Engineering Journal
issn: 0125-8281

Review

A Review of Building Information Modeling and Simulation as Virtual Representations Under the Digital Twin Concept

Bunnapub Visartsakul[a] **and Jirawat Damrianant**[b,*]

Department of Civil Engineering, Faculty of Engineering, Thammasat University, Thailand
E-mail: [a]bunnapub.visa@dome.tu.ac.th, [b,*]djirawat@engr.tu.ac.th (Corresponding author)

Abstract. Building Information Modeling (BIM) is a highly promising technique for achieving digitalization in the construction industry, widely used in modern construction projects for digitally representing facilities. Nevertheless, retains limitations in terms of representing construction operations. The digital twin concept may potentially overcome these limitations and initiate advanced digital transformation in the construction industry as it has revolutionized the product lifecycle management in the manufacturing industry. This research provides a critical review of applying digital twin in the construction industry. Altogether, 140 papers from related journals and databases were reviewed. The digital aspect of twinning consists of BIM and simulation modeling. These two techniques have been used to create virtual or digital representations of actual buildings and real-world construction processes. However, integrating and applying BIM and simulation modeling according to the digital twin concept remains to be fully studied. Comprehensive evaluations of BIM, simulation modeling, and digital twin will provide a well-defined framework for this research, to identify direction and potential for digital twin in the construction industry, thereby progressing to the next level of digitalization and improvement in construction management practice.

Keywords: Construction industry digitalization, construction management, Building Information Modeling (BIM), digital twin, simulation.

ENGINEERING JOURNAL Volume 27 Issue 1
Received 3 March 2022
Accepted 24 January 2023
Published 31 January 2023
Online at https://engj.org/
DOI:10.4186/ej.2023.27.1.11

1. Introduction

Over the past decade, Building Information Modeling (BIM) and simulation modeling have been successfully adopted in the academic and industrial construction sectors [1]. Many practical uses and research publications have established the practical usefulness of BIM and simulation [2], [3]. Internationally, these have become basic requirements and alternative approaches for project owners and related governmental organizations [4]. Research and development on BIM and simulation continues to fill gaps by innovating in industry practice [5]. Integrating BIM and simulation modeling contributes to advancing construction management field applications [6]. Whereas BIM extracts data from a building model, simulation applies it as input for analyzing specific purposes [7]. Despite well formulated construction planning and scheduling, construction problems remain inevitable for most projects [8].

One potential concept for overcoming these construction industry challenges is the digital twin, a virtual representation of the physical assets or systems. The concept has already been validated and widely adopted in the manufacturing and automotive industries. Much research raises awareness of the need for applying digital twin to the construction industry [9]. Other studies point to the potential of digital twinning for construction industry innovation solving industry-wide challenges [10].

This research contributes comprehensive reviews of BIM, simulation modeling, and digital twin, indicating the future directions and potential in the construction industry of BIM and simulation as virtual representations following the digital twin concept.

2. Review Approach

A review of simulation modeling, BIM, and digital twining is conducted by integrating thematic, chronological, and theoretical approaches identified in a literature review. The thematic approach was used to structure and organize this research. The developmental background and fundamentals of simulation modeling, BIM, and digital twin were examined by using chronological approach. The theoretical approach was used to establish existing scientific knowledge gaps and identify outstanding research questions, including opportunities for improvement. The goal is to understand the developmental background and fundamentals to analyze digital twin directions and potentials in the construction industry based on literature gaps and room for improvement.

Analyzed literatures were mainly obtained from Scopus and Google Scholar databases, comprehensive citation source containing influential multidisciplinary articles. Article types were limited to journal and conference papers as providing high-quality scholarly data. Defined terms for sourcing literature included simulation, simulation modeling, modeling and simulation, BIM, and digital twinning. Unlike BIM, simulation and digital twin did not originate in the construction industry, so the scope of simulation and digital twin was not limited to the construction industry.

3. Simulation Modeling

3.1. Roles of Process Simulation

Process simulation plays a significant role by imitating the operation of a real-world processes or systems. Applications of simulation comprise mainly system design and analysis, applicable to a wide range of industry sectors, including manufacturing, supply chains, business processes, transportation, healthcare, and construction [11].

Simulation modeling has often been used in the manufacturing sector for manufacturing process control [12], assembly lines design, productivity improvement, resource optimization, inventory management, and supply chain management [13].

Simulation has proven useful in the supply chain sector in several applications; adopted for designing and optimizing supply chain system. It also supports supply chain management by allowing the system to be evaluated and forecasted [14]. Simulation performs accurately to improve systems performance by investigating industrial plant logistics problems, boosting warehouse use efficiency, and reducing operating costs [15].

Simulation-based approaches have been employed for business management purposes in business model and strategy design [16], business process improvement [17], outcome prediction [18], and risk management [19].

Simulation is essential for analyzing system causality, coupling, feedback loops, and chaotic behavior involving transportation problems [20]. It supports decision-makers in making the right choices to resolve some issues [21]. The use of simulation in the transportation sector produces more sustainable transportation systems and diminishes traffic congestion and waiting time [22].

The healthcare sector has used simulation to evaluate system operational performance [23] and generate management guidelines and strategies to optimize the operation [24].

Simulation covers a variety of aspects in the construction sector. One common usage is in planning and scheduling construction activities. Simulation offers level construction resources more advantages than traditional resource-leveling methods. While the conventional method assumes activity durations to be deterministic, simulation allows for uncertain activity duration, providing more realistic results [25]. Simulation is performed as an optimization instrument for time-cost tradeoff analysis, enabling construction schedules and resources to be dynamically adjusted [26]. It also supports managing cost-baseline changes by continuously monitoring and updating the project status [27].

Process simulation has proven its potential and abilities in many of the aforementioned sectors. However, in construction, room remains for improvement in terms of ease of implementation and integration with other areas of knowledge.

3.2. Simulation in Construction

The first effort to adopt simulation to construction was directed by Halpin in 1977, with the introduction of cyclic operations network (CYCLONE) as a modeling and simulation method for construction operations [28]. The initial phase of simulation in construction was successfully executed in academic research with limited industrial implementations [29]. Barriers to industrial execution indicate relative complexity compared to traditional planning methods; limitations in construction implements and methods; time, cost, and skills required to create and simulate models; industrial culture; and lack of confidence in simulation technologies [30].

Over the past decade, with technology playing an essential role in industry, construction simulation has been widely developed as a computer-based analytical solution for operational problems, scheduling construction sequences, and optimizing construction resources [31]. CYCLONE and advances in computer technologies prompted the emergence of a series of simulation research methodologies applied to the construction industry.

At the beginning of the 1990s, object-oriented programming languages, including Java, Python, C++, Ruby, and C#, provided a series of research applications on construction simulation software [32]. Object-oriented programming has become fundamental for developing diverse construction simulation software such as MicroCYCLONE, Disco, COST, STROBOSCOPE-CPM, CIPROS, and COOPS as computer-based analytic instruments.

In the 2000s, when construction projects becoming increasingly complex, AbouRizk et al. [33] introduced Simphony as a simulation modeling tool for simplifying modeling processes. Simphony allows the developer to easily control simulation behaviors, graphical representation, statistics, and animation. It also enables dedicated simulation models to be developed for specific purposes through special purpose simulation. This feature transforms certain on-site construction activities into off-site planning activities, improving productivity and optimizing construction resources [34].

During the past ten years, three-dimensional (3D) visualization systems have played a role in describing simulation processes more intuitively through extensible and scalable functions [35]. They facilitate the use of simulation in the construction industry and permit building more realistic systemic model [36]. Combining 3D visualization systems with process simulation allows construction sequences and work progress to be visualized through 3D models [37]. Consequently, BIM, as a 3D representation of buildings, has proliferated and become involved in the field of construction simulation. Integrating simulation and BIM contributes valuable additional information for construction management purposes [38].

One barrier to adopt industry-wide construction simulation is the complexity of simulation methodologies. However, several research studies have suggested more simplified simulation methods by using discrete-event simulation (DES) [39]. DES plays an essential role in developing uncomplicated simulation methodologies. DES characteristics comply with construction industry nature and culture. Therefore, a variety of simulation approaches have been developed, such as CYCLONE and Petri nets, both widely adopted in several industries, including construction [40].

In 1962, Petri nets were developed by Carl Adam Petri [41] as graphical and mathematical modeling tools to describe information processing systems stochastic, concurrent, asynchronous, distributed, parallel, and non-deterministic. As graphical models, Petri nets help enable visual communication by representing dynamic and simultaneous system activities. As mathematical models, Petri nets permit mathematical analysis to be performed by several equations. Their analysis mechanisms can describe underlying systemic behaviors [42]. Petri nets have been adopted for diverse applications due to their generality, flexibility, adaptability, and extension of functions to suit particular areas.

Petri nets comprise four modeling elements; places, transitions, arcs, and tokens. A place represents the condition of having input resources or a place in which resources are found. A transition represents an event, task, or activity. Arcs are used to connect between places and transitions. They indicate direction and number of tokens flowing in the Petri nets. Tokens are initialized at a place and represent resources, allowing Petri nets to dynamically link between places and transitions [42].

Petri net-based simulations have become fundamental for many developed approaches. Comprehensive studies have introduced extended versions of Petri net-based simulations such as time Petri net [43], deterministically timed Petri net, stochastic timed Petri net, generalized stochastic Petri net, and colored Petri net [44].

