INVESTIGATING THE ROLE OF DIGITAL TWIN AND 5G TECHNOLOGY IN ENHANCING SMART ENERGY MANAGEMENT

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Smart Energy Management (SEM) backed by IoT devices and AI/ML algorithms is crucial for achieving energy reduction goals and meeting global sustainability targets such as COP 26. A Digital Twin (DT) allows for rapid analysis and real-time decisions made through accurate analytics for SEM. Furthermore, for urban-scale DT; the next generation of network connectivity can support a high volume of data transfer in real-time. Therefore, this paper analyses trends; technological readiness; and challenges and proposes mitigation strategies for applying DT in the SEM domain. The research status quo is objectively portrayed using scientometric analysis (e.g., clusters using the VOSviewer tool); and the research trends and challenges were identified using a thematic review. The number of publications has grown exponentially in the past four years; with China followed by the UK producing the most publications. Three distinctive trends are observed that are "real-time data analysis"(26%); "optimisation"(34%) and "operation/maintenance"(14%). Furthermore, it highlights the role of the 5G network in transformation and pushing the DT adoption in SEM, which can aid in decision-making and strategic planning in the construction sector.

Keywords: 5g network; digital twin; smart; AI; machine learning; sustainability

INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) identified in its 2018 report the need to reduce global emissions to net zero levels by 2050 (Masson-Delmotte *et al.,* 2018). Furthermore, the United Nations Climate Change Conference (COP 26) 2021 aimed to limit increased global temperature to 1.5 °C above pre-industrial levels (COP 26, 2021). It aimed to gain sustainable practices on climate change as agreed in Paris Agreement and UN framework convention. Such a transition towards net zero requires industrial, social, economic (corporations) and governmental interventions and moving towards technological innovations (Miller, 2022). Recent advancements in using digital technologies powered by Machine Learning (ML), Artificial Intelligence (AI), high-speed networks like 5G, cloud computing, and edge computing invoke a potential to deliver sustainable solutions that can help achieve net zero goals

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and reduced carbon emissions (Chew *et al.,* 2020; George *et al.,* 2021; Kumar and Teo, 2019). EU's Service Oriented Grid for the Network of the Future (SOGNO) initiative is one such large-scale project that aims to minimise customer outages due to storms and other events damaging overhead power lines, which can result in financial penalties for lost customer service minutes using 5G network that supports real-time data-driven monitoring and control, promoting cost-efficient solution (Ericsson, 2019).

Most energy consumption happens due to rapid urbanisation and consumption, resulting in increasing demand for cities to be a more thoughtful and significant push to reduce greenhouse gas emissions and carbon footprint (Pierce and Andersson, 2017). In cities, buildings account for most of the energy consumption, and therefore, we see increased demand for using intelligent technologies in energy management. Additionally, there is a more significant push to refurbish and retrofit existing buildings to achieve operational improvements and implement smart technologies to gain better energy management (Harrison and Donnelly, 2011; Le *et al.,* 2021).

Digital Twin

The demand for higher energy efficiency in buildings resulted in increased usage of real-time intelligent planning and energy management (Hastak and Koo, 2017). A recent endeavour in this sense is the increased interest in Digital Twin (DT) applications in various applications ranging from individual buildings to building complexes to urban/city level. Digital Twin (Figure 1) is a digital replica of physical space aimed at cloning the physical environment in the digital arena and supporting real-time linked data to improve monitoring, control and decision-making through automation and informed actions (Deren *et al.,* 2021). Figure 1 shows three support pillars of DT, i.e., a digital replica of the building/City/infrastructure (3D Information model), sensors providing real-time data using fast network connections and a Common Data Environment (CDE) acting as a single source of truth in terms of data. Boje *et al.,* (2020) proposed that three generations of digital twins will exist. The first generation (generation #1) DT will be monitoring platforms, the second generation (generation #2) will be intelligent semantic platforms, and the third generation (generation #3) will be agent-driven socio-technical platforms.

