Supply chain management for modular construction using building information modeling

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- This paper presents an example of an integrated construction system that uses building information modeling, the internet of things, and geographic information system technology to improve supply chain logistics management in construction projects.
- The authors developed and tested a digital twin platform for the proposed system, which allows real-time simulation of logistics in modular construction.
- The results show that potential logistical risks and accurate module arrival time can be detected via the suggested digital twin platform.

Modular construction is a promising method in the construction industry because of its potential to reduce project duration and costs. The advantages of modular construction lie in the prefabrication of a building module in a remote factory, while on-site assembly and foundations are performed simultaneously.[1] To achieve maximum benefits (such as avoiding downtime), the module must be manufactured and delivered on time to the construction site. Thus, modular construction requires effective coordination of the chain between external production, the on-site construction process, and logistics. However, because modular construction includes bulky, complex, and heavy construction components, there is the risk of delivery schedule deviations.[2] Furthermore, because many construction projects take place in dense urban environments with limited space for module storage, such deviations can increase downtime. For example, if a module arrives on site earlier than planned, there is downtime for the transporter; if it arrives late, there is downtime for machinery and workers at the project site. Therefore, to maximize the benefits of modular construction, it is necessary to accurately plan deliveries between project participants.[3]

Current industry practice has many challenges that prevent optimization of component storage and transportation. In current practice, modular components arriving at a construction site are typically stacked randomly at the storage site without real-time consideration of the construction schedule and subsequent component arrivals. As a result, the time to move components increases.[4] Some researchers[5–7] have conducted studies on optimizing component storage and transportation schemes. However, few studies have attempted to solve the problem of real-time transportation planning to coordinate with a project's construction schedule and to optimize component storage schemes, taking into account the effects of random factors and the arrival sequences of components.[8] Given such gaps in the research, there is a critical need for a solution to the problem of component storage and transportation optimization in the context of dynamically changing construction schedules. To address these challenges, this paper proposes a model for optimizing the transportation plan and component storage scheme based on real-time scheduling and tracking of facilities.

Literature review

Recent advances in navigation, sensors, and computer technology provide tools to incorporate dynamic construction information.[9] Four-dimensional (4-D) building information modeling (BIM) provides real-time information about vehicle movements. Radio-frequency identification (RFID) and global navigation satellite systems facilitate the tracking of construction components throughout the delivery process.

One solution that supports collaboration among enterprises in the construction process is BIM. Combined with the use of the common data environment (CDE), BIM is an indispensable tool to manage both the physical and digital aspects of construction processes. The CDE is a source of project information used to collect, manage, and distribute documentation to the construction project team. Creating this source of information facilitates collaboration among project team members and helps avoid mistakes and data duplication.[10]

The use of BIM and other integrated design methods in the construction process requires the involvement of all project team members at every stage of the process as well as an appropriate data exchange environment and integrated information management. CDE solutions have the power to meet this need because they not only make BIM models visible to all participants in a construction project but also help organize the transmission of available data.[11] CDE solutions also have approval and submission features that enable the tracking of information across the entire building life cycle. Thus, the use of CDE ensures better communication, improves transparency, minimizes risks, and enables the continuous assessment of investment milestones. However, research on the use of construction supply chain logistics integrated with 4-D BIM emphasized the lack of a single strategy for managing such infrastructure in the U.K. construction industry.[12]

BIM is a process of bundling and filtering information about building facilities and structures at various stages of the project life cycle.[13] The resulting BIM models are digital representations of the physical and functional properties of a building. Beyond this general definition of BIM, there are multiple inaccurate descriptions of BIM as a tool to improve the construction process or create and share information about project activities throughout the project life cycle, from planning and design to demolition. It seems more appropriate to treat BIM as a computer-aided technology designed to generate digital models of a building.[14] These models contain essential details about a construction object, such as geometry, physical and functional properties, and parametric rules and relationships between the components of a building. The same models can be used at different stages of a project life cycle: conception, planning and design, construction and operations, commissioning, renovation, and deconstruction. Other information stored within the BIM model can include material inventories, cost estimates, assembly time and procedures, inventories of installed equipment with operating instructions and warranties, and damage and renovation histories.[15] The BIM model can also be used to track changes over time in the functional parameters of the building's infrastructure (heating, ventilation, lighting, and other systems) or even to control those parameters.[16] To create a model with three-dimensional (3-D) geometry, architects and building designers can use parametric and "smart" objects (walls, columns, windows, bars, etc.) stored as semantic data structures. These objects are given proper parameters depending on the overall axial or geometric system of the entire construction system. This procedure makes it easier to edit and adjust the components of a building model.

BIM is commonly referred to as an extension of computer-aided design (CAD) technology.[17] However, the usefulness of BIM can extend far beyond the design process. Whereas CAD facilitates the preparation of project documentation, BIM can improve the entire process of investment realization, not just design. BIM has a broad range of applications. It is a powerful instrument to create conceptual designs, visualizations, and animations through 3-D rendering. BIM software provides a set of tools to create flat working drawings, simulate the construction process, and coordinate design and building operations. BIM models check whether a project design has geometric and sectoral contradictions. BIM models can also be used to determine the functional parameters and accessibility of the construction objects, prepare a project schedule, and predict the cost of a project. BIM is often used for marketing purposes, especially when integrated with virtual reality and augmented reality technologies. In addition, the integration of BIM data models and digital maps enables city information modeling.[18]

The literature often notes the multidimensional character of BIM models, which is somewhat conditional. Multidimensionality derives from the capabilities these models possess. The BIM third dimension (maturity level 1) is associated with geometry.[19] It is possible to create a 3-D model from scratch during the design phase of a project, either through laser scanning and point processing or based on existing documentation. In scientific research centers, mostly in Japan, many prototypes have been developed to automate construction processes of varying complexities. Most often, these prototypes include remote-controlled robots with a vision system designed to follow the steps specified in a work-cycle program—and adaptive robots—which seek to adapt to the said program.[20]

Yin and coauthors[21] offer a paradigm for semantic localization that is both learning free and mapping free. By using the physical positions and category names of BIM elements, they propose a BIM-to-map conversion. Their study also investigated a coarse-to-fine localization technique for tracking a 3-D light detection and ranging (LiDAR) sensor based on semantic maps, where data correlations consider both geometric and semantic information. Yin et al. concluded that, with just one BIM file and one mobile LiDAR sensor, the proposed system may perform effective and efficient localization, as shown by testing on real-world data sets.