A time Petri net was proposed by Hillion [43] to enable traditional Petri nets to allow delays after transitions are enabled, instead of being instantaneous. If transition times are deterministic, they become deterministically timed Petri net. If transition times may be random variables, they are called a stochastic timed Petri net. When they consist of two transitional types, timed and immediate, they are called generalized stochastic Petri net [44].

The original version of Petri nets allowed defining only one type of token (resource), while varied resources are used in construction projects. In this way, Petri nets cannot depict different objects that tokens are used to model. To enable Petri nets to define more than one type of resources, Jensen proposed the idea of identifying tokens by color. These Petri nets are called colored Petri nets, allowing diverse resources to be identified and analyzed [45-48].

Substantial extensions of Petri nets for construction process modeling and simulation were demonstrated by Damrianant [49] with the introduction of the construction-oriented simulation modeling system (COSMOS). A series of extensions were developed in COSMOS in addition to traditional Petri nets, enabling overlapping modeling among activities by using header, follower, pipe, and buffer as extensional elements [50]. Conceptually, situational interruptions during the operational period may also be modeled and simulated by using the modeling elements extensions switch, POI arc, and control arc [51]. COSMOS also allows more efficient resource allocation by using the new elements of alternative arc, alternative place, and multiple-branch arc [52].

Currently, the field is moving towards simulation integration with other areas of knowledge. As a highly promising development in the architecture, engineering and construction (AEC) fields, BIM has been comprehensively studied to invent more effective modeling and simulation in constriction. Extensive research newly integrates BIM with simulation to create advanced applications. Combining 3D models and construction schedule has become commoner industry practice, enabling construction sequences to be visualized and evaluated for constructability [37]. As BIM provides information to simulation models, simulation models evaluate construction performances and transmit valuable data to the BIM process for decision support [7].

One BIM essential capability is to estimate required construction materials. By using such information, simulation modeling can help generate project schedules [53]. Supply chain construction material models were integrated with BIM to prevent construction delays caused by lack of materials [54]. With BIM-based information supports, simulation modeling can evaluate dynamic productivities, improving project procurement schedule [56].

As mentioned above, integration of BIM and simulation modeling applies to both academic and industry practice, but requires a well-structured framework for each particular application area, as shown in Fig. 1.

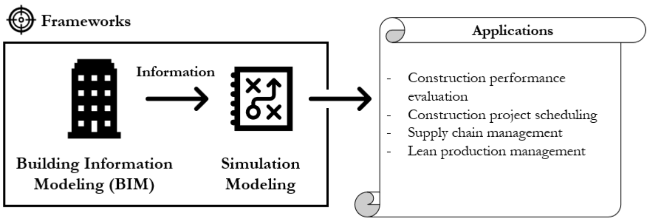

Fig. 1. Integrating of BIM and simulation.

Simulation software is indispensable for analyzing such complex systems in construction projects. For this reason, construction simulation relies heavily on developed software, and it is vital to understand the foundations and mechanisms of construction simulation software.

3.3. Construction Simulation Software

Since computer programming languages were devised, a series of construction simulation software has been developed to solve increasingly complex problems in real-world construction projects [33]. The software has become a computer-based analytical instrument essential for many construction management tasks. It can resolve operational problems, schedule construction operations, and optimize construction time and resources [31]. A series of construction simulation modeling is shown in Fig. 2.

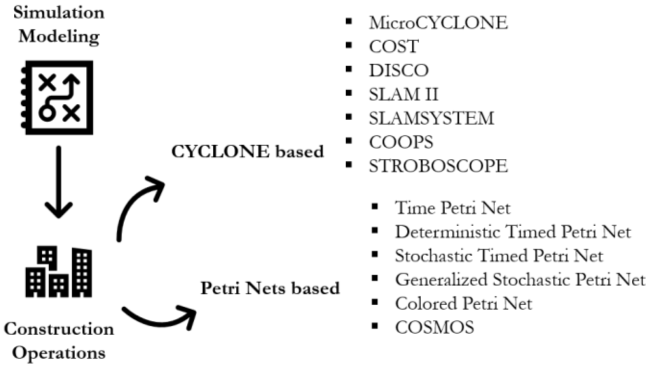

Fig. 2. Series of construction simulation modeling.

Technological advancement offered innovations in simulation software capabilities in flexibility, design improvement, and heightened efficiency [56]. In 1977, Daniel W. Halpin introduced CYCLONE, the first significant effort in construction simulation language [28]. Later, it became a prototype for modern construction simulation software.

MicroCYCLONE was the first construction simulation software developed following the CYCLONE concept, offering flexible adaptive characteristics for construction practice. MicroCYCLONE has been adopted for many uses, such as modeling and simulation repetitive construction processes [57], cost optimization of earthmoving operations [58], and construction process planning and analysis [59].

Object-oriented programming plays a significant role in developing construction simulation software by simplifying coding and improving model readability [60-61]. Together with discrete-event simulation, it generates an automated system for selecting optimal fleet configuration and providing a vehicle for estimating construction time and costs, by considering different practical scenarios [62].

Although MicroCYCLONE notably contributed to promoting CYCLONE, it was a DOS-based program and was not updated since the introduction of Windows-based computer operations systems. To modernize MicroCYCLONE, construction operation simulation tool (COST) was introduced as an improved version of MicroCYCLONE. COST is able to model uncertain events by using a fuzzy data simulation function [63].

Meanwhile, Huang and Halpin [64] introduced an alternative construction simulation approach, dynamic interface simulation for construction operations (DISCO), applying visual simulation to facilitate construction operational planning and analysis activities. The application allows system dynamic behavior to be visualized as the simulation is executed.

Since 1979, in addition to CYCLONE, a simulation language for alternative modeling (SLAM II) was also influential in construction simulation as a general-purpose language. It enables the modeling of different manufacturing, transportation, and communication systems. SLAM II language user facility was significantly increased by the development of SLAMSYSTEM and SLAMSYSTEM Version 4.5 in 1988 and 1994, respectively [65].

Ioannou and Liu [66] introduced a construction object-oriented process simulation system (COOPS), using modeling elements to create interactive onscreen graphical networks. COOPS can simplify complex systems by exploiting graphical networks dedicated to the modeling construction process.

In the 2000s, STROBOSCOPE and Simphony became mainstream simulation approaches in the construction field. STROBOSCOPE was introduced by Martinez and Ioannou [67] as a modeling and simulation language with an open platform for generating models from open-environment source coding. It can model many simulation systems, including CYCLONE. Simphony was introduced by Hajjar and AbouRizk [68] as a platform for creating tailor-made simulation instruments for general applications, including construction.

Basically, the aforementioned simulation systems require profound knowledge and understanding of process modeling and simulation mechanisms. The knowledge required becomes a barrier to adopting industry-wide simulation [69]. In 1999, activity-based construction (ABC) was introduced to simplify such impediments, designed to use a single element, rather than multiple ones, for construction process modeling. In this way, knowledge required is minimized and construction simulation difficulties addressed [70].

Simplification is a key to spreading practical adoption of simulation. Therefore, AbouRizk and Mather [71] introduced a 3D-based simulation approach to further simplify the modeling and simulation process by using 3D-CAD.

Similarly, to minimize required skill, Chua and Li [72] proposed a resource-interacted simulation (RISim) approach, enabling users incompletely informed about simulation technology to generate a simple simulation model by emphasizing model resource and process levels.

Generating efficient construction schedules is challenging, especially in complex construction projects. Therefore, optimization techniques were combined with discrete-event simulation to generate a multi-method optimization package (MOPACK), a computer-based optimization framework. MOPACK enhances construction planning and scheduling processes more optimally [31].

Since 3D visualization systems have become essential to the industry, they have been integrated into simulation to conduct construction sequences and work progress visualization for 3D modeling [37]. To integrate simulation with 3D visualization, Kamat and Martinez [73] introduced VitaScope as a 3D visualization extension for construction simulation, allowing the process model to link with 3D objects to visualize and validate the operation.

While CYCLONE-based modeling and simulations developed over time, Petri net-based systems were also present industrially. Although Petri nets derived from a different industry and application areas, its generality and flexibility allowed for adaptation to the construction industry [42].

Petri nets are graphical and mathematical modeling approaches capable of performing static and dynamic analyses. Damrianant [49] adapted these capabilities for construction process modeling and simulation. COSMOS, a simulation modeling methodology, was developed based on these capabilities. COSMOS is a Petri net-based modeling methodology with several modifications to the original Petri nets. For example, it provides capabilities for modeling overlapping activities [50], interrupting situations during the operational period [51], and efficient resource allocation [48].

A COSMOS simulator was developed as computer software to emphasize the practical execution of COSMOS, allowing for modeling and simulating construction processes created with COSMOS methodology. COSMOS simulator reliability and performance were verified by using coloured Petri nets [74], the Arena simulator [75], and critical path method [76].

Although simulation is essential in the construction industry as a powerful analytical instrument for different application areas, it requires sufficient reliable information, collection of which is challenging in practice and adds further material for examination.

