller et al., (2008), predictive maintenance Carnero (2005), prognostic and health management Lee et al., (2014), maintenance 4.0, Kans et al. (2016), and smart maintenance (Munzinger et al., 2009). These concepts can be of great benefit to the construction industry. This study defined smart maintenance as the practice of using technology to perform maintenance activities to ensure an efficient and sustainable maintenance result. A study by Turner et al. (2019) fused the predictive maintenance method with e-maintenance. The study further stated that incorporating predictive maintenance into e-maintenance aims at integrating developments in web-enabled communication technologies. This semantically describes resources, sensing artificial intelligence, and technologies to realize new remote and ubiquitous maintenance activities capabilities.

The concept of smart maintenance deals with the remote monitoring and management of infrastructure using internet-based technology (Levrat et al., 2008). Furthermore, an e-maintenance model developed by Levrat et al. (2008) covered business processes, information architecture, and infrastructure issues. However, further research is needed regarding unified computing for offering maintenance services and decision support, including technology enablers for maintenance training (Turner et al., 2019 and Holmberg et al., 2010). Augmented reality has been explored for engineering maintenance functions and knowledge creation (Henderson and Feiner, 2011). The discoveries were worthy of note as it was revealed that the development of augmented reality allows production system models to be fed with data in real time and overlaid on the actual physical view of the asset (Turner et al., 2016). Monitoring and maintenance of infrastructure can be done by introducing systems composed of hardware and software with sensing abilities to detect early deterioration in engineering infrastructure. This can be adopted within the built environment to improve its competitive advantage.

However, this process of smart maintenance is being implemented in the aerospace, road, and rail transportation industry in some developed countries, sensed data on static and mobile assets are collected and analyzed to make decisions about present and future maintenance (Ben-Daya et al., 2016). Although, it is not as prominent as it is in the manufacturing and banking industries. This is because the construction industry is slow in adopting technology in construction activities, including infrastructure maintenance. The sensor system was also proposed in the study by Nicola et al. (2020), which stated that implementing a sensor system in maintenance could improve the efficiency and effectiveness of maintenance services. This study was based on optimizing smart building maintenance services using ultrasonic sensor networks. One of the merits of smart maintenance is its ability to collect and analyze data, which can be achieved using semantic technology (Turner et al., 2019).

Borja García de Soto et al. (2019) studied the effect of Construction 4.0 on the structure of the construction industry. The study opined that introducing technology in construction would change every aspect of the construction industry, including construction infrastructure maintenance. Furthermore, construction 4.0 will attract a tech generation of workers to the construction industry. It will reduce the risks involved in working in dangerous conditions, enhance job satisfaction for construction workers and improve the outcome of construction projects. Shim et al. (2019) proposed a new method of bridge maintenance system that involves using a digital twin model concept for maintenance decision-making. The proposed method aims to enhance the bridge maintenance system by using a maintenance information management system grounded on a 3D information model and a digital inspection system using image processing.

1. **Methodology**

This study aims to determine the critical success factors for implementing smart maintenance within the built environment in the fourth industrial revolution era. This was achieved through a bibliometric analysis and critical review of the literatures. The bibliometric approach is used to map out the existing research trends systematically. The building block approach was used to systematically review the literature. According to Booth (2008), the building block technique is a major and widely accepted technique for conducting literature searches. The building block technique allows the decomposition of the research topics into different components, also known as building blocks(Wang et al., 2020). Breaking the research topic into blocks allows the identification of potential terms that includes the synonyms and antonyms of the research topics. The building blocks are the keywords used in searching the articles.