Elghaish et al.[22] have proposed a blockchain technology solution that can offer a comprehensive answer to some of the main obstacles and difficulties in implementing a construction circular supply chain. This solution makes it possible to consider existing features in new project designs by enabling designers to create BIM families that are similar to existing buildings and share the generated families with other designers to use the circular design idea. The proposed construction circular supply chain–based blockchain technology does the same thing, enabling regional organizations to monitor the specifics of materials, the amounts, delivery locations, and treatment processes on a secure and linked platform.

The problem statements

A robust and well-designed logistics management strategy is critical to ensure optimal construction site efficiency and safety and for controlling costs. The increased adoption of BIM has aided the construction industry to grow faster than it did previously. Through the expanded implementation of BIM-based logistics management methods and procedures, this evolution can be accelerated. However, no definitive results have been obtained to show whether potential logistical risks and accurate module arrival time can be detected via the digital twin platform explored in this paper. A digital twin is a real-time digital copy of a physical object that contains its current state, dynamic behavior, and properties. Moreover, there is little information about whether integrated systems are effective in product delivery management tasks.

The study goals were to develop a supply chain and an algorithm for monitoring logistics processes for a construction project using BIM, as well as to evaluate the economic effect of switching projects from CAD to BIM. To do this, management model costs were analyzed using the example of a specific construction organization.

The objectives of this research were formulated as follows:

- The research proposes a model for dynamic optimization of construction component transportation in real time based on construction progress data. The model will dynamically use the actual component requirements based on 4-D BIM technology and thus be able to provide a transportation plan that is consistent with the actual progress of construction.

- A component tracking model will be developed that will combine global navigation satellite system and RFID methods to provide component positioning. The platform will provide real-time information on component arrivals to optimize the use of warehouses and construction sites. A dynamic storage optimization model will be proposed to manage the placement of each component, considering real-time transportation tracking and the construction schedule. The model will be able to help reduce travel time and transportation time, thereby improving construction efficiency.

Methods and materials

Methodology for BIM-based construction process management

In this study, BIM-based construction process management was guided by the provisions of the British Standards Institution's publicly available specification PAS-1192-2,[23] which is a fast-track standard intended to meet the needs of the construction industry. PAS-1192-2 provides a consistent framework for collaborative working and information management in a BIM level 2 environment. The concept of BIM levels involves a set of generally accepted minimum necessary criteria for determining the degree of compliance of the design process with BIM technology. BIM level 2 is characterized by organized collaboration—all participants use their own 3-D models and working in a single shared model is not a key feature of this level. Collaborative work is ensured in this case through the established process of data exchange; that is the defining aspect of the second level of BIM. Project data are published in a publicly available file format that allows anyone involved in the process to combine these data with their own work and then create an integrated BIM model. PAS-1192-2 explains how to create and submit project documentation at various stages of the life cycle, from procurement to the transfer of investment information for operational (management) purposes. The PAS-1192-2 framework was developed based on the British Standard Institution's BS 1192,[24] which was issued in 2007 and offers specifications for collaborative design and construction (delivery) of a project. BS 1192 constitutes the first part of the BIM standards and is also known as PAS-1192-1. Whereas PAS-1192-2 focuses on project information that is originated, exchanged, or managed in BIM format, BS 1192 also touches on other areas of project information management.[11]

BIM-enabled information supply chain

Participants in the construction process exchange information along the supply chain until the construction process is completed. The pivot data traveling along the information supply chain are known as the information model. Another type of data are 3-D models, but they represent only one part of the BIM concept. BIM should be seen as a process, not just 3-D modeling. Data from the design and construction phase of a project constitute a project information model (PIM). As the project enters the operational phase (that is, the asset usage and management stage), PIM becomes a platform to develop an asset information model (AIM). The operational phase of a building is described in BS EN ISO 19650-3:2020,25 which sets out the requirements for authorization and information exchange in CDE. The key documents in the construction project formed at the onset of the project are the employer information requirements (EIR), which define the data required by clients for project handover and decision-making, and the BIM execution plan, which explains how the EIR will be delivered. Upon signing the construction project contract, a master information delivery plan (MIDP) is created to define what project information is to be prepared for investment, who is responsible for preparing that information, and which procedures are used to prepare it.[25] The MIDP can only be created once the BIM and EIR documents are in place. With such a solid foundation, the project team can begin the project delivery process by producing an information model that meets the client's needs (**Fig. 1**).

PAS-1192-2 is also concerned with phases that follow the commissioning of a building, namely operation and maintenance. With a data-rich information model, investors and contractors can evaluate project progress and investments as time passes. This opportunity allows users to access all investment data when upgrading a given facility or an infrastructure and reduce design and execution errors while building a new supply chain. The entire cycle is dependent on a constant exchange of information between the project team and key decision-makers. PAS-1192-2 is a key specification in BIM-enabled project management.

Development of a BIM-based module for monolithic construction

An important step in constructing a 3-D model of a building is checking the adequacy of the floor plan. A floor plan consists of several standardized modules that perform specific functions. The following variables are defined: *i* refers to the fundamental element of the precast concrete (for example, a corridor and the kitchen), *j* denotes one of the modular units, which are mostly public areas (for example, a staircase), and *T* represents the floor plan orientation. The execution phase of the model involved assembling the fundamental prefabricated structures for each element *t* within the floor *T*. The element *t* physically corresponds to the volume of the planned structure and is calculated from the coordinates of vectors. The computation formula is provided.

$$t = \sum_{i=1}^{i} \sum_{j=1}^{j} Z_i^j \left(\sum G \right)$$

where

Z = height of a structural element

G = gross area of an element

The following conditions were set: The floor has the area $S(t) > G$. The next step was to measure the efficiency of premises $P(t)$. The execution command is triggered when $t \in T$. The minimum efficiency threshold is set in advance. If the condition $P(t) <$ min is satisfied, then the condition min $= P(t)$ gets updated for the corresponding floor plan *t*.