4. Building Information Modeling (BIM)

4.1. Overview of BIM

The concept of BIM was first introduced by Eastman et al. [77] as a building description system (BDS) for storage and manipulation of design information. Later, in 1992, the term BIM was first used by Nederveen and Tolman [78]. The BIM concept is similar to BDS insofar as both use models to store and manipulate information. In addition, BIM promotes cooperation between project stakeholders with multiple perspectives on building project data. As an integration platform containing specific data on each participant, BIM has become a highly influential industrial innovator.

In 2003, Autodesk, a leading software company, published a white paper to demonstrate its software developed following the BIM concept. It initiated BIM software development and disseminated a substantial series of BIM software with wide-ranging functionality [79].

However, changing traditional industry practice was challenging. A key driver was computer-aided design (CAD), a software to aid design processes. CAD played a crucial role in expediting this transformation, especially in changing from 2D-based to 3D-based information, with labor-intensive drafts evolving into more efficient documentation [80].

BIM is a virtual model of a facility containing comprehensive data on physical and functional characteristics [81]. In addition to being a traditional 3D model, it stores and manipulates information, distinctly helping to express semantics. This means that all its objects possess functional characteristics as well as the physical characteristics expected from 3D geometric representation [82].

Over the past two decades, BIM has proven its ability in several academic and industrial application areas. It facilitates knowledge resources sharing and promotes collaboration among different stakeholders through the project lifecycle [83].

BIM adds significant advantages to the design and engineering process in the pre-construction phase. As a physical representation, it can conduct digital visualizations to conceptualize and eliminate conflicts between different parties. Through functional representation, it complies comprehensive useful data for building design and project development activities, including structural design, cost estimation, and construction planning [84]. It also allows automatically mutually consistent technical drawings to be sourced directly from models, saving documentation time and avoiding errors [85]. Azhar et al. [86] developed BIM-based sustainability analyses for sustainable building design to achieve leadership in energy and environmental design (LEED) certification, a sustainable building rating system. The developed system streamlines the certification process and saves substantial time and resources.

However, difficulties remain. Arrotéia et al. [87] indicated that principal obstacles with BIM execution during the development phase pertain more to managerial problems than BIM itself. They also noted that design professionals and construction stakeholders should collaborate closely during this phase to improve project results in terms of constructability, cost optimization, and time management.

During the construction phase, BIM assists construction management in many aspects. Through physical representation as a 3D model, it enables buildings to be visualized, adding to construction team understanding of building sequences [84]. BIM supports monitoring and controlling construction activities, especially in complex architectural projects. It facilitates resource planning and sequencing alternatives for complex building construction systems [88]. Jiang [89] applied BIM in the construction phase of a large-scale construction project to reduce waste and ensure progress and quality. His findings indicate that BIM aided construction management and promoted project sustainable development through waste reduction. Jian et al. [90] emphasized improved construction productivity by executing five large-scale public projects. Handayani et al. [91] developed a BIM-based system used during the construction phase for analyzing the impacts from altering orders. The system assists users to observe and visualize the effect of change orders through 3D BIM models, in addition to evaluating impacts on project costs and scheduling.

During the post-construction phase, BIM can be used for asset management as a digital representation of buildings. It allows changes in tangible facilities to be recorded and updated in its digital model [84]. Using this capability, BIM has been adapted to several specific cases. A common usage for BIM is to support operational; maintenance; and repair and replacement decision-making for facilities [87]. BIM accelerates buildings management and operation while providing more accurate and richer data [92]. In consonance with construction professionals and academic research results, BIM diversely benefited cost control and environmental issues throughout project lifecycles [91]. BIM applications are concluded in Table 1.

Table 1. Overview of BIM main applications.

Stages	Main Applications
Pre-construction	- Building and engineering designs - Collaborations - Budgeting and planning - Drawings and documentations - Visualization and constructability
Construction	- Construction management - Quality and safety management - Construction sequence review
Post-construction	- Asset management - Operation and maintenance - Energy performance

As mentioned above, BIM clearly enhances industrial projects. Concomitant difficulties in adopting BIM are due to users and the industry itself. However, BIM retains potential for developing and expanding its application areas.

4.2. BIM Developments and Applications

BIM has innovated and new offered new visions to the architectural, engineering, and construction (AEC) industry [94]. It has revolutionized conventional AEC processes into more efficient workflow and ameliorated collaboration between project stakeholders [79].

In the initial BIM phase, before standards and guidelines have established, several barriers and challenges existed to BIM adoption in industry practice; these include interoperability issues and process-related contractual and organizational obstacles [95]. To resolve these problems, BIM standards and protocols were published and promoted by the government and its subsidiary authorities to encourage practical adoption of BIM [82].

Over the past decade, BIM has played an essential role and was widely adopted to improve efficiency of the integrated design and construction process. In 2003, Lee et al. [96] introduced nD Modeling (also known as nD CAD) as an extension of BIM by integrating data from entire building lifecycle stages. While the 3D model represents the object's geometric dimensions, integrating time sequencing into the 3D model is referred to as the 4D model. It enables a sequence of events to be depicted visually on a timeline populated by a 3D model [97]. The 4D model can also demonstrate building construction processes before actual construction activities occur [98].

In addition, cost-related information was added to the 4D model, making it into what is termed a 5D model, which allows construction progress and related costs over time to be visualized. Awareness of potential additional costs promotes project management and enables visualizing running construction progress-related costs [99].

BIM-based frameworks have continuously developed for several purposes, to expand and improve functionalities to cope with increasing industrial complexity. Jeong et al. [6] developed a BIM-based framework to forecast productivity dynamics for erecting a steel structure at the planning stage. The framework was claimed to be efficient in terms of realistic productivity prediction, schedule reliability, resource allocation, cost optimization, and material waste minimization.

Handayani et al. [91] developed a BIM-based system for evaluating cost, time, and physical condition impact from changing orders during the construction phase. The system was applied to a real-life 18-story building project to demonstrate its efficacy and practicality. It successfully assessed and reported on all three categories of impacts from altering orders and mitigated conflicts between the project owner and contractor relating to construction claims following the orders.

Song et al. [100] introduced a system developed according to the BIM concept, enabling comparison of different construction schedules to determine optimal construction schedules in terms of time and cost for large-scale projects.

Kim et al. [101] proposed a framework for evaluating construction activities required, estimating activity tasks, and sequencing construction activities. As a result, the proposed framework can automatically generate construction schedules by using relevant data stored in the BIM model.

Liu et al. [5] developed a BIM-based scheduling approach using simulation modeling techniques and optimization algorithms. Using constantly updated resources, the approach facilitates of construction scheduling generation and optimization.

To simplify the development sequence, BIM-based frameworks scheme is shown in Fig. 3.

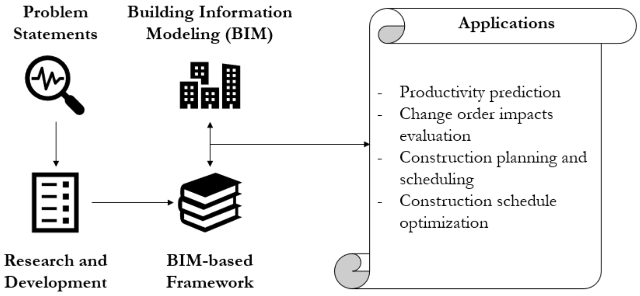

Fig. 3. Basic BIM-base frameworks scheme.

Many studies have attempted to develop BIM-based frameworks according to increasing industrial competition and complexity. These developments contribute to industrial advancement of BIM applications. However, practicality is another vital factor that must be considered along with advancement of the applications.

5. Digital Twin

5.1. Overview of Digital Twin

In 2002, digital twin was first introduced by Michael Grieves as a virtual representation of a physical asset or system in the product lifecycle management domain [102]. At that time, digital twin was used to describe properties, conditions, and behavior of represented physical assets by which modeling and simulation were performed. Grieves describes digital twin as consisting of three components: a physical object, a virtual representation of that object, and the connection linking the two components.

Grieves later introduced a taxonomy of digital twin, namely digital twin prototype, digital twin instance, digital twin aggregate, and digital twin environment [103]. As he explained, digital twin prototype virtually describes a prototype entity containing all data necessary for developing a physical twin. It is an initial form of digital twin during the design phase. A digital twin instance is a specific instance of a physical product that remains linked to an individual product throughout that product's lifespan. It contains data about that asset and the asset's history, captured from sensors, tests, and inspections. A digital twin aggregate is an aggregate collection that can access all digital twin instances. A digital twin environment is a virtual representation of the physical product's environment, covering all digital twin taxonomies as mentioned and interconnecting all relevant aspects.

Digital twin is categorized based on level of integration between a physical object and a virtual representation of that object. Three levels of integration evaluate how the data and object interact: digital model, digital shadow, and digital twin [104].

A digital model is described as a virtual representation of an existing or planned physical entity. For this level of integration, data exchange between a physical object and virtual object is not automatic. If data exchange from the physical object to the virtual object becomes automated, such integration might be referred to as a digital shadow. At this level of integration, if any change occurred in the physical object's state, the virtual object's state is likewise be altered automatically. If data exchange between the physical and virtual objects becomes automated, such integration might be termed digital twin. As the highest level of integration, digital twin allows objects to act as controlling instances for physical objects. Therefore, a change in the physical object's state leads directly to a change in the virtual object's state and vice versa. Simplified configurations for digital model, digital shadow, and digital twin are illustrated in Fig. 4.