The articles were obtained from the Scopus index database, a complete database with significant multidisciplinary research articles. Also, Scopus has a fast-indexing procedure and has more recent articles than any other database (Meho and Rogers 2008). The articles used in this study were limited to journal articles and conference papers. This is because journal articles contain high-quality research information, either complete research or review research. Also, it has undergone multiple peer-review processes. Conference papers also contain important recent information, especially Scopus-indexed conference papers (Jin et al., 2018). Furthermore, conference papers have recently undergone rigorous peer review processes. Since this study sets out to determine the critical success factors of smart maintenance research within the built environment, there was a need to use numerous related keywords for article extraction. Also, this will make the study exclusively detailed and exhaustible. In this case, the following retrieval keywords were used in the Scopus database: ("smart maintenance") OR ("intelligent maintenance") OR ("technological maintenance") OR ("automated maintenance") OR ("computerized maintenance") OR ("digitalized maintenance") OR ("programmed maintenance") AND ("construction industry") ("architecture industry") OR ("engineering construction industry") OR ("construction management industry") OR ("building infrastructure") OR ("road infrastructure") OR ("mobility infrastructure") OR ("highway infrastructure") OR ("construction infrastructure maintenance") OR ("construction infrastructure"). Figure 1 represents the entire methodological process adopted in achieving the objectives of the study after the extraction of the articles using

When these keywords are keyed in the search box, the related papers are identified when the keywords appear in the abstract, keyword, and title; this will ensure that the data is as comprehensive as possible. The document's language was limited to English, with a time span between 2006 to 2021. The period was chosen to understand the most critical issues within the study domain in the last 15 years. The article search was limited to the built environment, which comprises the engineering and construction industry for this study. Furthermore, after downloading the documents, they were transferred into an Excel sheet for analysis. Vosviewer was used for the various analysis because it is suitable for bibliometric studies. Bibliometric analysis is significant for reviewing literature because it covers both the macro levels (source of the literature) and their micro-level (author and citation analysis). Likewise, Cui et al. (2018) submitted that adopting bibliometric analysis for reviewing articles assists in uncovering the citation analysis, co-citation coupling, bibliographic coupling, and keyword analysis. Zupic and Čater (2015) opined that bibliometric analysis provides robust findings when adopted for reviewing literature due to its ability to draw on a variety of theories and models. Therefore, the inherent strength of bibliometric analysis makes the adoption suitable for this study. This study also adopted the articles' content analysis to complement the bibliometric analysis's strength. van Eck and Waltman (2017) submitted that bibliometric analysis is an inherent strength in the quantitative analysis of published articles. Therefore, content analysis was used to interpret the published articles literally.

Thus, this study adopted Vosviewer under the bibliometric principles to develop the co-occurrence network of keywords, overlay visualization map, identify the highest publishing authors, the number of publications per year, the most cited publication and author, number of publications per source, and country. To further elaborate on the methodology adopted in the study, this study adopted the interpretivist philosophical approach in the bibliometric search, where each research article represented a unit of analysis (Aghimien et al., 2021). The initial number of retrieved articles was 1,048; however, a sample frame of 288 was retained for analysis after the filtration. Furthermore, 260 articles were from the engineering domain, while 28 were from environmental science. Regarding the critical success factors, the authors composed these success factors because no existing study has identified the critical success factors necessary for smart maintenance within the built environment. This was successfully done using a brainstorming approach amongst the authors. Brainstorming is a group discussion to produce ideas or solve problems; it is also a process capable of generating wonderful ideas and concepts.

1. **Discussion of Findings**

*4.1 Publication per year*

The number of publications per year spanned from 2006 to December 2021 (see Figure 2), with the possibility of more publications in the year 2021. The publications were extracted from journals and conference proceedings numbering 90 and 198, respectively. The publication analysis (figure 2) per year revealed a fluctuating number of articles across the different years. The year 2020 had the highest number of publications, followed by 2016, while 2021 has the lowest number of publications, with 7.

Insert Figure 2 here

*4.2 Leading publications in the smart maintenance domain within the built environment*

The citation analysis was adopted to determine the leading publication source of smart cities within the built environment domain. This was done using the VOS viewer software and was set at the default setting of a minimum of 1 citation. This revealed that 174 research publications met this threshold. Closer observation revealed that 122 research publications had citations between 1-10, 25 research publications had citations between 11-20, 6 research publications had citations between 21-30, 7 research publications had citations between 31-40, while 6 research publications had citations between 41-49.