Real-time monitoring of logistic processes was conducted in accordance with the new model of optimization of the said processes proposed by the authors. The model is built on the

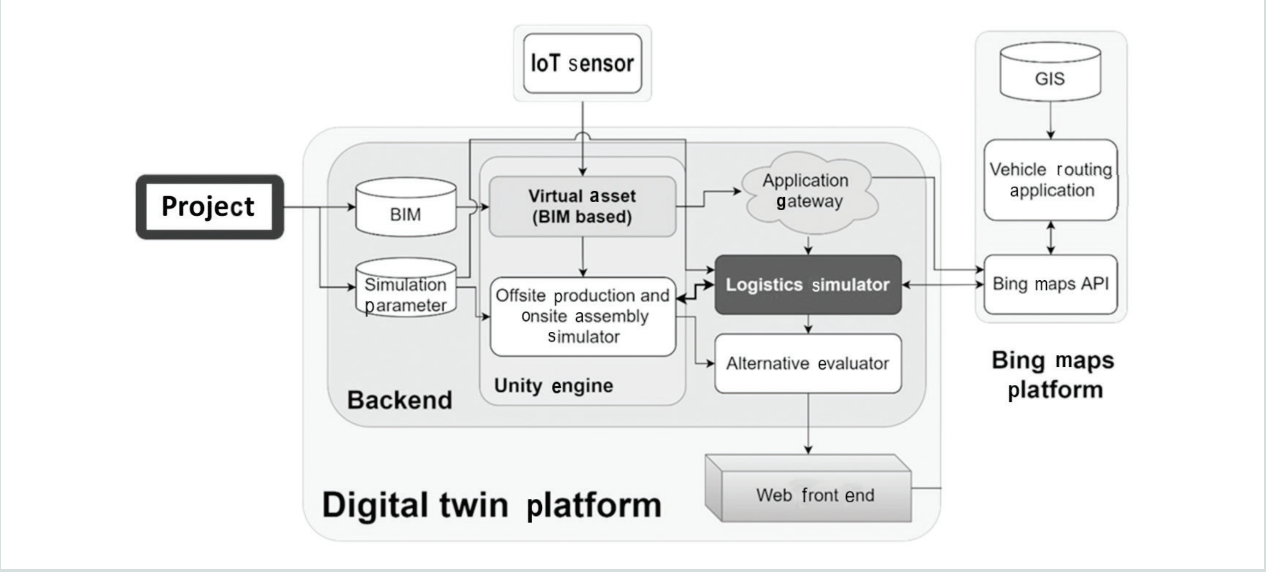

Figure 1. Information supply chain in a BIM-enabled construction project. Note: API = application programming interface; BIM = building information modeling; GIS = geographic information system; IoT = internet of things.

information solved in 4-D BIM and real-time tracking of the transportation of components to the construction site. Four-dimensional BIM is used to obtain real-time information about the need for construction components. The real-time tracking system proposed by the authors is combined with the automatic RFID system and the global navigation satellite system. Such a combined system is effectively used to determine the location of construction components, so that arrival times, component quantities, and component types can be accurately predicted. The transportation optimization model is solved using linear programming algorithms. The proposed model is based on optimizing a transportation plan for construction components based on the pace of construction and real-time demand for components.

The proposed model assumes that a construction project will require I different types of construction components supplied by J number of plants. The construction-site management personnel give orders to transport the required construction components to the factories according to the construction schedule. Then, the necessary building components will be delivered to the construction site within τ days after placing the order. The variable for the proposed model can be expressed as $X(J, I, \tau)$, denoting the amount of components I coming to the site from the Jth plant, on the τth day ($J = 1, 2, 3, \ldots J$; $I = 1, 2, 3, \ldots I$; $\tau = 1, 2, 3, \ldots \tau$).

The model is based on the following elements:o

- Minimizing the difference between the rational and actual quantity of construction components at the site L. An increase in the construction-site inventory of components can satisfy the situation when the construction rate exceeds the design rate. However, if the construction speed is lower than the design speed, there may not be enough space at the construction site to store the excess components. Considering possible changes in the speed of the construction plan to determine a rational stock of construction components, the authors introduce a stockpile factor u. The goal is to minimize the difference between the real and rational stock amounts.

  $$\min L = \sum_{\tau=1}^{\tau} \sum_{i=1}^{I} \left[Q(\tau,i) - uD(\tau+1,i)\right]$$

  where

  $Q(\tau, i)$ = amount of stock on the τth day of the ith component

  $D(\tau + 1, i)$ = demand on the τth + 1 day for the ith component

- Minimizing transportation costs. The proposed model assumes that standard vehicles of the same type are used for transportation of construction components and that the cost of transportation per unit distance is fixed. The minimum cost of transportation S is calculated using the following formula.

  $$\min S = \sum_{j=1}^{J} \sum_{\tau=1}^{\tau} \left\{\left[d(j)\right]\left[b(\tau.j)\right]\right\}$$

  where

  $d(j)$ = distance to the construction site from the jth plant

  $b(\tau, j)$ = number of cars shipped on the τth day from the jth plant

- Optimizing the amount of construction components stored on site. To meet construction demand, the quantity of components stored on site must be at least as large as the next day's demand for components.

  $$Q_i(\tau,i) \geq \left[D(\tau+1,i)\right]$$

  where

  $Q(i)$ = initial stock of the ith building component

- Optimizing the storage area. The component transportation plan should consider the storage capacity of the construction site.