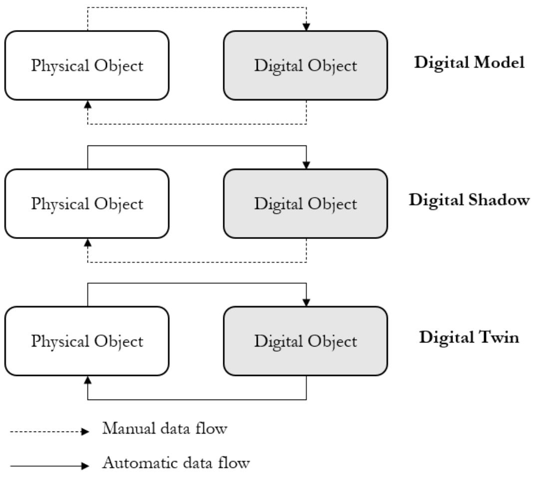

Fig. 4. Digital twin integration level [104].

The interest in digital twin has significantly increased academically and industrially, as seen by the growth of many related publications [105]. Apart from product lifecycle management, manufacturing system optimization is another favored research area. For instance, Schluse et al. [106] applied a digital twin-based approach to optimize systematic parameters and structures for various areas of applications. Zhang et al. [107] developed a digital twin framework for equipment energy consumption management in a manufacturing system. Hu et al. [108] directed a new method for building a cloud-based digital twin which can be adapted to cyber-physical cloud manufacturing. This smart manufacturing concept helps reduce overhead costs and saves resources. While digital twin plays a significant role in digitalizing the manufacturing industry, it has also been adapted to other industries with a wide range of applications.

5.2. Digital Twin Applications

Digitalization is a key driver encouraging industries to adopt the digital twin concept academically and practically. Digital twin applications are reported to contribute to innovating, optimizing, and streamlining products and processes [109]. Many research studies have demonstrated practical implementations of digital twin in diverse applications, while highlighting perceived and potential benefits of the digital twin concept.

Cost reduction is one such essential advantages [102] integrated with the cloud system to successfully reduce overhead costs, and conserve manufacturing industry resources [108]. Its digital representation capacity allows digital twinning to eliminate expenses incurred by physical simulation and diagnosis. It also provides better systematic understanding [110]. Apart from cost reduction, since physical models can be replaced by digital entities, risk assessment and mitigation may be performed digitally in a risk-free environment [111].

Following the digital twin concept, advanced technologies such as the Internet of Things (IoT), wireless technology, and sensors, are used to connect physical with digital objects. Consequently, digital twin promotes operational changes and highlighted efficiency [114-115]. In addition to physical entities, digital twin can also represent the network systems, allowing any kind of experiment to be performed with highly developed security [115]. The reliability of digital twin has been confirmed by many leading enterprises [116-117], with verified outcomes of digital twin execution supporting decision-making in several aspects [118-121].

The publication of extensive studies in multiple areas has increased many digital twin-related definitions, with a variety leading to confusion among practitioners and ineffective execution. Van Der Horn and Mahadevan [122] described digital twin generalization and characterization by comparing it contextually with digital and simulation models. From this perspective, digital twin updates its systematic twin status over time and corresponds to physical twin in addition to traditional digital modeling.

However, the simulation model resembles digital twin insofar as both are used to predict future states of a modelled system. The simulation model predicts by using a set of initial assumptions [123], but digital twin employs actual experienced states. In this way, the digital twin concept can provide more accurate output compared to typical simulation models.

Multi-industrial applications of digital twin await comprehensive study, since each industry offer its own unique characteristics. This is especially true of the construction industry, where external factors play an essential role and uncertainties abound.

5.3. Digital Twin Applications in Construction Projects

Since 2018, the number of academic publications on digital twin in the construction industry has increased. The consensus is that digital twin can digitalize and resolve several industrial challenges [10].

In the design and engineering phase, research mainly centered around BIM. By connecting physical and digital model, BIM somewhat resembles digital twinning, helping construction projects reduce the overall design process, minimizing additional costs and optimizing construction resources [124]. As a collaborative platform, BIM allows information to be shared and adjusted among project stakeholders. Through these capacities, BIM promotes collaboration and facilitates the project domain management [125]. Although BIM and digital twin share some similarities, they remain different in facility life purpose, technology, users, and stages. Specifically, BIM works with static information, while digital twin uses with real-time information [126].

Xu et al. [127] integrated digital twin with a deep transfer learning approach to diagnose failure during the design phase of a car body-side production system. The integration allows fault diagnosis to be performed using real-time information, which is more realistic in dynamic processes. In addition, digital twin has been adopted to improve building energy performance. Lydon et al. [128] introduced structural modeling methodology using the digital twin concept to optimize thermal design of heating and cooling systems. The research implications indicate the potential of digital twin for design phase digital fabrication.

In a construction project, the construction phase may be viewed as parallel to the manufacturing phase in the manufacturing industry. For this sector, digital twin has been dedicated to construction management purposes, streamlining time, cost and quality outcomes. Angjeliu et al. [129] applied the digital twin concept to study structural system integrity in historic masonry buildings by developing a digital twin model of a building. The model helped users understand structural behaviors at different construction stages, verifying that the structure could handle designed forces applied to the building. Gerhard et al. [130] applied the digital twin concept for producing pre-cast concrete segments. The proposed method linked real-time products, processes, and systemic networking from the physical system to its twin. This interactive model reformed the prefabrication process and significantly minimized production errors [131].

In the operation and maintenance phase, the digital twin concept plays a role in asset management by improving operational efficiency, optimizing operation and maintenance costs, and supporting decision-making [126]. To demonstrate this concept practically, Kaewunruen and Lian [132] developed a digital twin of a railway turnout system by using BIM integrated field data information to improve maintenance efficiency. The system was designed to change the mutual respective directions of trains, an essentially complex design and construction challenge. The approach as developed delivered key benefits through information sharing, efficient communication, improved design quality, and design errors reduction. Lu et al. [133] indicated that BIM could not contribute to satisfactory asset management in the operation and maintenance phase, especially in terms of information richness and analytical capability. Consequently, an intelligent asset management framework was proposed by integrating BIM with the digital twin concept. The framework aimed to create dynamic digital models allowing physical building status to be known and updated over time by artificial intelligence, machine learning, and data analytics. Digital twin applications are concluded in Table 2.

Table 2. Overview of digital twin applications.

Stages	Main Applications
Pre-construction	- Design optimization - Collaboration platform - Preventive design
Construction	- Construction management - Real-time monitoring - Risk management
Post-construction	- Asset management - Predictive maintenance - supports decision-making

Digital twin has verified its functionality through several construction industry applications. Nevertheless, room for improvement remains, especially in the construction phase. Previous literature applied BIM as a real-time representation of a building with the real-time data. Further comprehensive study is required, especially on development direction and potential applications.

6. Directions and Potentials of Digital Twin in the Construction Industry

6.1. Interrelationships between Simulation, BIM, and Digital Twin

One similarity between simulation modeling, BIM, and digital twin is the concept of virtual representation of physical entities or systems. They also share common objectives such as productivity optimization, enhancing process visibility, and effective collaboration. However, areas of application for BIM and simulation modeling are limited compared to digital twin. BIM and simulation modeling represent physical entities and real-world systems respectively, and both apply static data for analysis. By contrast, digital twin represents both physical entities and systems in real time (see Table 3). This gives the digital twin concept potential for innovating in the construction industry and a respected place in construction management practice [10].

Digital twin can be exemplified in the construction industry context by virtual design and construction (VDC) [134], or using BIM and other relevant data to digitally design all aspects of a construction project. Digital twin offers a similar concept in terms of designing an entire project before the construction phase.

Table 3. Comparing BIM, simulation, and digital twin.

Approaches	Representations	Operations
BIM	Physical entities	No real-time synchronization
Simulation	Real-world systems	No real-time synchronization
Digital Twin	Physical entities and real world systems	Real-time operational response

Following the VDC concept, construction project components may be categorized into three manageable aspects: product, process, and organization (the POP model). Product represents the building to be constructed; organization refers to groups performing the design and construction; and process alludes to activities and milestones that the organization adheres to.

Digital twin can also be illuminated by BIM since both are highly related in research terms [135]. While BIM represents a virtual model of a facility, digital twin displays the entire system of a construction project. Therefore, in the digital twin for construction project (DTCP) model, the construction process model is part of the system, in addition to the building. Simulation modeling can play a role in this aspect [136] by representing a virtual construction model throughout the project lifecycle.

Integrating BIM and simulation modeling promotes adoption of digital twin in the construction industry. It brings out the next level of industry practice by providing BIM and simulation the ability to utilize real-time data instead of the static information. While BIM takes place in a virtual representation of a facility, simulation modeling represents the construction process as illustrated in Fig. 5.

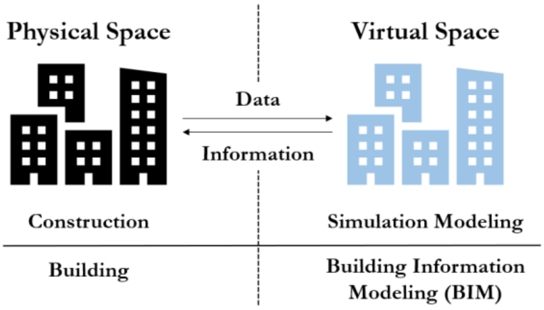

Fig. 5. Digital twin concept in the construction industry.