Insert Table1 here

The results in Table 1 show those research publications with citations of 50 and above. Reviewing the most cited research publication (Table 1) reveals a diverse research focus aside from smart maintenance of civil engineering infrastructure. The studies by Brownjohn (2011), Popov et al. (2010), and Koch et al. (2014) were the only specific study to have discussed the concept of smart maintenance concerning civil engineering infrastructure and construction engineering. Furthermore, it can be noted that these publications were made only in "automation in construction," a top international journal that publishes referred materials on every aspect of information communication technology in design, engineering, construction technologies, and maintenance management of constructed facilities. This highlights the need for more specific research on smart maintenance concerning civil engineering and construction. Brownjohn (2011) stated that adopting technology in the maintenance and management of infrastructure is slow. Therefore, the construction industry needs to continue promoting technology adoption, with special attention to management and maintenance. The study by Brownjohn (2011) showcased successful vibration-base monitoring (VBM) technology application.

The study further showed that VBM provides valuable real-world application information when used correctly. Popov et (2010) assessed the practical, intelligent application, computer-aided evaluation, and construction process simulation techniques based on virtual project development (VPD). Popov et (2010) further noted that building information modeling (BIM) facilitates creating and sharing information relevant to buildings' design, construction, and maintenance throughout their life cycle. The VPD can be implemented as a 3D model for simulation of the construction process and management to prevent collision of construction equipment onsite. Koch et al. (2014) proposed a neural marker augmented reality model to support digital facility maintenance operators when conducting maintenance. This study showcased the potential of neural markers for augmented reality-based maintenance support. Furthermore, as obtained from Table 1, the most cited research publication by Bocchini et al. (2014) was not explicit on smart maintenance of civil engineering infrastructure and construction engineering. This further highlights the need for more research on smart maintenance in relation to civil engineering and construction.

*4.3 Leading Publication per source.*

The leading publication source for smart maintenance in the fourth industrial revolution era was analysed in this section. This was done using citation analysis, revealing that in 179 sources with at least five publications per source and a minimum of 1 citation per source, only 8 sources met the thresholds. Figure 3 shows eight sources, of which only two are from journals, while the rest are from conference proceedings. This highlights that civil and construction engineering journals are not paying much attention to smart maintenance as a relevant topic that enhances civil and construction engineering practice. From Figure 3, automation in construction emerged as the source with the highest number of extractions, with 12 documents that have been cited 400 times, which is also the highest number of citations. Procedia engineering followed with 11 documents and 54 citations. Proceedings of the 3rd international conference on bridge maintenance, safety, and management - bridge maintenance, safety, management, life-cycle performance, and cost, ranked 3rd with 10 documents extracted and 11 citations obtained. Also, IET conference publications and Procedia CIRP ranked 4th with 7 extracted documents each and 13 and 285 citations, respectively. Proceedings, annual conference - Canadian Society for civil engineering ranked 5th with six extracted documents and 3 citations, Energy, and buildings. IFAC-papersonline ranked 6th with 5 extracted documents each and 141, and 5 citations, respectively.

Insert Figure 3 here

*4.4 Publication per country.*

In terms of publications per country. Figure 4 reveals the countries with at least 5 publications and 10 citations. The USA has the highest number of smart maintenance-related research with 89 publications and 1194 citations. The UK follows this with 29 publications and 417 citations; Italy obtained 24 publications with 276 citations. Furthermore, Germany, Canada, China, Australia, Japan, Portugal, France, India, Greece, and Hong Kong all obtained the following number of publications 18, 13, 12, 11, 9, 8, 7, 7, 6, 6, respectively, and with a respective number of citations of 524, 198, 24, 50, 19, 59, 101, 76, 44, 210. The countries with the lowest number of publications are Austria, Netherlands, South Korea, and Spain, with 5 publications each, 235, 22, 47, and 43 citations. Interestingly, China and India are the only developing countries to appear in this analysis based on the threshold adopted. No African country made the cut based on the threshold used for this analysis. Although South Africa and Nigeria had 4 and 1 publications, none have obtained any citations. This analysis has revealed the need for more research on smart maintenance in construction engineering. This will improve the competitive advantage of the construction industries in developing countries.