  $$\sum_{i=1}^{I} \frac{Q(\tau,I)}{A(I)} \leq 1$$

  where

  $A(I)$ = maximum quantity of the Ith component that can be stored in the warehouse

  $\frac{Q(\tau,I)}{A(I)}$ = percentage of storage space that the Ith building component occupies

The proposed model is a multicriteria equation for linear programming with integer variables and is solved by linear programming methods.

$$f = k_1\left(\frac{S - \min S}{\max S - \min S}\right) + k_2\left(\frac{L - \min L}{\max L - \min L}\right)$$

where

k_1 = optimal planned specific minimization coefficient ($k_1 + k_2 = 1$)

k_2 = optimal planned specific minimization coefficient ($k_1 + k_2 = 1$)

To solve the model, the authors used a tool for solving mathematical optimization problems. The tool interface provides accurate and fast solutions for multinomial and multidimensional optimization models such as linear programming, integer programming, and quadratic programming.

The authors developed a systematic structure to track the entire component logistics process (**Fig. 2**), which basically consists of three parts: the storage of components at the factory before shipment, transportation tracking, and storage management at the construction site.

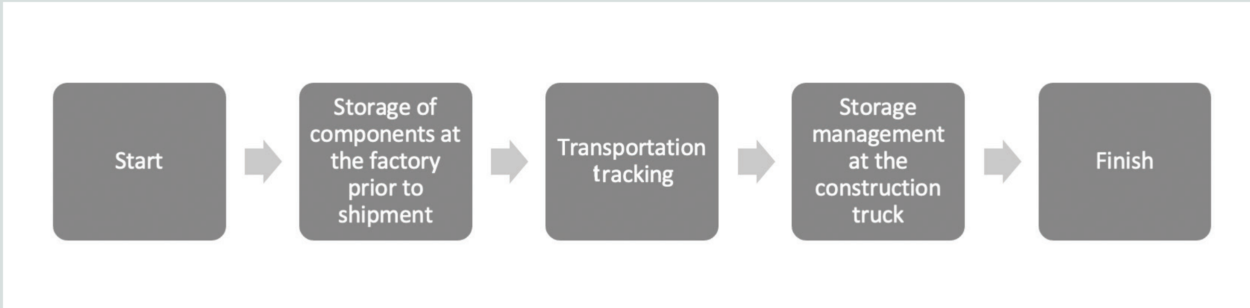

Figure 2. Flowchart of logistics process.

- Storage of components at the factory before shipment. An RFID chip (tag) is embedded in each construction component before it is shipped from the factory. The tag is scanned by a handheld RFID scanner to download information such as the component's identification, manufacturer, type, and status into the system. When loaded onto vehicles, components must be rescanned to associate the construction component with the vehicles. Meanwhile, the status of components in the system database changes on the handheld reader. **Figure 3** shows this process.

- Transportation tracking. Vehicles are equipped with global navigation satellite system positioning devices to provide real-time geographic information about their locations. Because each vehicle is associated with the components it transports, the geographic location and route information of the components are also recorded in real time. With information about transportation speed and estimated location, it is possible to accurately predict the arrival time of components to plan their placement in advance. **Figure 4** shows an example of a vehicle position and transportation route.

- Storage management at the construction site. When the vehicle arrives, the RFID tags embedded in the components are scanned again to update the system on the location of the components. According to the storage optimization model and storage location, the components are placed at the warehouse construction site. The warehouse BIM is dynamically updated on a constant basis to reflect the actual component layout at each arrival of a new transport vehicle (**Fig. 5**).

To determine logistical risks and alternative routes based on the proposed structure of the digital twin platform, the authors performed logistical modeling. Geographic information system (GIS) data (traffic, geographic data, road availability, accidents) were updated in real time in the mapping application. GIS and BIM do not interact at the data level and are stored on different platforms. Internet of things (IoT) sensor

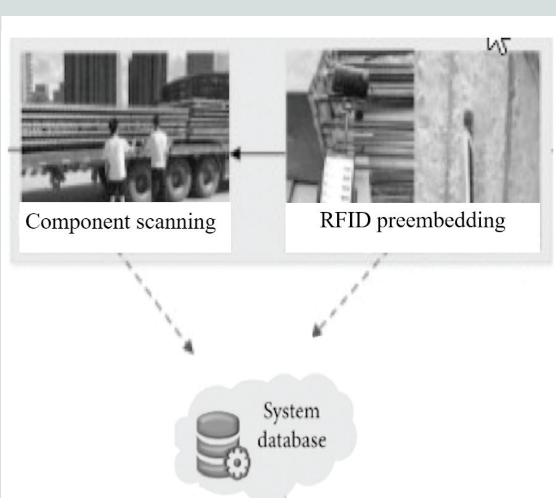

Figure 3. Scanning components before shipping. Note: RFID = radio-frequency identification.

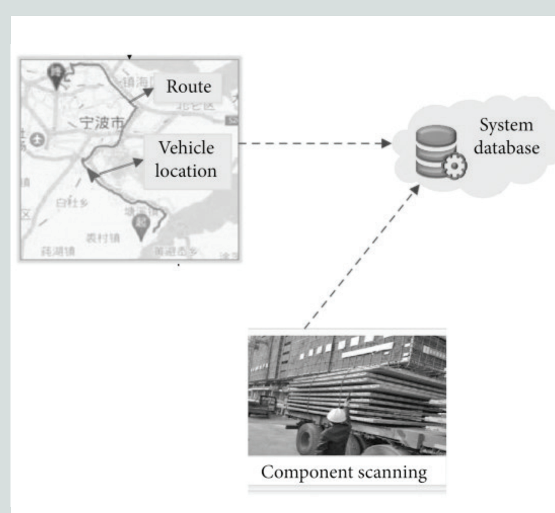

Figure 4. Vehicle position and transportation route.