6.2. Directions of Digital Twin Executions in Construction

Cost is a key consideration for digital twin executions in construction projects, insofar as digital twin requires higher initial costs when applied to projects, mainly due to advanced technological applications for tracking and feeding real-time information [137]. Digital twin execution reportedly contributes significant benefits in return [138]. Nevertheless, a higher initial cost is required for projects.

Optimizing digital twin execution cost will significantly boost its adoption in industry practice. For this purpose, the scope and purpose of digital twin executions much be clarified and explicated. From a technical and economic viewpoint, at first it may appear challenging to adopt completely automated digital twin in the construction industry [139]. To avoid these difficulties, gradational implementation should be considered. As described earlier, BIM and simulation modeling are well-established candidates as instrumentation and techniques for developing DTCP. Representing construction project products and processes, DTCP is manageable and connected to physical entities, as shown in Fig. 6.

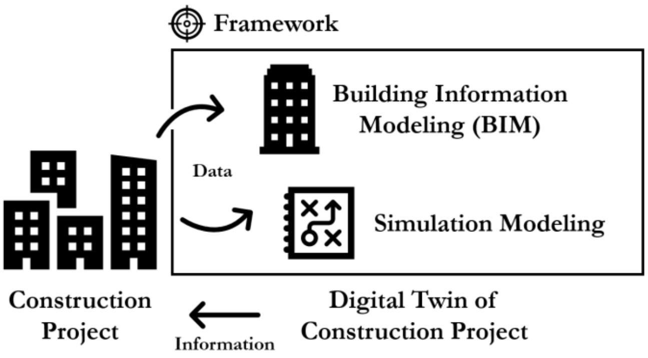

Fig. 6 Scheme of a construction project digital twin.

In this sense, DTCP consists of three components: BIM, simulation modeling, and framework. The framework should be designed to indicate how BIM and simulation modeling may cooperate to achieve a specific purpose and satisfactory result.

6.3. Potentials of Digital Twin in the Construction Industry

The construction industry is listed as being among the least digitalized industries, particularly in adoption of digital technology [140]. Therefore, the digital twin concept has potential to innovate and digitalize the industry, as other industries have verified it, akin to the way BIM was adopted [1].

In the design and engineering phase, BIM and simulation modeling integration creates DTCP. In this phase, DTCP is concurrently developed in the virtual building and construction process model. As BIM participates in building design, it provides required data to the construction process model to determine construction scheduling optimization and constructability. With well-structured frameworks, DTCP is a promising concept for bringing a wide range of potential applications.

In the construction phase, the designed DTCP is involved in construction management. During the construction, the building and its construction model are simultaneously updated according to the actual progress of the project under construction. Then, based on its progress, actual construction performance is analyzed as part of deviation investigation compared to baseline milestones. In case any deviation, DTCP can weigh corrective and preventive action by using its capacity for simulation modeling. Also, if any orders change, the model can handle them by using the same logic. However, real-time construction projects tracking and monitoring are challenging, requiring further study [131].

In the operation and maintenance phase, DTCP becomes a digital asset for facility management. It can support decision-making for operations, maintenances, repair, and replacement of the existing facilities [88]. Supplementary to BIM capabilities, the digital model will become dynamic, enabling the status of physical buildings to be known and updated over time [133].

Although the digital twin concept appears to be a promising innovation diversely benefits the industry, comprehensive research investigating its further potential and practical guidelines remains wanting.

7. Conclusions and Future Research

This research contributes to the body of knowledge by presenting a review of simulation modeling, BIM, and digital twin from fundamental and domain application perspectives. The goal was to shed light on current limitations and prominent areas for future research and development, knowledge gaps, significant issues and challenges, developmental directions and potential applications for BIM and simulation following the digital twin concept.

Knowledge gaps – Previous research attempted to apply the digital twin concept to the construction industry by integrating BIM with real-time information through IoT and sensors. However, BIM can represent only the product part of construction projects as physical facilities. Whereas during the construction phase, construction operation processes cannot be represented following a BIM-based digital twin concept. Despite the fact that simulation modeling is appropriate for representing the construction operation process, practical guidelines and frameworks for integrating BIM and simulation remain to be fully studied.

Significant issues and challenges – Problems in implementing the digital twin concept in the construction industry include: lack of practical guidelines and frameworks; higher initial cost than general industry practice; absence of data integration and management standards; and lack of one-size-fits-all software. Further challenges comprise: inability to adopt technological advancements, unlike the manufacturing and automotive industries; integrating real-time data from construction sites; and entry barriers to embracing new technologies practically.

Directions – Developmental directions of digital twin in the construction industry are based on current limitations and prominent areas for development. BIM alone cannot represent entire construction projects, including facilities and construction. Simulation modeling is a promising approach for overcoming these limitations as an integral part of using digital twin in construction projects. Practical guidelines and frameworks are essential for initiating practical implementation, with features and applications requiring further study. Potential features might include generating optimal construction schedules; analyzing construction progress status; and evaluating corrective and preventive plans.

Potentials – Digital twin has contributed digital transformation and confirmed their potential in the manufacturing and automotive industries. Disrupting product lifecycle management, digital twinning duplicates an entire system in a virtual space, providing promising features such as optimizing production processes, anticipating potential problems, and lowering operational and maintenance costs. In the construction industry, digital twin has the potential to contribute similar features throughout construction project lifecycles by optimizing building design and constructability, facilitating construction management, and supporting decision-making.

Future research – Future research directions related to the digital twin concept in the construction industry are based on knowledge gaps and the aforementioned digital twin-related significant issues and challenges. BIM must be integrated with simulation to overcome limitations of each approach, following the digital twin concept. Potential future research directions include: BIM and simulation modeling integration practical guidelines and frameworks following the digital twin concept; potential features and applications; industrial standards for information integration and management; and BIM and simulation system architecture modeling integration software.

References

[1] H. Begic and M. Galic, "A systematic review of construction 4.0 in the context of the BIM 4.0 premise," *Buildings*, vol. 11, no. 8, 2021.

[2] J. Li, Y. Wang, X. Wang, H. Luo, S. Kang, J. Wang, J. Guo, and Y. Jiao, "Benefits of building information modelling in the project lifecycle:

Construction projects in Asia," *International Journal of Advanced Robotic Systems*, vol. 11, no. 1, 2014.

[3] R. P. Nithin, S. Gopikrishnan, and A. Sumesh, "A case study on simulation and design optimization to improve productivity in cooling tower manufacturing industry," in *IOP Conference Series: Materials Science and Engineering*, Bengaluru, India, 2018.

[4] C. P. Jack and Q. L. Qiqi, "A review of the efforts and roles of the public sector for BIM adoption worldwide," *Journal of Information Technology in Construction*, vol. 20, pp. 442-478, 2015.

[5] H. Liu, M. Al-Hussein, and M. Lu, "BIM-based integrated approach for detailed construction scheduling under resource constraints," *Automation in Construction*, vol. 53, pp. 29-43, 2015.

[6] W. Jeong, S. Chang, J. Son, and J. Yi, "BIM-integrated construction operation simulation for just-in-time production management," *Sustainability*, vol. 8, no. 12, 2016.

[7] C. Wu, R. Jiang, and X. Li, "Integration of BIM and computer simulations in modular construction, a case study," in *Proceedings of the 2016 MOC Summit*, Canada, 2016.

[8] A. Arantes, P. F. Silva, and D. F. Ferreira, "Delays in construction projects—Causes and impacts," in *Proceedings of the 6th IESM Conference*, Seville, Spain, 2015.

[9] D. Opoku, S. Perera, R. Osei-Kyei, and M. Rashidi, "Digital twin application in the construction industry: A literature review," *Journal of Building Engineering*, vol. 40, no. 3, 2021.

[10] C. Bojea, A. Guerrieroa, S. Kubickia, and Y. Rezguib, "Towards a semantic construction digital twin: Directions for future research," *Automation in Construction*, vol. 114, p. 103179, 2020.

[11] J. Banks, "Principles of simulation," in *Handbook of Simulation Principles, Methodology, Advances, Applications, and Practice*. New York: John Wiley & Sons, 1998, ch. 1, pp. 13-15.

[12] P. Grznár, M. Gregor, M. Krajˇcoviˇc, Š. Mozol, M. Schickerle, V. Vavrík, L. D. urica, M. Marschall, and T. Bielik, "Modeling and simulation of processes in a factory of the future," *Applied Sciences*, vol. 10, no. 13, 2020.

[13] O. Benedettini and B. Tjahjono, "Towards an improved tool to facilitate simulation modelling of complex manufacturing systems," *The International Journal of Advanced Manufacturing Technology*, vol. 43, pp. 191-199, 2008.

[14] X. Zheng, H. Yu, and A. Atkins, "An overview of simulation in supply chains," in *Advanced Design and Manufacture to Gain a Competitive Edge*. London, UK: Springer London, 2008, pp. 407-416.

[15] J. G. Macro and R. E. Salmi, "A simulation tool to determine warehouse efficiencies and storage allocations," in *Proceedings of the 2002 Winter Simulation Conference*, San Diego, CA, USA, 2002.

[16] A. J. Bock, M. Warglien, and G. George, "A simulation-based approach to business model design and organizational change," *Innovation: Organization & Management*, vol. 23, no. 1, pp. 7–43, 2021.