Insert figure 4 here

*4.5 The smart maintenance research and practice trend.*

The trend of previous studies was evaluated using keyword co-occurrence from the bibliometric data obtained from the VOSviewer. To make this study as inclusive and broad as possible, this study adopted all keywords present within the VOSviewer tool (author's keywords and indexed journal keywords). This produced a total of 3610 keywords and with the VOSviewer set at a default minimum threshold of 5 co-occurrence keywords, a total of 146 keywords met this threshold. This means a keyword must be mentioned in five documents to appear on the map (Nazir et al. 2020). The process of obtaining these keywords was passed adequately because there is no unified agreement regarding the number of minimum co-occurrence keywords to be adopted in any bibliometric study (Aghimien et al., 2021). Figure 5 represents the network visualization map with 6 clusters represented in various colors, revealing the area of focus of smart maintenance research. A close observation of the map reveals that each keyword relates to maintenance and the 4th industrial revolution concept. Furthermore, the keyword clusters were named after a careful observation of the similarities among the keywords in each cluster.

**Cluster 1:** **Smart maintenance management and data handling**: This is represented by the red dots on the map and has 20 co-occurring keywords. These are asset management, budget control, condition assessments, cost estimate, data handling, decision support system, deterioration assessment, forecasting, highway administration and planning, infrastructure maintenance, infrastructure management, inspection, investments, maintenance planning, neural network, quality control, repair, risk assessment, risk management, service life. These keywords are linked to smart maintenance management and data handling. This study referred to it as a computerized programmed network of various management and maintenance services related to the built environment. It can be in the form of a computer application developed and installed within the infrastructure for real-time data collection and handling as the infrastructure continues to function. It should be able to provide condition assessment of infrastructure, cost estimation for the current maintenance needs or cost forecasting, data handling, and other infrastructure maintenance-related activities in real-time. Thus, this study encourages the development of a smart maintenance management and data handling system for infrastructure management and maintenance.

According to Gang et al. (2021), in achieving intelligent management of urban roads, researchers have constantly improved the functions of road operations and management systems in various aspects: wireless sensor network management, external data access, data processing, data management, and service management. These systems can assist operators in maintenance planning, execution, enhancement, and assessment (Kullolli 2008). Furthermore, this system will be beneficial in other construction engineering infrastructure maintenance planning and condition assessments. Digitalisation within the built environment, which involves adopting a smart maintenance system, requires significant financial expenses and investment. Furthermore, it requires proper budget control, effective costing and estimation, and adequate management of the overall economic aspect of technology adoption. Jonek-Kowalska and Wolniak (2021) noted that adopting new technologies, modern transportation, infrastructure development, and an improved environmental protection system is challenging without considering its economic and financial aspects. Smart maintenance decision support systems provide a predictive analytical framework for various industries, including the construction industry (Bumblauskas et al., 2017). This cluster suggests that the construction industry needs a smart maintenance management and data handling system capable of performing the required maintenance activities in real-time. Furthermore, the smart maintenance management and data handling system should be able to predict the necessary maintenance activities to be performed and provide real-time information on the condition of the infrastructure through its service life. A well-developed smart maintenance management and data handling system can achieve adequate infrastructure risk assessment and quality control of construction materials.