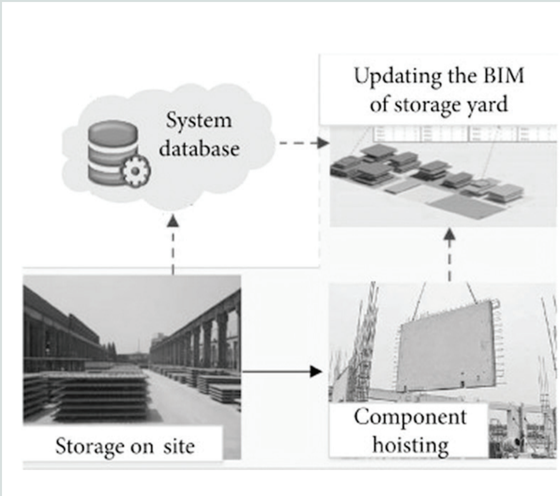

Figure 5. The warehouse BIM is dynamically updated on a constant basis to reflect the actual component layout at each arrival of a new transport. Note: BIM = building information modeling.

data must be collected from the module and vehicle to create a virtual object. Thus, the authors created a virtual server that generates IoT sensor data in real time. The IoT sensor data were injected into a digital twin platform that created virtual objects in virtual space based on BIM. The data needed in the virtual asset are the dimensions and weights of the truck and the module. These data were sampled and delivered via an application gateway to the mapping application programming interface. The mapping application then used the GIS and input data to find the optimal route.

If logistics risks arise on the expected route, the digital twin platform finds and presents an alternative route. Because various unplanned events (such as vehicular accidents) during transportation can affect the optimal delivery route and logistics risks, it is important that such logistics modeling is available in near-real time. Evaluating information from the module about routes and traffic conditions from scratch can take considerable time and effort. In contrast, when vulnerable conditions arise during transportation, the digital twin platform can be used to efficiently estimate arrival times and search for alternate routes in real time.

Also, the digital twin platform can take data from connected IoT sensors that collect real-time information about the status of the module (such as location) to facilitate quick decision-making by project stakeholders when unforeseen problems arise in the logistics process. For example, if the digital twin platform detects damage to a module, that information is transmitted in real time to the parties involved, who can then request that the manufacturer ship a replacement for the damaged part or schedule an on-site repair.

A designated specialist enters BIM data required for the modular project and modeling parameters. For logistics monitoring, data from the BIM model and IoT sensors are tied to a GIS module. The exchange of information takes place in real-time and permits the investigation of alternative scenarios. Therefore, it is possible to execute 3-D simulations in real time and search for the optimal logistics scenario where alternative routes are available.

Simulation of logistics processes

Digital twin simulation technology is an effective team coordination tool for supply chain management. Throughout the construction supply chain, the digital twin platform simulates construction machines, modular construction components, vehicles, warehouses, and other process facilities to monitor the status and progress of the project. In addition, the digital twin platform simulates various real-world process scenarios to accurately predict potential supply chain risks, such as delivery schedule deviations. The digital twin platform collects real-time data from global positioning system sensors on vehicles and construction machines, analyzes it, and provides useful information about the supply chain, such as the optimal delivery route, the exact delivery time, and the optimal time to order modules. Therefore, in modular construction, the digital twin platform can help project participants effectively coordinate activities and be more productive.

Despite their considerable potential for supply chain management, existing uses of digital twin platforms are mostly found in the context of product operations and shop floor management. Digital twin platforms are only used to a limited extent for the logistics of the modular construction process, in which modules are manufactured in a factory, stored in a warehouse, and then delivered to the construction site.

To demonstrate the relevance of digital twin platforms for solving logistical challenges in modular construction processes, the authors developed and tested a digital twin platform for the proposed system, which allows real-time simulation of logistics in modular construction. The proposed digital twin platform uses BIM and GIS as its foundation because BIM includes information about the plans, detailed geometry, properties, and quantities of modules, while GIS provides geospatial data with vehicular information (such as traffic, signs, traffic restrictions, etc.). The digital twin platform also collects real-time IoT sensor data from its physical twin (such as a construction module), simulates and analyzes the data to predict potential logistical risks, and finds possible alternative delivery routes with accurate delivery time calculations.

To search for logistics risks in a modular construction project, the investigators performed a simulation of logistics processes based on a digital twin platform. BIM project data (for example, module geometry, weight, and assembly schedule) were entered into the server system in the digital twin platform. GIS data (for example, traffic, geographic data, road accessibility, rules, curfews, and traffic accident locations) were updated in real time. A virtual server was created to generate hypothetical IoT sensor data, including the location of modules in real time.

To model the logistics in the virtual asset, information about the geometry and weight of the vehicle carrying the module is needed. These data were used as input to the GIS to find a suitable route.

The simulator requested two routes for the project: one was the route used in the real project (base route, which was explored without considering logistical risks), and the other was precisely calculated with all logistical risks. The downtime that would occur in the actual logistics process for 100 modules was quantified by comparing the estimated time of arrival values of the base route and the improved route.

If potential logistical risks arise on the expected route, the digital twin platform finds and presents an alternative route and continually updates the estimated time of arrival. This capability is provided by data from connected IoT sensors that collect information such as module status in real time (for example, the module's quality and location).

Results

The present study investigated how the use of BIM technology affected documentation creation time in a specific company. The focus was on the company's performance in the first five years since its inception. For the first four years, the company relied on conventional CAD techniques to create documents. The incorporation of BIM technology in the fifth year of the company's operation was linked with revenue increases. Data obtained during the study includes information about the software programs used in the design process, both conventional CAD and BIM. The study analyzed BIM-aided phases and operations. Individual tasks were accompanied by a commentary explaining why it was important to use BIM, rather than CAD, in the design process.

Table 1 presents the costs associated with the execution of an integrated construction management model. The data show a downward trajectory of software costs and an upward trajectory of consumable costs within a period of five years.

To integrate BIM, enable the delivery of materials, and support the execution of project-related operations, a project delivery framework was adopted from Fig. 1. **Table 2** presents the outcomes, showing that BIM was associated with a decrease in construction costs and an increase in automation and computerization expenses.