[17] K. Mehdouani, N. Missaoui, and S. A Ghannouchi, "An approach for business process improvement based on simulation technique," *Procedia Computer Science*, vol. 164, pp. 225-232, 2019.

[18] D. A. Levinthal and L. Marengo, "Simulation modelling and business strategy research," in *The Palgrave Encyclopedia of Strategic Management*. London, UK: Palgrave Macmillan, 2016.

[19] Z. Tsiga, M. Emes, and A. Smith, "Implementation of a risk management simulation tool," *Procedia Computer Science*, vol. 121, pp. 218-223, 2017.

[20] G. Papageorgiou and D. Charalalambous, "A review of modelling and simulation methods for transportation planning," in *Proceedings of International Trade and Freight Transportation Conference (ITFTC)*, Ayia Napa, Cyprus, 2008.

[21] M. E. Akpınar, S. A. Yıldızel, Y. Karabulut, and E. Dogan, "Simulation optimization for transportation system: A real case application," *TEM Journal*, vol. 6, no. 1, pp. 97-102, 2017.

[22] R. D. L Torre, C. G. Corlu, J. Faulin, B. S. Onggo, and A. A. Juan, "Simulation, optimization, and machine learning in sustainable transportation systems: models and applications, *Sustainability*, vol. 13, no. 3, 2021.

[23] B. Berg, B. Denton, H. Nelson, H. Balasubramanian, A. Rahman, A. Bailey, and K. Lindor, "A discrete event simulation model to evaluate operational performance of a colonoscopy suite," *Medical Decision Making*, vol. 30, no. 3, 2010.

[24] E. Cabrera, M. Taboada, M. L. Iglesias, F. Epelde, and E. Luque, "Optimization of healthcare emergency departments by agent-based simulation," *Procedia Computer Science*, vol. 4, no. 4, pp. 1880-1889, 2011.

[25] S. S. Leu and T. H. Hung, "An optimal construction resource levelling scheduling simulation model," *Canadian Journal of Civil Engineering*, vol. 2, pp. 267-275, 2002.

[26] R. A. T. Pena, "Project management: A simulation-based optimization method for dynamic time-cost tradeoff decisions," M.S. thesis, Department of Industrial and Systems Engineering, Rochester Institute of Technology, New York, 2009.

[27] Project Management Institute, *A Guide to The Project Management Body of Knowledge*, 5th ed. Pennsylvania: Project Management Institute, 2013.

[28] D. W. Halpin, "CYCLONE: Method for modeling of job site processes," *Journal of the Construction Division*, vol. 103, no. 3, pp. 489-499, 1997.

[29] S. M. AbouRizk, J. Shi, B. McCabe, and D. Hajjar, "Automating the process of building simulation models," in *Proceedings of the 1995 Winter Simulation Conference*, New Jersey, USA, 1995.

[30] G. Lucko, P. C. Benjamin, and M. G. Madden, "Harnessing the power of simulation in the project management / decision support aspects of the construction industry," in *Proceedings of the 2008 Winter Simulation Conference*, New Jersey, USA, 2008.

[31] K. Szczesny, M. Hamm, and M. König, "Adjusted recombination operator for simulation-based construction schedule optimization, in *Proceedings of the 2012 Winter Simulation Conference*, Berlin, Germany, 2012.

[32] J. A. Joines, K. A. Powell, and S. D. Roberts, "Building object-oriented simulations with C++," in *Proceedings of the 1993 Winter Simulation Conference*, Los Angeles, CA, USA, 1993.

[33] S. M. AbouRizk and Y. Mohamed, "Symphony: An integrated environment for construction simulation," in *Proceedings of the 2000 Winter Simulation Conference*, Orlando, FL, USA, 2000, pp. 1907-1914.

[34] H. Liu, M. S. Altaf, Z. Lei, M. Lu, and M. A Hussein, "Automated production planning in panelized construction enabled by integrating discrete-event simulation and BIM," in *Proceedings of ICSC15: The Canadian Society for Civil Engineering 5th International/11th Construction Specialty Conference*, Vancouver, Canada, 2015.

[35] V. Kamat and J. Martinez, "Software mechanisms for extensible and scalable 3D visualization of construction operations," *Journal of Advances in Engineering Software*, vol. 39, no. 8, 2008.

[36] V. R. Kamat and J. C. Martinez, "Visualizing simulated construction operations in 3D," *Journal of Computing in Civil Engineering*, vol. 15, no. 4, 2001.

[37] M. Fischer, J. Haymaker, and K. Liston, "Benefits of 3D and 4D models for facility managers and AEC service providers," in *4D CAD and Visualization in Construction*, 1st ed. London, UK: CRC Press, 2003.

[38] W. Lu and T. Olofsson, "Building information modeling and discrete event simulation: Towards an integrated framework," *Automation in Construction*, vol. 44, pp. 73-83, 2014.

[39] E. Forcael, M. González, J. S. Muñoz, F. Ramis, and C. Rodriguez, "Simplified scheduling of a building construction process using discrete event simulation," in *Proceedings of the 16th LACCEI International Multi-Conference for Engineering, Education, and Technology: "Innovation in Education and Inclusion,"* Lima, Peru, 2018.

[40] Z. Chen and B. Shan, "The application of petri nets to construction project management," *Advances in Intelligent and Soft Computing*, vol. 137, pp. 151-158, 2012.

[41] T. Murata, "Petri nets: Properties, analysis, and applications," in *Proceedings of the IEEE*, vol. 77, no. 4, pp. 541-580, 1989.

[42] C. A. Petri, "Kommunikation mit automaten (Communication with Automata)," Ph.D. Thesis, University of Bonn, 1962.

[43] H. P. Hillion, "Timed petri nets and applications to multi-stage production systems," in *Advances in Petri Nets 1989*, Springer, 1989.

[44] M. A. Marsan, "Stochastic Petri nets: An elementary introduction," in *Advances in Petri Nets 1989*, Springer, 1989.

[45] K. Jensen, "Colored Petri nets," in *Petri Nets: Central Models and Their Properties*, Springer, 1986, pp. 248-299.

[46] K. Jensen, "Colored Petri nets: A high level language for system design and analysis," *DAIMI Report Series*, vol. 19, no. 338, 1993.

[47] K. Jensen, "Colored Petri nets: Basic concepts, analysis methods and practical use," in *EATCS Monographs in Theoretical Computer Science*, vol. 1, Springer, 1992.

[48] K. Jensen, "Colored Petri nets: Basic concepts, analysis methods and practical use," in *EATCS Monographs in Theoretical Computer Science*, vol. 2, Springer, 1994.

[49] J. Damrianant, "COSMOS: A discrete-event methodology for construction processes," *International Journal of Internet and Enterprise Management*, vol. 1, no. 2, pp. 128-152, 2003.

[50] J. Damrianant and R. R. Wakefield, "A Petri nets based methodology for modeling of overlapping activity processes," in *Proceedings of the Second International Conference on Construction Process Re-engineering (CPR-99)*, Sydney, Australia, 1999, pp. 375-386.

[51] J. Damrianant and R. R. Wakefield, "An alternative approach for modeling of interference in discrete-event systems," *Civil Engineering and Environmental Systems*, vol. 17, pp. 213-235, 2000.

[52] J. Damrianant and R. R. Wakefield, "An alternative approach for construction process modeling," in *Proceedings of the 8th ISPE International Conference on Concurrent Engineering: Research and Applications (CE2001)*, Anaheim, California, 2001, pp. 722-727.

[53] W. Wang, S. Weng, S. Wang, and C. Chen, "Integrating building information models with construction process simulations for project scheduling support," *Automation in Construction*, vol. 37, pp. 68-80, 2014.

[54] M. Maghrebi, T. Waller, and C. Sammut, "Integrated building information modeling (BIM) with supply chain and feed-forward control," *YBL Journal of Built Environment*, vol. 1, no. 2, 2013.

[55] S. Chang, J. Son, W. Jeong and J. Yi, "BIM-integrated simulation of construction operations for lean production management," in *Proceedings of Modular and Offsite Construction (MOC) Summit*, Edmonton, Alberta, Canada, 2015.

[56] C. A. Murphy and T. Perera, "Role of simulation in industries: The definition and potential role of simulation within an aerospace company," in *Proceedings of the 2001 Winter Simulation Conference*, Arlington, VA, USA, 2001.

[57] S. M. AbouRizk and D. W. Halpin, "Probabilistic simulation studies for repetitive construction process," *Journal of Construction Engineering and Management*, vol. 116, no. 4, pp. 575-594, 1990.

[58] L. E. Bernold and D. W. Halpin, "Microcomputer cost optimization of earth moving operation," in *Proceedings of International symposium on organization and management of construction*, Waterloo, Canada, 1984.

[59] D. W. Halpin and L. S. Riggs, *Planning and Analysis of Construction Operations*, New York, NY: Wiley, 1992,

[60] A. A. Oloufa, "Modeling operational activities in object-oriented simulation," *Journal of Computing in Civil Engineering*, vol. 7, no. 1, pp. 94-106, 1993.

[61] J. Shewchuk and T. Chang, "An approach to object-oriented discrete-event simulation of manufacturing systems," in *Proceedings of the 23rd Winter Simulation Conference*, Phoenix, Arizona, 1991, pp. 302-311.