Insert Figure 5 here

**Cluster 2: smart construction algorithm:** This is represented by the green dots in the map and has 24 co-occurring keywords. These are smart homes, application programs, architectural design, artificial intelligence, building information modeling, building maintenance, construction industry, construction projects, decision making, design and construction, digital twin, engineering education, facility management, information management, information modeling, information theory, infrastructure assets, learning systems, maintenance management, smart office buildings, operation and maintenance, project management, scheduling, and urban planning. This study defined a smart construction algorithm as a computerized problem-solving operation in engineering construction. It is a calculated procedure for solving recurrent construction problems by following a specified line of action. This study proposed that the smart construction algorithm should be supported by artificial intelligence to execute the structural and architectural design, building information modelling, digital twinning of infrastructure, and other related infrastructure maintenance and planning activities using computer algorithms.

According to Kochovski and Stankovski (2019), every project in the construction industry is unique in its design, location, professionals and organizations, contract length, cost, and other aspects of construction. Therefore, organising smart services and applications supporting the construction process is significant to every construction firm (Kochovski and Stankovski 2019). Past studies have focused mainly on artificial intelligence as a set of algorithms for solving energy problems in smart homes or buildings. However, no study currently focuses on smart construction algorithms in relation to smart maintenance. This leaves a gap in the study of smart maintenance, as maintenance should be a recurrent activity. Over the years, the tools for designing, constructing, and management of infrastructure have upgraded into building information modeling (BIM) and geographical information systems (GIS) (Meza et al. 2015). However, there are no proper frameworks to exploit all the advances of IoT (Internet of things) in the construction process, even though augmented reality (AR) has been adopted in the construction industry for architectural design, structural design, maintenance, construction safety, project inspection, error reduction, cost and time reduction (Genders et al. 2016).

Shim et al. (2019) noted a need to adopt a digital twin model concept for reliable decision-making in the construction and maintenance of infrastructure. This entails a maintenance information management system built on a 3D information model. This cluster is a computer-based solution to infrastructure maintenance only that it promotes the adoption of computer algorithms in setting out infrastructure maintenance plans. Furthermore, this cluster shows that adequate maintenance can be achieved through a computerized system algorithm. Therefore, construction firms aiming to reform their recurrent maintenance activities digitally should implement a smart construction algorithm for effective infrastructure maintenance management. This can be achieved by proper collaboration between the construction and technology industries.

**Cluster 3: smart integrated and embedded systems for maintenance:** This is represented by the royal blue dots in the map and has 29 co-occurring keywords. These are: automation, buildings, computer software, computer software maintenance, condition-based maintenance, condition monitoring, cost-benefit analysis, cost reduction, data acquisition, design/methodology/application, digital storage, electric power transmission, embedded systems, energy efficiency, industry 4.0, integration, Internet of things, machinery, maintenance, maintenance cost, manufacture, predictive maintenance, railroad transportation, rails road, reliability analysis, structural analysis, systems engineering, technology, wireless sensor network. These keywords are interrelated to the cluster smart integrated and embedded systems for smart maintenance. Automation and smart technologies offer opportunities to enhance construction management activities (Rossi et al., 2019). Construction management activities are complex, dynamic, and risk-imposing because when one aspect lacks proper management, the resulting consequences might have a devastating economic impact. There is a need to adopt a smart integrated, and embedded system for the maintenance, monitoring, and management of infrastructure. Furthermore, due to the complexity of construction projects Rossi et al. (2019), a smart integrated and embedded system can manage material flow, machinery, human resource, safety, cost-benefit analysis, and reduction. Furthermore, smart integrated and embedded systems such as radio waves technologies create an easy building material and equipment management method for identification and tracking (Singh et al., 2017).

The Internet of things is one of the revelations of the 4th industrial revolution. It connects several devices to the Internet ranging from equipment to sensors (Kreische et al. 2015). It is an interconnected embedded system that connects two wireless technologies and smart sensors (Oke et al. 2020). In line with the technological needs of the 4th industrial revolution, construction firms aiming to enhance their maintenance procedure must adopt a smart integrated, and embedded system for infrastructure maintenance. This can be in the form of sensors alerting the maintenance department of possible infrastructure dilapidation in real-time. This submission is acknowledged by Oke et al. (2020), who stated that the Internet of things (IoT) can be adopted in the construction industry. With the help of a sensor, it gives merit for maintenance, movement of materials and equipment onsite, and structural and reliability analysis.