The integrated project delivery model facilitates automation of the construction process and the avoidance of temporary loss. Data from BIM, GIS models, and IoT sensors show that, unlike the existing routing applications, the proposed technology can help build more accurate routes in real time using the estimated time-of-arrival data. The proposed technology can also assist in identifying a range of potential risks in logistics.

To calculate the transportation time to the site, the process of storing and transporting components was simulated. The

Table 1. Expenses involved in the execution of the integrated construction management model

Category	Cost, U.S. dollars						Total
	Onset	Year 1	Year 2	Year 3	Year 4	Year 5	
Software	4673.50	2910.50	3813.00	1254.50	0.00	1970.50	14,622.00
Software updates	0.00	0.00	70.50	0.00	0.00	0.00	70.50
BIM software	0.00	0.00	0.00	0.00	2560.00	19,710.00	22,270.00
BIM software updates	0.00	0.00	0.00	0.00	0.00	2560.00	2560.00
Computer	1910.50	799.50	0.00	0.00	2164.50	3050.00	7924.50
Training	0.00	0.00	0.00	1000.00	1000.00	0.00	2000.00
Consumable supplies	1663.50	0.00	250.00	0.00	250.00	2175.50	4339.00
Phone services	100.00	420.00	420.00	420.00	420.00	600.00	2380.00
Office	0.00	0.00	0.00	1230.00	3690.00	3690.00	8610.00
Vehicles	0.00	5341.50	4470.00	4470.00	4470.00	4470.00	23,221.50
Fuel	0.00	1500.00	3600.00	3600.00	3600.00	3600.00	15,900.00
Total	8347.50	10,971.50	12,623.50	11,974.50	18,154.50	41,826.00	103,897.50

Note: BIM = building information modeling.

Table 2. The cost change of phases in the project life cycle after transitioning from CAD to BIM

Project phase	Difference between costs, %	
	CAD	BIM
Preliminary draft	100	102.9
Approval	100	n/a
Document phase	100	n/a
Tendering	100	n/a
Design	100	104
Monitoring and control	100	91
Scheduling	100	n/a
Construction	100	84

Note: BIM = building information modeling; CAD = computer-automated design; n/a = not applicable.

transport time of the component to the construction site $\tau(n)$ was calculated with the following equation.

$$\tau(n) = w_i(\tau_d \tau_f \tau_h \tau_v)$$

where

w_i = transport complexity factor

τ_d = component overload time

τ_f = $2d_e/v_v$ = component of the horizontal transport time and time of displacements (ac)

d_e = horizontal transport distance by truck

v_v = horizontal transport speed by truck

τ_h = h/v_h = vertical transport time of components during transshipment

h = vertical transport height

v_h = cranes' lifting speed of components when transshipped

a = number of displacements

c = time spent on displacement

Thus, the time calculation modeling considered the number of transfers; the total number of components to be transferred; the initial state of the warehouse; the time required for each movement of components; the time and speed of cranes; the time and speed of vehicles; and the distance between storage areas.

The components of the same type can be stored in different warehouses. Consequently, when a component is needed, the simulation should determine the location from which the component will be delivered. Two principles were used to determine the preferred location: minimizing distance and minimizing travel time. These two principles could sometimes contradict each other. To account for the effect of these principles on the speed of construction, two modeling rules were used: first, the distance was accounted for; then, the travel time was counted.

Figure 6 shows the results of the module delivery time monitoring experiment. It appears that the integration of BIM and building supply chain management can reduce the delivery time of materials by 1.62 hours.

Figure 7 shows that the use of an integrated construction management technology significantly reduced the average traffic load and, accordingly, the delivery time. The ability to build alternative routes decreased the amount of idle time.

BIM integration increases the efficiency of construction project management. To effectively implement the technology, management must make several decisions:

- to develop and incorporate BIM software training policies for site project management personnel into the overall set of policies
- to organize staff training to improve skills in the use of BIM software systems
- to implement policies for systematic review and adjustment of the model during construction activities

These approaches promote better coordination and control at the site, which will lead to more efficient, effective, and safer logistics processes.

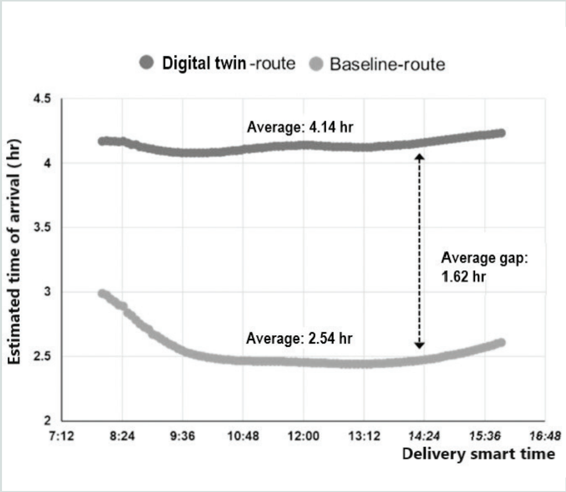

Figure 6. Average module delivery time.