[62] M. Marzouk and O. Moselhi, "Object-oriented simulation model for earthmoving operations, *Journal of Construction Engineering and Management*, vol. 129, no. 2, pp. 173-181, 2003.

[63] T. Cheng, S. Wu, and Y. Tseng, "Construction operation simulation tool – cost," in *Proceedings of the 17th International Symposium on Automation and Robotics in Construction*, Taipei, Taiwan, 2000.

[64] R. Huang and D. W. Halpin, "Dynamic Interface Simulation for Construction Operations (DISCO)," in *Automation and robotics in construction X: Proceedings of the 10th ISARC*, Elsevier, 1993, pp. 503-510.

[65] J. J. O'Reilly, "Introduction to SLAM II and SLAMSYSTEM," in *Proceedings of the 1994 Winter Simulation Conference*, FL, USA, 1994.

[66] P. G. Ioannou and L. Y. Liu, "COOPS—Construction object-oriented process simulation system," in *Proceedings of the 9th ISARC*, Tokyo, Japan, 1995, pp. 459-468.

[67] J. C. Martinez and P. G. Ioannou, "General-purpose systems for effective construction simulation," *Journal of Construction Engineering and Management*, vol. 125, no. 4, pp. 265-275, 1999.

[68] D. Hajjar and S. M. AbouRizk, "Unified modeling methodology for construction simulation," *Journal of Construction Engineering and Management*, vol. 128, no. 2, pp. 174-185, 2002.

[69] M. A. Abdelmegid, V. A. González, M. Poshdar, M. O'Sullivan, C. G. Walker, and F. Ying, "Barriers to adopting simulation modelling in construction industry," *Automation in Construction*, vol. 111, 2020.

[70] J. Shi, "Activity-based construction (ABC) modeling and simulation method," *Journal of Construction Engineering and Management*, vol. 125, no. 5, pp. 354-360, 1999.

[71] S. M. AbouRizk and K. Mather, "Simplifying simulation modeling through integration with 3D CAD," *Journal of Construction Engineering and Management*, vol. 126, no. 6, pp. 475-483, 2003.

[72] D. K. H. Chua and G. M. Li, "RISim: Resource-Interacted Simulation modeling in construction," *Journal of Construction Engineering and Management*, vol. 128, no. 3, pp. 195-202, 2002.

[73] V. R. Kamat and J. C. Martinez, "Validating complex construction simulation models using 3D visualization," *Systems Analysis Modelling Simulation*, vol. 43, no. 4, 2003.

[74] W. Chokeanankun, "Formal modeling and verification of COSMOS based construction process using coloured petri nets, in *Proceedings of the 6th National Conference on Computing and Information Technology (NCCIT)*, Bangkok, Thailand, 2010.

[75] N. Suri and J. Damrianant, "Comparing construction process simulation between the Arena and COSMOS programs," *Engineering Journal of Research and Development*, vol. 30, no. 4, pp. 89-104, 2019.

[76] B. Visartsakul and J. Damrianant, "Determining costs and time required for building construction by using 3D structural models, unit costs, productivity rates, and project simulations," *Engineering Journal of Research and Development*, vol. 31, no. 4, pp. 63-75, 2020.

[77] C. Eastman, D. Fisher, G. Lafue, J. Lividini, D. Stoker, and C. Yessios, "An outline of the building description system," Institute of Physical Planning, Carnegie-Mellon University, 1974.

[78] G. A. Nederveen and F. P. Tolman, "Modelling multiple views on buildings," *Automation in Construction*, vol. 1, pp, 215-224, 1992.

[79] Autodesk, "Building Information Modeling," Autodesk Inc., San Rafael, CA, USA, 2003.

[80] Z. Ondogan and C. Erdogan, "The comparison of the manual and CAD systems for pattern making, grading and marker making processes," *Fibres and Textiles*, vol. 14, no. 1, pp. 62-67, 2006.

[81] NIBS, "National BIM standard United States version 3," National Institute of Building Sciences, Washington DC, USA, 2015.

[82] A. Borrmann, M. König, C. Koch, and J. Beetz, in *Building Information Modeling Technology Foundations and Industry Practice*. Cham, Switzerland: Springer, 2018.

[83] F. H. Abanda, D. Mzyece, A. H. Oti, and M. B. Manjia, "A study of the potential of cloud/mobile BIM for the management of construction projects," *Applied System Innovation*, vol. 1, no. 2, 2018.

[84] C. Eastman, P. Teicholz, R. Sacks, and K. Liston, *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors*. New Jersey: John Wiley & Sons, 2011.

[85] F. Khosrowshahi, "Building Information Modelling (BIM) a paradigm shift in construction," in *Building Information Modelling, Building Performance, Design and Smart Construction*. Cham, Switzerland: Springer, 2017.

[86] S. Azhar, W. A. Carlton, D. Olsen, and I. Ahmad, "Building information modeling for sustainable

design and LEED rating analysis," *Automation in Construction*, vol. 20, no. 2, pp. 217-224, 2011.

[87] A. Arrotéia and S. Melhado, "BIM in the pre-construction phase: An infrastructure case study project," in *Proceedings of the 37th CIB W78 Information Technology for Construction Conference (CIB W78)*, São Paulo, Brazil, pp. 156-167.

[88] I. B. Kjartansdottir, S. Mordue, P. Nowak, D. Philp, and J. T. Snæbjörnsson, "Building Information Modelling – BIM," Faculty of Civil Engineering, Warsaw University of Technology, 2017.

[89] X. Jiang, "Research on application of BIM 5D technology in central grand project," in *Proceedings of the 13th Global Congress on Manufacturing and Management (GCMM)*, Zhengzhou, China, 2016.

[90] L. Jian, W. Ying, W. Xiangyu, L. Hanbin, K. Shih-Chung, W. Jun, G. Jun, and J. Yi, "Benefits of building information modelling in the project lifecycle: Construction projects in Asia," *International Journal of Advanced Robotic Systems*, vol. 11, no. 1, 2014.

[91] T. N. Handayani, V. Likhitruangsilp, N. Yabuki, "A Building Information Modeling (BIM)-integrated system for evaluating the impact of change orders," *Engineering Journal*, vol. 23, no. 4, 2019.

[92] A. H. Husain, M. N. Razali, and S. Eni, "Stakeholders' expectations on Building Information Modelling (BIM) concept in Malaysia," *Property Management*, vol. 36, no. 4, pp. 400-422, 2018.

[93] A. Enshassi, L. A. AbuHamra, and S. Alkilani, "Studying the benefits of Building Information Modeling (BIM) in Architecture, Engineering and Construction (AEC) industry in the Gaza Strip," *Jordan Journal of Civil Engineering*, vol. 12, no. 1, pp. 87-98, 2018.

[94] L. M. Khodeir and A. A. Nessim, "BIM2BEM integrated approach: examining status of the adoption of building information modelling and building energy models in Egyptian architectural firms," *Ain Shams Engineering Journal*, vol. 9, no. 4, pp. 1781-1790, 2018.

[95] S. Azhar, M. Khalfan, and T. Maqsood, "Building Information Modeling (BIM): Now and beyond," *The Australasian Journal of Construction Economics and Building*, vol. 12, no. 4, pp. 15-28, 2012.

[96] A. Lee, A. J. Marshall-Ponting, G. Aouad, S. Wu, I. Koh, C. Fu, R. Copers, M. Betts, M. Kagioglou, and M. Fischer, "Developing a vision of nD-enabled construction," University of Salford, Salford, UK, 2003.

[97] M. Fischer, "Construction planning and management using 3D & 4D CAD models," Construction IT 2000, Sydney, Australia, 2000.

[98] J. Kunz, M. Fischer, J. Haymaker, and R. Levitt, "Integrated and automated project processes in civil engineering: Experiences of the centre for integrated facility engineering at Stanford University," in *Proceedings of Computing in Civil Engineering*, ASCE, Reston, VA, 2002, pp. 96-105.

[99] H. Kim, C. Benghi, N. Dawood, D. Jung, J. Kim, and Y. Baek, "Developing 5D system connecting cost, schedule and 3D model," *IABSE Symposium Report*, vol. 97, no. 24, pp. 32-38, 2010.

[100] S. Song, J. Yang, and N. Kim, "Development of a BIM-based structural framework optimization and simulation system for building construction," *Computers & Industrial Engineering*, vol. 63, no. 9, pp. 895-912, 2012.

[101] H. Kim, K. Anderson, S. Lee, and J. Hildreth, "Generating construction schedules through automatic data extraction using open BIM (Building Information Modeling) technology," *Automation in Construction*, vol. 35, pp. 285-295, 2013.

[102] M. Grieves, "Digital twin: Manufacturing excellence through virtual factory replication," *Google Scholar*, 2014.

[103] M. Grieves and J. Vickers, "Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems," in *Transdisciplinary Perspectives on Complex Systems*, Springer, 2017, pp. 85-113.

[104] W. Kritzinger, M. Karner, G. Traar, J. Henjes, and W. Sihn, "Digital twin in manufacturing: A categorical literature review and classification," *IFAC PapersOnLine*, vol. 51, no. 11, pp. 1016-1022, 2018.

[105] D. Jones, C. Snider, A. Nassehi, J. Yon, and B. Hicks, "Characterising the digital twin: A systematic literature review," *CIRP Journal of Manufacturing Science and Technology*, vol. 29, pp. 36–52, 2020.