**Cluster 4: smart building maintenance:** This is represented by the yellow dots on the map and has 20 co-occurring keywords. These are: building, building construction, building materials, design, energy utilization, environmental impact, environmental management, greenhouse gases, infrastructure, intelligent buildings, life cycle analysis, life cycle assessment, material handling, optimization, reliability, residential building, sustainability, sustainable building, sustainable development, uncertainty analysis. The keywords are associated with building infrastructure and its related management processes. Smart buildings are structures integrated with sensors as an aspect of their wiring control system (Agarwal et al. 2010, Shrivastava and Chini, 2012, Osunsanmi et al., 2020). Smart buildings are developed with materials and smart sensors to ensure their automation (Buckman et al., 2014). It is a building that adopts intelligent technologies to achieve comfort and good energy consumption level (Wang et al. 2012). Jina et al. (2018) and Khaddour et al. (2023) opined that to meet environmentally friendly requirements, there is a need to build energy management systems to monitor energy consumption and management. Furthermore, building energy management systems can be designed to discover abnormal energy usage, modify device running plans, ensure a comfortable indoor environment, and eradicate energy loss. These are the functions expected of a smart building which translates to the overall maintenance of the building. This study further suggests that a smart building should be able to identify stress areas/crack formation in a building, regulate the building temperature to suit the occupant's body temperature, identify the level of building settlement, and provide adequate security for the occupants.

**Cluster 5: smart structural technologies:** This is represented by the purple dots on the map and has 16 co-occurring keywords. These are:civil infrastructure, concrete beams, and girders, concrete buildings, concrete construction, concretes, corrosion, cracks, damage detection, fiber optics sensors, structural health monitoring, highway bridges, image processing, non-destructive examination, reinforced concrete, safety engineering, sensors, structural design. The keywords for this cluster centered on structural engineering and its related attributes. This study suggests that the consistent infrastructural deterioration has necessitated the need to adopt smart structural technologies to mitigate concrete cracks, prevent reinforcement corrosion, provide damage detection capabilities, provide non-destructive structural tests, provide safety during construction, provide structural image processing in 3D, provide adequate structural design and the overall structural health monitoring in real-time.

Yun et al. (2011) noted that fiber optics sensors are perfect for real-time structural health monitoring of civil infrastructures. Furthermore, they can easily be integrated within the structure and are capable of multiplexing. They are unaffected by electromagnetic noise and have the flexibility of sensor size and high sensitivity (Yun et al., 2011). This tool can be adopted for infrastructure maintenance activities in highway bridges, corrosion detection on concrete reinforcements, cracks and damage detection on infrastructure, and non-destructive testing of concrete structures. Furthermore, its recent application has centered on developing a data interrogation system for fibre Bragg grating sensors using wavelength division multiplexing and code division multiple access methods (Ryu et al. 2001, Ryu and Hong 2002). Fibre optics sensors can also be applied in structural integrity testing using fibre bragg grating, temperature monitoring using (BOTDA) Brillouin optical time domain analysis sensors specially used for fire detection, tunnel monitoring using FBG sensors, railway displacement calculation using FBG sensors (Kim et al. 2005 and Kwon et al. 2004).