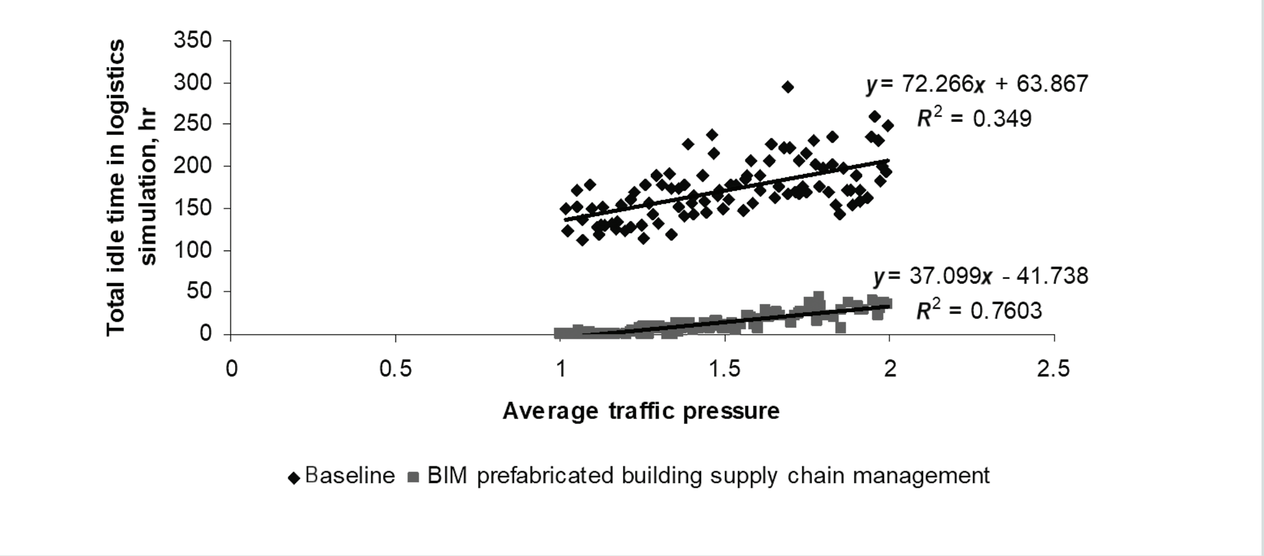

Figure 7. Total idle time for 100 modules. Note: BIM = building information modeling.

Discussion

Two objectives of our study were to develop a model for dynamic optimization of construction component transportation in real time, and to develop a component tracking model that provides real-time information on component arrivals.

In modular construction, deviations in the supply chain schedule can have a critical impact on project costs and timelines. Such deviations occur frequently because modules are problematic to transport due to their large size and complexity. To solve this problem, a digital twin platform is proposed that combines BIM, IoT, and GIS technologies to predict the various risks that may arise in the logistics process and calculate accurate arrival times based on various scenarios. One important aspect of the digital twin platform is that it does not require data conversion between different BIM and GIS formats, but rather those platforms perform the conversion on demand to avoid data loss during data conversion. This aspect is especially important in modular construction, where different stakeholders use different data formats and tools. For example, because a manufacturer does not use the routing of vehicles implemented in GIS, it may not know what logistical risks will arise at the transportation stage and how those risks will affect transportation. Conversely, it is difficult for a carrier to know the schedule, geometry, cost, and weight of a transported module because they do not use BIM in their work.

Figure 7 shows that the digital twin platform is associated with less downtime and lower standard deviations, regardless of traffic conditions. These results are achieved because the digital twin platform uses real-time IoT sensors to update the module's location and retrace the route with potential risks, so it can accurately predict deviations from the schedule. Providing accurate timing to all project participants (model makers, on-site assembly crews, etc.) will improve coordination in the modular construction supply chain. Specifically, module shipment schedules, module production schedules at the factory, and on-site assembly schedules can be coordinated based on expected arrival times of components. For example, if an unexpected accident occurs along the route during module delivery and the vehicle is delayed by several hours, the manufacturer can adjust production and shipping schedules for the next modules, and crews at the assembly site may shift priorities and first perform other tasks (such as foundation tasks) or adjust the assembly schedule to prevent equipment and worker downtime. Having this information about the exact time of arrival is especially important if the modular plant is located far from the construction site or if the delivery vehicle must pass through several warehouses or storage centers.

The technology proposed in this paper should be understood as part of a larger strategy to use technology innovations to improve the modular construction industry. The mechanization of individual construction processes has little effect on the efficiency and effectiveness of the whole project. Therefore, construction companies in technologically advanced countries, mainly Japan and South Korea, strive for computerization in every stage of the journey, including each step from planning and design to prefabrication and construction. The incorporation of technologies enables a better use of resources involved in the investment and construction process. This approach, which is called computer-integrated construction, is an adaptation of computer-integrated manufacturing for the construction industry.

The first step toward computer-integrated construction is to incorporate software solutions for architectural designing, structural designing, construction project management, and cost estimation purposes. BIM software is useful for these purposes. The technology should allow testing the functionality of a building through its design, and this feature requires the use of virtual reality simulations. The standardization of construction projects facilitates the application of computer-integrated solutions and makes the use of equipment more efficient, mainly by reducing the complexity of construction processes. The next step toward computer-integrated construction is to use high-quality prefabricated structures. The final stage is the design of construction systems, especially erection systems. There are existing systems that facilitate the automated construction and erection process.[26–33]

The fast construction of buildings means that office and residential property owners can start collecting rents sooner. On some projects, such as the construction of multistory buildings in the city center, inventory management solutions are needed because the working area must be limited.[34] Just-in-time management systems alleviate the need to store building materials and prefabricated elements, which take up considerable space.[35]

Recently, 3-D printing methods to print finished structures on site have gained popularity. Three-dimensional printers can generate structural designs using common materials, such as clay, gypsum, wood, metal alloys, thermoplastics, and ceramic composites. The first 3-D-printed steel bridge was opened in Amsterdam, the Netherlands, in 2021. The company that launched the project adapted six-axis robots to 3-D print elements in all directions possible. The first 3-D-printed house was built by a Chinese construction company. It is a 400 m^2 (4300 ft^2) two-story building made from concrete. The construction time was 45 days. The foundation and reinforcement operations were done conventionally, while other elements of the building were printed. Another Chinese company used 3-D printing technology to produce prefabricated elements. According to HuaShang Tengda,[30] the 3-D printing method can speed up the construction process by up to 70%, significantly reduce labor and execution costs by 50% to 80%, and improve construction site safety.

Three-dimensional modeling and BIM can be used to construct high-quality structures with accuracy. Some BIM software can construct two- and three-dimensional models of simple and complex shapes as well as support many file formats.[36] This versatility permits the insertion of additional "reference" models and the use of other modeling programs. The use of blockchain technology will help stakeholders achieve "smart" contracts and avoid the intervention of intermediaries. Such a strategy can substantially cut costs, save time for document processing, and make the industry more profitable.