[106] M. Chluse, L. Atorf, and J. Rossmann, "Experimentable digital twins for model-based systems engineering and simulation-based development," in *Proceedings of the IEEE International Systems Conference (SysCon)*, 2017, pp. 1-8.

[107] M. Zhang, Y. Zuo, and F. Tao, "Equipment energy consumption management in digital twin shop-floor: A framework and potential applications," in *Proceedings of the IEEE 15th International Conference on Networking Sensing and Control (ICNSC)*, 2018.

[108] L. Hu, N. T. Nguyen, W. Tao, M. C. Leu, X. F. Liu, M. R. Shahriar, and S. M. Al Sunny, "Modeling of cloud-based digital twins for smart manufacturing with MT connect," *Procedia Manufacturing*, vol. 26, pp. 1193-1203, 2018.

[109] C. A. Schumann, J. Baum, E. Forkel, and F. Otto, "Digital transformation and industry 4.0 as a complex and eclectic change," in *Proceedings of the 2017 Future Technol. Conference*, 2017, pp. 645–650.

[110] Z. B. Miled and M. O. French, "Towards a reasoning framework for digital clones using the digital thread," in *Proceedings of the 55th AIAA Aerosp. Sci. Meet*, American Institute of Aeronautics and Astronautics, Reston, Virginia, 2017.

[111] H. Millwater, J. Ocampo, and N. Crosby, "Probabilistic methods for risk assessment of

airframe digital twin structures," *Engineering Fracture Mechanics*, vol. 221, 2019.

[112] A. Kusiak, "Smart manufacturing must embrace big data," *Nature*, vol. 544, pp. 23-25, 2017.

[113] V. Martinez, A. Neely, A. Ouyang, C. Burstall, and D. Bisessar, "Service business model innovation: The digital twin technology," in *Proceedings of the EurOMA Conference*, 2018.

[114] J. Meierhofer, S. West, M. Rapaccini, and C. Barbieri, "The digital twin as a service enabler: From the service ecosystem to the simulation model," in *Lect. Notes Bus. Inf. Process*, Springer, 2020, pp. 347-359.

[115] R. Bitton, T. Gluck, O. Stan, M. Inokuchi, Y. Ohta, Y. Yamada, T. Yagyu, Y. Elovici, and A. Shabtai, "Deriving a cost-effective digital twin of an ICS to facilitate security evaluation," in *Lect. Notes Comput. Sci.*, Springer, 2018, pp. 533-554.

[116] E. H. Glaessgen and D. S. Stargel, "The digital twin paradigm for future NASA and U.S.," in *Proceedings of the Air Force Vehicles, in: 53rd Struct. Struct. Dyn. Mater. Conf.*, 2012, pp. 1-14.

[117] K. Reifsnider and P. Majumdar, "Multiphysics stimulated simulation digital twin methods for fleet management," in *Proceedings of the 54th Struct. Struct. Dyn. Mater. Conf.*, American Institute of Aeronautics and Astronautics, Boston, Massachusetts, 2013.

[118] M. Macchi, I. Roda, E. Negri, and L. Fumagalli, "Exploring the role of digital twin for asset lifecycle management," *IFAC-PapersOnLine*, vol. 51, pp. 790–795, 2018.

[119] C. Li, S. Mahadevan, Y. Ling, S. Choze, and L. Wang, "Dynamic Bayesian network for aircraft wing health monitoring digital twin," *AIAA Journal*, vol. 55, pp. 930-941, 2017.

[120] C. Zhou, J. Xu, E. Miller-Hooks, W. Zhou, C. H. Chen, L. H. Lee, E. P. Chew, and H. Li, "Analytics with digital-twinning: A decision support system for maintaining a resilient port," *Decision Support Systems*, 143, p. 113496, 2021.

[121] P. M. Karve, Y. Guo, B. Kapusuzoglu, S. Mahadevan, and M. A. Haile, "Digital twin approach for damage-tolerant mission planning under uncertainty," *Engineering Fracture Mechanics*, vol. 225, 2020.

[122] E. Van Der Horn and S. Mahadevan, "Digital twin: Generalization, characterization and implementation," *Decision Support Systems*, vol. 145, 2021.

[123] C. Yin and A. McKay, "Introduction to modeling and simulation techniques," in *Proceedings of the 8th Int. Symp. Comput. Intell. Ind. Appl. 12th China-Japan Int. Work. Inf. Technol. Control Appl.*, Shandong, China, 2018.

[124] J. Li, D. Greenwood, and M. Kassem, "Blockchain in the built environment and construction industry: A systematic review, conceptual models and practical use cases," *Automation in Construction*, vol. 102, pp. 288-307, 2019.

[125] S. Rokooei, "Building information modeling in project management: necessities, challenges and outcomes," *Procedia-Social and Behavioral Sciences*, vol. 210, pp. 87-95, 2015.

[126] S. H. Khajavi, N. H. Motlagh, A. Jaribion, L. C. Werner, and J. Holmstrom, "Digital twin: Vision, benefits, boundaries, and creation for buildings," *IEEE Access*, vol. 7, pp. 147406-147419, 2019.

[127] Y. Xu, Y. Sun, X. Liu, and Y. Zheng, "A digital-twin-assisted fault diagnosis using deep transfer learning," *IEEE Access*, vol. 7, pp. 19990-19999, 2019.

[128] G. P. Lydon, S. Caranovic, I. Hischier, and A. Schlueter, "Coupled simulation of thermally active building systems to support a digital twin," *Energy and Building*, vol. 202, 2019.

[129] G. Angjeliu, D. Coronelli, and G. Cardani, "Development of the simulation model for digital twin applications in historical masonry buildings: The integration between numerical and experimental reality," *Computers and Structures*, vol. 238, 2020.

[130] D. Gerhard, M. Neges, and M. Wolf, "Transfer of digital twin concepts to the production of precast concrete parts in the construction industry," *ZWF Zeitschrift fuer Wirtschaftlichen Fabrikbetrieb*, vol. 115, pp. 58-61, 2020.

[131] R. Sacks, I. Brilakis, E. Pikas, H. S. Xie, and M. Girolami, "Construction with digital twin information systems," *Data-Centric Engineering*, vol. 1, 2020.

[132] S. Kaewunruen and Q. Lian, "Digital twin aided sustainability-based lifecycle management for railway turnout systems," *Journal of Cleaner Production*, vol. 228, pp. 1537-1551, 2019.

[133] Q. Lu, X. Xie, A. K. Parlikad, J. M. Schooling, and E. Konstantinou, "Moving from building information models to digital twins for operation and maintenance," in *Proceedings of the Institution of Civil Engineers – Smart Infrastructure and Construction*, 2020.

[134] J. Kunz and M. Fischer, "Virtual design and construction: Themes, case studies and implementation suggestions," in *CIFE Working Paper*, 2012.

[135] Q. Lu, W. Xie, J. Heaton, A. K. Parlikad, and J. M. Schooling, "From BIM towards digital twin: strategy and future development for smart Asset management," in *Service Oriented, Holonic and Multi-agent Manufacturing Systems for Industry of the Future*, 2020, pp. 392-404.

[136] J. Wu, Y. Yang, X. Cheng, H. Zuo, and Z. Cheng, "The development of digital twin technology review," in *Proceedings of the Chinese Automation Congress (CAC)*, 2020.

[137] T. D. West and M. Blackburn, "Is digital thread/digital twin affordable? a systemic assessment of the cost of DoD's latest Manhattan

project," *Procedia computer science*, vol. 114, pp. 47-56, 2017.

[138] A. M. Madni, C. C. Madni, and S. D. Lucero, "Leveraging digital twin technology in model-based systems engineering," *Systems*, vol. 7, no. 1, 2019.

[139] T. D. Oesterreich and F. Teuteberg, "Understanding the implications of digitization and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry," *Computers in Industry*, vol. 83, pp. 121-139, 2016.

[140] R. Agarwal, S. Chandrasekaran, and M. Sridhar, *Imagining Construction's Digital Future*. McKinsey, 2016.

* * *

Bunnapub Visartsakul received a B.Eng degree in civil engineering and construction management in 2016 and an M.Eng degree in engineering and business management in 2019 from Thammasat University. He is currently a Ph.D. candidate in civil engineering with a major in construction management at Thammasat University.

He has been working at TTCL Public Company Limited since 2016. From 2016 to 2020, he was a structural engineer. Since 2021, he has become a business development analyst focusing on renewable energy project development. His research interests include Building Information Modeling (BIM), simulation modeling, and digital twin.

Jirawat Damrianant has a B.Eng. (Hons) in Civil Engineering from Chiang Mai University, an M.Eng. in Structural Engineering and Construction from the Asian Institute of Technology, Thailand, and a Ph.D. in Civil Engineering from the University of New South Wales, Australia.

He has worked in the construction industry as a structural designer and a construction manager for several years. He is currently an associate professor in the Faculty of Engineering at Thammasat University, Thailand. His research interests include construction-process modeling and simulation, and building information modeling.

Assoc. Prof. Damrianant is a registered professional civil engineer and a member of the Council of Engineers (Thailand) and the Engineering Institute of Thailand under H.M. the king's patronage. He is also a senior professional specialist of the Council of Engineers.