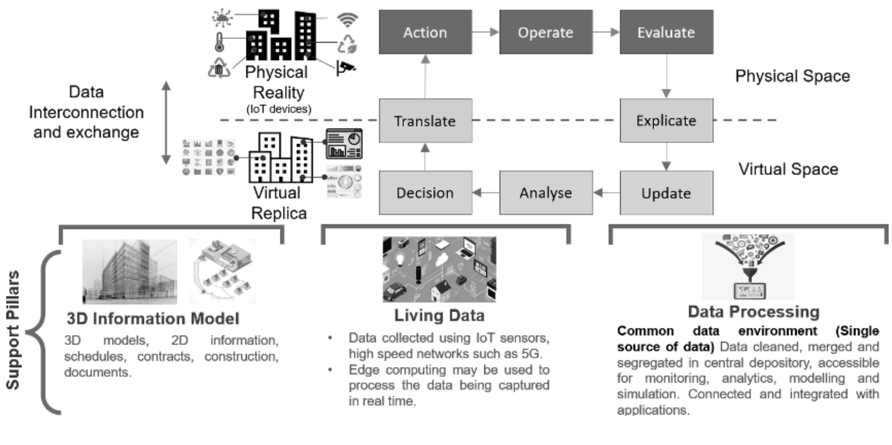

Figure 1: Digital Twin and Supporting its supporting Pillars

Smart city and its component digital twins' purpose is to make Facilities Management (FM) easier through better real-time data capture and devising automation algorithms to optimise the usage without human interventions reducing dependence on humans to make complex decisions in real-time (Smart FM). Figure 2 shows an example of DT architecture, whereby data from various physical equipment and Internet of Things (IoT) devices provide data to a CDE using a high-speed network (5G), leading to a broader 3D information model-based DT. Various algorithms using ML/AI can be developed that can perform automated tasks. One of the most significant parts of FM is Energy Management (EM). EM will get smarter, coined as Smart Energy Management (SEM), with DT due to recent advancements in network connectivity with the advent of 5G technology, AI and ML algorithms. While AI and ML help process the data faster, 5G ensures data migrates from the cloud to IoT devices in real-time.

5G Network

5G is the 5th generation of mobile networks. It is designed to connect virtually everyone with everything, such as machines, objects, and devices. 5G network aims to provide high bandwidth data (up to 20 Gbps speed), ultra-low latency, better reliability, high cybersecurity, and connection to a high number of devices per square kilometre. It also aims to provide a much better, consistent user experience (Qualcomm, 2020). To reduce interference, 5G is based on OFDM (Orthogonal frequency-division multiplexing) that modulates digital signals across different channels (Wild *et al.,* 2014). 5G also uses broader bandwidth technologies such as sub-6 GHz and mmWave (Bhushan *et al.,* 2017). This means more people will have access to 5G for various use cases like gaming, VR/AR, video streaming, and analytics. The flexibility to operate in both bands, i.e., a lower band (e.g., sub-6 GHz) and mmWave (e.g., 24 GHz and up), gives 5G more capacity for high throughput and low latency (Qualcomm, 2020).5G is designed to support all kinds of spectrums, such as licensed, shared, or unlicensed and multiple bands. Furthermore, it will provide new ways to interconnect, such as device-to-device and multi-hop mesh (Qualcomm, 2020).

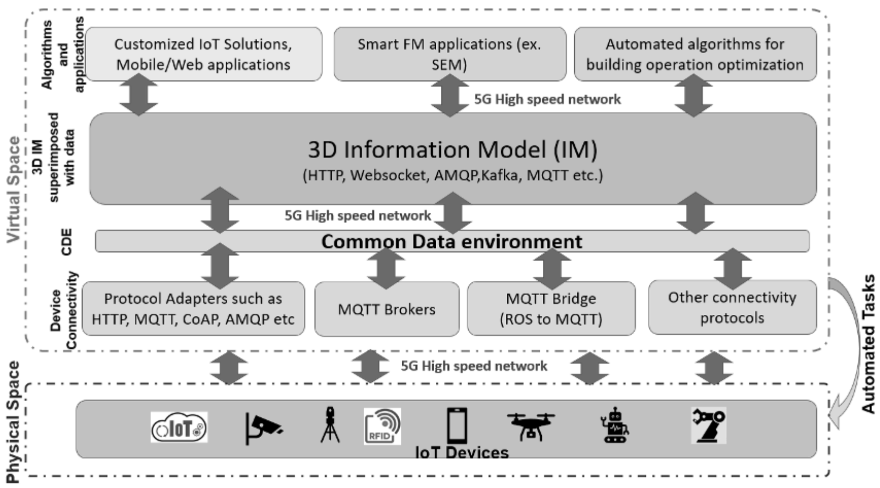

Figure 2: Digital Twin Architecture using a 3D information model

This paper, therefore, explores the current research in SEM and the usage of DT and 5G network application in the domain of SEM through a literature review. The review identifies the progress made in applying DT and 5G network in SEM, the challenges and possible mitigation strategies.