Conclusion

In this study, transportation optimization models and storage patterns for modular construction components were developed based on real-time scheduling and material tracking. Four-dimensional BIM technology was used to obtain a real-time schedule. A system was developed to track construction components throughout the process. A simulation model was developed to optimize the storage layout, and models were used to optimize transport and handling times. With the proposed system, real-time tracking of the entire process and management of components from exit from the factory, transportation, on-site storage, lifting, and construction was implemented. The results demonstrate the effectiveness of the proposed models in the following three aspects:

- Compared with the situation without transportation tracking, the results obtained with the proposed model can effectively reduce the transportation time and the number of movements during component assembly.
- Using the proposed simulation model for component storage and lifting, it is possible to determine the transport time for each component.
- If storage space is limited, the storage optimization model can make rational use of storage space and improve component lifting efficiency.

The authors developed a digital twin platform to model and monitor logistics in modular construction in real time. The digital twin platform created BIM-based virtual objects and simulated GIS-enabled routing-based logistics scenarios. The authors tested the proposed structure, and the results show that the digital twin platform can predict the risks that may arise in logistics and calculate the exact time of arrival. Accurate prediction of the expected time of arrival reduced the loss of downtime. The main contribution of this research for reliable logistics modeling is the development of a new data structure that combines BIM, IoT, and GIS. Accurate risk prediction and arrival time calculation facilitate the coordination of deliveries between project participants and ensure timely delivery of construction modules. Timely delivery reduces the time and cost of modular construction, which helps modular construction become more widespread in the industry.

Limitations of the study were as follows:

- The duration of work in the scheduling was estimated only to allow modeling of vehicle traffic and loading and unloading operations; vehicle and equipment productivity were not included in the analysis.
- The results should be tested in other projects. For example, if the project to be tested is a bridge or road construction project, the BIM models will be different.

Innovative concepts and methods of construction can be means to improve construction project efficiency and cut project-related costs. This study focused on a manufacturing company operating in the modular construction industry. Established five years ago, the examined company has four years of experience in CAD and one year of experience in BIM. The paper offers a conceptual model of BIM-based information supply chain and an integrated BIM-aided framework for logistics management in construction projects. The proposed technology does not cause conflicts between BIM, IoT and GIS modules. The system aligns with PAS-1192-2 standards. The paper also compares the company's expenses before and after BIM integration. The suggested integration of IoT, BIM, and GIS sensors into a single network is expected to help predict various risks in the logistics process and accurately calculate delivery time based on multiple if-then scenarios. Conducted simulations of logistics processes for modular construction show that use of BIM technology reduces the average delivery time of the material by about 1.6 hours. The study found that BIM integration increased the cost of equipment and consumables. An advantage of the investigated approach was that it cut construction expenses. The following management strategies are proposed for the implementation of BIM technology in the construction company: develop policies for BIM software training for staff involved in project management at the facility; organize training of staff to improve their skills in using BIM software systems; and introduce policies for systematic review and adjustment of the model during construction work.

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Notation

a = number of displacements

$A(I)$ = maximum quantity of the Ith component that can be stored in the warehouse

$b(\tau, j)$ = number of cars shipped on the τth day from the jth plant

c = time spent on displacement

d_e = horizontal transport distance by truck

$d(j)$ = distance to the construction site from the jth plant

$D(\tau + 1, i)$ = demand on the τth + 1 day for the ith component

G = gross area of an element

h = vertical transport height

i = fundamental element of the precast concrete

I = number of different types of construction components supplied by J number of plants

j = modular unit

J = number of plants

k_1 = optimal planned specific minimization coefficients ($k_1 + k_2 = 1$)

k_2 = optimal planned specific minimization coefficients ($k_1 + k_2 = 1$)

L = site

$P(t)$ = efficiency of premises

$Q(i)$ = initial stock of the ith building component

$Q(\tau, i)$ = amount of stock on the τth day of the ith component

S = transportation cost

t = volume of the planned structure

T = floor plan orientation

u = stockpile factor

v_h = cranes' lifting speed of components when transshipped

v_v = horizontal transport speed by truck

w_i = transport complexity factor

$X(J, I, \tau)$ = proposed model denoting the amount of components I coming to the site from the Jth plant, on the Tth day ($J = 1, 2, 3, \dots J$; $I = 1, 2, 3, \dots I$; $\tau = 1, 2, 3, \dots \tau$)

Z = height of a structural element

τ = number of days after placing the order

τ_d = component overload time

τ_f = component of the horizontal transport time

τ_h = vertical transport time of components during transshipment

τ_v = time of displacements

$\tau(n)$ = transport time of the component to the construction site

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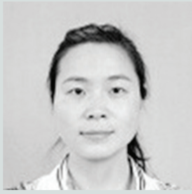

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Abstract

This paper presents an example of an integrated construction system that uses building information modeling (BIM), the internet of things (IoT), and geographic information system (GIS) technology to improve supply chain logistics management in construction projects, thereby increasing project efficiencies and controlling construction costs. The authors developed and tested a digital twin platform for the proposed system, which allows real-time simulation of logistics in modular construction. The proposed digital twin platform uses BIM and GIS as its foundation because BIM includes information on the plans, detailed geometry, properties, and quantities of modules, whereas GIS provides geospatial data for the modules along with vehicular information during transport. This system with integrated BIM, IoT, and GIS modules was applied in a new manufacturing company within its first five years. The results show that potential logistical risks and accurate module arrival time can be detected via the suggested digital twin platform. The integrated system proved to be effective in product delivery management tasks.

Keywords

BIM, block chain, building information modeling, geographic information system, internet of things, IoT, prefabricated building, supply chain.

Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute's peer-review process. The Precast/Prestressed Concrete Institute is not responsible for statements made by authors of papers in *PCI Journal*. No payment is offered.

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