**Cluster 6: smart mobility maintenance:** This is represented by the sky blue dots in the map and has 8 co-occurring keywords. These are: civil engineering, climate change, intelligent systems, intelligent transportation, intelligent vehicle highway, operations and maintenance, transportation, and vehicle. The keywords for this cluster centered around smart mobility systems and its related attributes. Smart mobility is the infusion of information communication technology (ICT) to transportation systems, which enhances the city's sustainability (Giffinger et al., 2007). This involves the use of electric and self-driving vehicles, which is a trending transportation technology. The adoption of electric vehicles in transportation will help mitigate climate change, which is currently one of the greatest threats to human health. Infrastructure deterioration and greenhouse gases are recognized as the main cause, especially carbon dioxide (Choi, 2019). However, Pavić et al. (2020) noted that adopting low-carbon emission vehicles is slow despite its importance in city development. Due to the infrastructure deterioration caused by climate change, there is a need to account for climate change effects when developing an infrastructure maintenance plan. Furthermore, a city's transportation infrastructure is a significant aspect because of its economic services. Therefore, there is a need to adopt a sustainable maintenance model for its continued improvement and existence. Choi (2019) noted that there are two challenges faced by highway agencies which are: reducing the life-cycle cost of construction, reducing the maintenance cost of highway infrastructure, and reducing carbon emission for sustainable pavement construction and maintenance to cope with climate change. This study suggests that a well-thought-out maintenance plan, including preventive maintenance, light rehabilitation, medium rehabilitation, and heavy rehabilitation plans should accompany the adoption of a smart mobility system. Preventive maintenance includes treatments that are designed to slow down the deterioration rate of a pavement section or the entire mobility infrastructure. However, this does not lead to a significant improvement in the structural capacity of the mobility infrastructure (France-Mensaha et al., 2019). Meanwhile, any form of rehabilitation (light and medium) can add to the structural capacity of the entire mobility system (France-Mensaha et al., 2019).

*4.6 Direction of research and practice of smart maintenance*

The direction of research and practice of smart maintenance is presented in Figure 6. A close observation of Figure 6 revealed that early research between 2012 – 2013 focused on areas related to cost, safety engineering, data handling, structural analysis, maintainability, design, service life, sustainable building, maintenance cost, technology, wireless sensor network, and forecasting. These keywords are represented in the purple region. Between 2013 and 2014, the study shifted focus to the construction industry, highway administration, deterioration, uncertainty analysis, maintenance, digital storage, reinforced concrete, and sustainable development. Between 2014-2015 the focus was on optimization, road and street maintenance, architectural design, concrete beams and girders, concrete buildings, life cycle, sustainability, energy efficiency, data acquisition, corrosion, and cracks.

Between 2015-2016 the focus was on intelligent systems, monte carlo methods, information management, buildings, construction, railroads, and rail transportation. Between 2016-2017 the focus was on facility management, buildings, decision-making, structural health monitoring, embedded systems, operation, and maintenance. Then the last year, 2017, reveals more diverse topics in industry 4.0, preventive maintenance, Internet of things, digital twin, construction projects, infrastructure maintenance, infrastructure assets, learning systems. These are the current research focus on smart maintenance concerning construction engineering. This implies that the current research focuses on the trending 4th industrial revolution, Internet of things, digital twin technologies, and how these technologies can be applied in infrastructure development and maintenance.

Insert Figure 6 here

With the emergence of the 4th industrial revolution and the 3rd generation of information communication technologies, digital technologies have emerged as a significant proposition for improving efficiency (Ozturk, 2021, Herterich et al., 2016). Adopting digital technologies in construction engineering improves risk mitigation, provides market intelligence, provides automated manufacturing systems, and improves infrastructure maintenance processes (Rymaszewska et al., 2017). The new era of the 4th industrial revolution and digital technologies have resulted in smart mobility, smart building, smart grid, smart cities, smart logistics Ozturk, (2021), and in the context of this study, smart maintenance. The digital twin technologies allow the virtual representation of physical assets condition as data that can be embedded in a certain approach at anytime (Herterich et al. 2016). Furthermore, the introduction of new technologies such as the Internet of Things, digital twins, virtual reality, and artificial intelligence will improve the service approach in the construction industry. This includes infrastructure maintenance services. Shim et al. (2019) opined that adopting the digital twin model assists engineers in making a long-term plan for the operation and maintenance of infrastructure, which is preventive maintenance. In this context, maintenance inspection can be conducted within a short time with high precision. The adoption of digital twins, and Internet of things in infrastructure maintenance saves the maintenance cost as the initial technology equipment can be reused in future maintenance and inspection schedule (Shim et al. 2019). The introduction of Internet of things with digital twin buildings made it possible for smart maintenance to evolve into maintenance 4.0. This will, in return, support the ability to maintain infrastructures in the built environment autonomously.