METHOD

A systematic literature review methodology is adopted for analysing DT's application in SEM research. The literature search was conducted using the SCOPUS database, one of the largest online scientific literature databases (Martín *et al.,* 2021). The search string and Boolean operators which were used for searching is "(TITLE-ABS-KEY (Smart energy management AND digital twin))". The search resulted in 133 documents after removing 11 papers published in other than the English language. Conference review (21 nos.), which commonly consists of entire conference proceedings and book chapters (6 nos.), was also excluded, resulting in 106 documents. This preliminary screening was conducted using the SCOPUS database filter features. The initial investigation was performed using the analysis feature provided by the SCOPUS database itself. It was followed by analysing the co-occurrence network of all keywords using VOSviewer, a visualisation tool.

Further processing by screening the title and abstract was conducted to identify the relevant literature for the building and construction sector. The available research for the application of DT in SEM focuses on various fields such as grids (19 nos.), energy storage and distribution (7 nos.), power plants (including renewable) (13 nos.), manufacturing (11 nos.), transport (11 nos.), communications (3 nos.), agriculture (2 nos.), water utilities (3 nos.), equipment management (2 nos.). A sizable of 35 documents published for the building and construction sector till early March 2023 were filtered for detailed investigation. Additionally, nine papers were added to the list, obtained through multiple searches in google scholar and found relevant to the topic. The final number of documents is 44, adequate to draw meaningful thematic insight from the literature and is reported in this article.

FINDINGS

Technological readiness

The research on the application of DT in SEM has been exponentially growing for the last four years (refer to Figure 3a).

Figure 3: A) Documents published per year, b) Documents published Sectors wise, c) Documents published country wise, and d) Top five source of publication of documents for digital twin and smart energy management.

As mentioned in the previous method section, the application of DT in SEM happens in various sectors, with the most dominant in the building construction section (refer to Figure 3b). China, followed by the United Kingdom, Italy and the United States, lead the research (refer to Figure 3c). The top 5 publication sources are highlighted in Figure 3d, with Solar Energy with the highest number of around ten documents.

a) Scientometric analysis of DT in SEM

Keyword co-occurrence analysis can help to identify the cluster that constitute the theoretical blocks or foundational topics for the current and future topic. Three clusters are identified with the network visualisation graph (refer to Figure 4) of the co-occurrence of the keywords. The first cluster (Cluster 1 in Figure 4) focuses on data analysis and advance technologies for improving security, and reliability. The cluster that can be identified include digitalisation and data-driven decision-making techniques (blockchain, digital storage, cyber-physical systems, and embedded systems), energy systems and smart grids. The second cluster (Cluster 2 in Figure 4) focuses on real-time data analysis, automation and machine learning and similar techniques to optimise energy management and infrastructure, including energy storage, microgrids, renewable energies, and intelligent buildings. The third cluster (Cluster 3 in Figure 4) focuses on applying digital technology to improve energy efficiency, sustainability, industrial research, and information management.

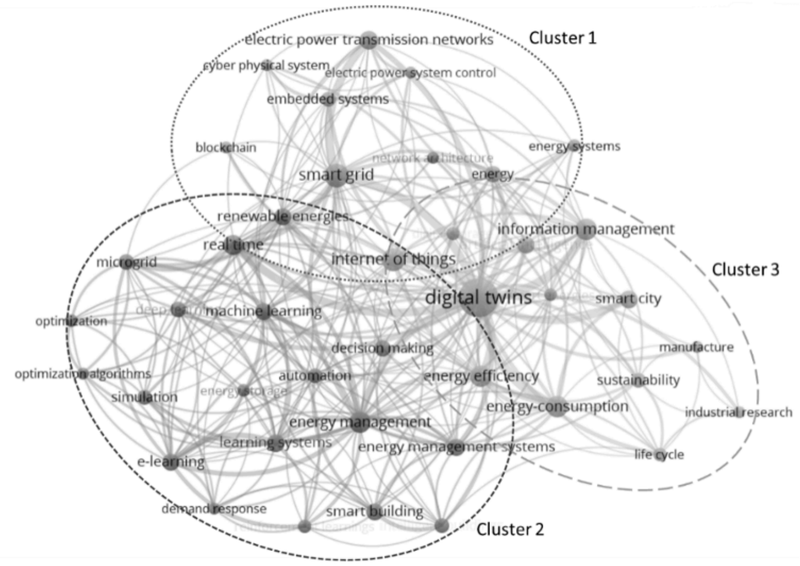

Figure 4: Network visualisation of co-occurrence of all keywords (minimum five occurrences) using the VOSviwer tool combining similar keywords using the thesaurus feature of the tool

The clustering presented by the VOSviewer was essential in providing visually a holistic and logical classification for ongoing and future trends. Subsequently, a rigorous systematic review for applying DT in SEM was conducted on 44 documents selected in the final stage (as mentioned in the Method Section) to identify the themes focused on by the researchers. These are mainly focused on three themes, i.e., operation and maintenance, optimisation, and real-time data analysing and decision. These studies are conducted at various scales, such as building, campus and urban levels. Academicians are also interested in other research topics, though less frequently, such as energy storage, study advancement, and construction facilities.

Operation and maintenance

The end users of a building are the most critical stakeholder in ensuring facility performance following design criteria, which necessitates technology-task fit, particularly for DT applications in the case of SFM (Wong *et al.,* 2022). The application of technologies such as extended reality are being explored for DT in SEM to improve the maintenance process; however, the use of DT in SEM for operation and maintenance is limited in the construction industry as compared to other sectors such as manufacturing, the energy industry and aerospace (Coupry *et al.,* 2021). The research also emphasizes the relevance of user acceptability as well as the impact on return on investment for the feasibility of such advanced technologies. The occupant's behaviour (or building's behaviour, such as operation faults or change in an energy storage device) also impact the use of SEM system, especially the way they interact with the control mechanism in DT, which affects the indoor environment conditions such as heating, ventilation, and Air-conditioning (Englezos *et al.,* 2022).

Optimisation
Improving the performance without impacting the occupant's comfort is complex due to the co-existence of multiple systems in a building sector. A multi-layer DT architecture to mimic the SEM and an edge-based reinforcement learning technique are developed to decrease energy costs in residential sectors while increasing user comfort. Experiments on synthetic and real-world smart home datasets reveal that the suggested strategy efficiently lowers the dispersion of the collective diurnal energy demand by 20.9% and 20.4%, respectively, and reduces the energy cost per family by 10.7% and 17.7% (Fathy *et al.,* 2021). A similar % energy-saving contribution of 20.5% was also observed through the optimisation of equipment energy-saving mode (Xiong *et al.,* 2021). The optimisation based on the temperature modulation has also been conducted by developing a three-layered architecture framework (data processing, building classification models, and high-end analysis) using data collection through IoT, simulation and experiments and gathering (Zakharov *et al.,* 2019). Moreover, O'Dwyer *et al.,* (2020) have developed a theoretical modular framework for city applications which uses machine learning techniques for forecast generation and model predictive control systems to manage the energy for maintaining the coordination between numerous sub-systems.

Real-time data analysis and decisions
To create optimal and decentralised choices for household devices, Huang *et al.,* (2023) proposed an hour-ahead demand response algorithm for energy management in homes. It uses a multi-agent reinforcement learning approach and an artificial neural network approach. The findings demonstrate the effectiveness of the suggested algorithm in managing the energy consumption of various devices, lowering customer electricity costs and discomfort levels, and lowering energy costs compared to a benchmark with no demand response. However, Francisco *et al.,* (2020) propose using smart metering data analytics to create daily building energy benchmarks segmented by strategic periods. The findings suggest that temporally segmented energy benchmarks can offer a more precise and detailed measurement of building efficiency, enabling the identification of building retrofit strategies and near-real-time efficiency in the context of an entire building portfolio and supporting the development of digital twin-enabled urban energy management platforms.

b) 5G technology in SEM

5G networks have four major application scenarios in smart energy management. These are control services, collection services, mobile application services and multi-station integration (Deloitte, 2021). In control services, 5G will help in precise load control and differential protection for the distribution network by suitable algorithms that disconnect the switch and isolate the faulty distribution network. For the collection services, 5G will help in real-time electricity consumption data to perform various analyses such as metering anomaly monitoring, consumption analysis and so on (Zeinali *et al.,* 2017). Similarly, mobile application services aim to monitor the safety and environmental data to reduce the manual inspection workload and improve efficiency. The fourth application scenario is multi-station integration aimed at resource sharing, such as a smart grid (Ericsson, 2019, Ahmadzadeh *et al.,* 2021). Among many, two recent examples of 5G applications in SEM are EU's SOGNO initiative and the Smart5Grid project. SOGNO aims to minimise fault detection in real-time and reconfigure the network to minimise the electricity outage due to adverse weather conditions, besides increasing network monitoring through remote optimisation (Ericsson, 2019). Smart5grid is another EU-funded project that aims to support the energy sector evolution with high bandwidth, low latency, high-density network architecture (i.e., 5G network) that can provide digital layers and help use edge computing and cloud-native applications to support high-end processing and real-time monitoring (smart5grid, 2021).