*4.7 Critical success factors for smart maintenance (SM) adoption in the construction engineering industry*

Table 2 below displays the critical success factor for smart maintenance adoption and its descriptions in the construction and engineering industry. The authors composed the success factors because no current study on smart maintenance related to the construction industry has composed the critical success factors for smart maintenance adoption within the built environment. These critical success factors will enable further research on smart maintenance as they will provide the base for smart maintenance model development in the 4IR era. The critical success factors were determined using the combination of abstract keywords search and submitting the keywords to a critical review of literature.

Insert Table 2 here

Table 2 revealed that the critical success factors for adopting smart maintenance in the 4IR era are collaboration, adoption of fibre optic sensors, energy management system, decentralised automated data storage system, smart maintenance education, and digital twin design. Among the critical success factors extensive research has been conducted concerning the collaboration of stakeholders involved with smart maintenance. The collaboration would cut across government parastatal, research institutes, and computer scientists targeted at creating a symbiotic relationship. At the same time, few research has been conducted on decentralised automated data storage systems and digital twin as a success factor in ensuring smart maintenance. This study recommends developing a framework to validate the critical success factors.

1. **Conclusion**

This paper presented an extensive systematic review of smart maintenance research through a bibliometric analysis. The study sets out to determine the future direction of smart maintenance research in the 4IR era concerning the built environment. The existing research areas from which the concept of smart maintenance can be built upon in the 4IR era was also explored. The study also composed the critical success factors necessary for achieving smart maintenance in the 4IR era. Regarding the future practice of smart maintenance in the 4IR era, It was revealed that smart maintenance is possible to evolve into maintenance 4.0. This will support the ability to maintain infrastructures in the built environment autonomously.

Also, smart maintenance has not been given much attention in research and practice within the built environment. Further findings revealed that the areas from which the concept of smart maintenance can be built upon both in research and practice are smart mobility maintenance, smart building maintenance, smart structural technologies, smart integrated and embedded systems, smart construction algorithm, and smart maintenance management and data handling. For the maintenance approach to be improved within the built environment, a smart maintenance management and data handling system for infrastructure management needs adequate development. This is a real-time computerized approach towards asset management, budget control, condition assessments, cost estimate, data handling, decision support system, and other maintenance-related activities. Furthermore, the various clusters described in this study are interrelated as they all narrate how technology can be efficiently used in infrastructure maintenance, management, and planning.

Therefore, professionals within the built environment must seize the opportunity provided by technology to improve its maintenance approach and competitive advantage. More findings of this study revealed the need for integrated embedded systems with algorithms supported by artificial intelligence for building and transportation infrastructure maintenance. This will translate to smart building maintenance and smart mobility maintenance. Practically, this study contributed towards revealing smart maintenance success factors not identified in the few previous studies on smart maintenance in the built environment. Some of the success factors alluded to the significance of collaboration between the stakeholders within the built environment and other sectors. Firstly, the collaboration between the stakeholders in the built environment and the government can bring about technology policy development that suports the adoption of smart maintenance in the built environment. Also, the professionals within the built environment should partner with the technology industry and research institutes to exchange ideas that will drive smart maintenance technology development.

Theoretically, this study's contribution is evident as no existing bibliometric study has utilized the bibliometric concept to explore smart maintenance research concerning the built environment. Further theoretical contribution lies in the fact that this study created a knowledge relationship between education within the built environment and computer science. This will help in curriculum reform within the built environment globally. While this study made great contributions to the body of knowledge, it is essential to note that only papers published in English were reviewed, meaning that other significant works on smart maintenance published in other languages may have been excluded. This study recommended that further research be conducted on developing a smart maintenance implementation framework based on critical success factors identified in this study.

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