Challenges and Mitigation Strategies

Multiple researchers have laid the foundation for implementing Digital Twin in Smart Energy management and using a 5G network to support this cause. Though the relevant technologies seem to provide an excellent solution to energy optimisation, enhanced operation and maintenance, and real-time data analysis and decision, implementing these technologies to the bottom of the pyramid (user level), multiple roadblocks need to be addressed (Table 1).

Table 1: Current challenges and Mitigation strategies for DT implementation in SEM

Key parameter	Current Challenges	Mitigation Strategies
Network Speed	High bandwidth, low latency network speed is required to support DT based on edge and cloud computing (Ericsson, 2019).	5G promises to provide low latency, high bandwidth network with network slicing options for customised configuration and real-time data processing capabilities.
Scalability	Scaling DT at an urban scale level to handle large number of buildings can be challenging.	Adopting a modular approach in the implementation of DT leveraging cloud-based scalable and flexible solutions and utilising edge computing for distributing the processing load (Castelli *et al.,* 2019).
Cyber-security	High digitalisation needs a secure environment to perform efficiently. Though 5G network can be tailored to various security protection mechanisms, the development in this direction is still nascent (Deloitte, 2021).	Different entities must work together to clarify the boundaries. Such boundaries and their respective security development must develop in parallel. Industry-specific security protocols must be designed for DT and 5G network utilisation as both technologies are new.
Open-source platforms	Proprietary systems, though they perform efficiently in their own environment, the major challenge faced by the AECO industry is the interoperability of these systems. Interoperability hinders performing cross-platform simulations, analyses, and decision-making (Chew *et al.,* 2020).	Government-led initiatives such as SOGNO and SMART5Ggird or others should promote open-source development that can help the industry to develop their own customised, innovative application on top of it and learn from the innovation. Closed systems will be a hinderance to faster adoption of such energy saving technologies.
Infrastructure and workforce development cost.	High digitalisation efforts like DT and using the 5G network have new investment requirements, which is a big challenge to MSMEs (Micro, small and medium enterprises). Additionally, continuous workforce development will be required to catch up with the pace of technological advancement (Ahmadzadeh *et al.,* 2021).	Top to bottom approach is needed to tackle such investment. Singapore has been leading in such an approach whereby government use multiple channels to fund the industry for adopting various new digital technologies such 5G network (5G innovation grant total to 30 million SGD) or their Skills future workforce development programs whereby government give subsidies to companies to enrol their staffs to get upgraded with technical skills. (IMDA,2021)

CONCLUSIONS

To achieve sustainability goals and reduce overall carbon emissions, the use of digital twins for smart energy management is gaining popularity in the last four years. The use of 5G technology, which provides high-speed data transfer, low latency, improved reliability, and the ability to connect a significant number of IoT devices, will push the digitalisation and real-time analytics in SEM and accelerate the implementation of DT. Therefore, this scientometric and thematic review analysed the trend and development, especially in the context. Furthermore, the trials of 5G networks in the SEM domain have shown some complex use cases for SEM being undertaken using IoT, edge and cloud computing to enhance real-time optimisation, maintenance, and remote monitoring. This review used the SCOPUS database as the literature source, resulting in 106 journals, conferences, and review articles. Numerous scholars from different sectors have investigated the use of the digital twin in smart energy management, such as manufacturing, transport, communication, energy storage/distribution/generation/ consumption, operation and maintenance, optimisation and building and urban infrastructure. Three broad themes in the application of DT in SEM, i.e., operation and maintenance, optimisation and real-time data analysis and decision, emerged from this Scientometric analysis. However, broader issues highlighted in the reviewed literature should be resolved to gain wider implementation in the Sem domain. These issues, such as the expense of hardware, software, network speed, cybersecurity, open-source platforms, support funding, and their possible mitigation strategies, are discussed briefly. To fully utilise new technologies and optimise, the construction sector must adopt them more quickly.

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