



# Article Digital Twin for Supply Chain Coordination in Modular Construction

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**Abstract:** Over the past decades, the construction industry has been attracted to modular construction because of its benefits for reduced project scheduling and costs. However, schedule deviation risks in the logistics process of modular construction can derail its benefits and thus interfere with its widespread application. To address this issue, we aim to develop a digital twin framework for real-time logistics simulation, which can predict potential logistics risks and accurate module arrival time. The digital twin, a virtual replica of the physical module, updates its virtual asset based on building information modeling (BIM) in near real-time using internet of thing (IoT) sensors. Then, the virtual asset is transferred and exploited for logistics simulation in a geographic information system (GIS)-based routing application. We tested this framework in a case project where modules are manufactured at a factory, delivered to the site via a truck, and assembled onsite. The results show that potential logistical risks and accurate module arrival time can be detected via the suggested digital twin framework. This paper's primary contribution is the development of a framework that mediates IoT, BIM, and GIS for reliable simulation which predicts potential logistics risks and accurate module delivery time. Such reliable risk prediction enables effective supply chain coordination, which can improve project performance and the widespread application of modular construction.

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**Copyright:** © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). **Keywords:** modular construction; digital twin; building information modeling (BIM); geographic information system (GIS); logistics simulation

# 1. Introduction

Recently, modular construction has emerged as a promising construction method in the construction industry because of its potential to reduce project scheduling and costs [1]. The benefits of modular construction come from prefabricating a building module at an offsite factory while onsite foundations and assemblies are simultaneously performed [2]. To achieve maximum benefits (e.g., avoiding idle time for concurrent work), the module should be manufactured and delivered to the construction site on time. Thus, modular construction requires effective supply chain coordination among offsite manufacturing, logistics, and the onsite construction process [3–5]. However, modular construction typically involves complicated, volumetric, and large building components which can cause schedule deviation risks in the supply chain process [5,6]. Furthermore, since many modular construction projects take place in dense urban areas with limited space for module storage, such deviations exacerbate idle time [7]. For example, if a module arrives at the site earlier than planned, idle time occurs for the transporter; if it arrives late, idle time occurs for field workers and equipment. Therefore, it is essential that supply chain scheduling among project participants be certain in order to maximize the benefits of modular construction.

Recent studies have noted that digital twin technology can be an effective team coordination tool for supply chain management [8–11]. A digital twin can be described as a real-time digital replica of a physical asset that contains its current condition, properties, and dynamic behaviors [12]. In the supply chain process, a digital twin can represent manufacturing machines, module components, transportation, warehouses, delivery trucks, assembly workers, and cranes to visually monitor the project's current condition and progress. Also, a digital twin simulates diverse "what-if" real-world scenarios to accurately predict potential supply chain risks such as schedule deviation [8,9]. If the digital twin collects real-time sensor (e.g., global positioning system (GPS)) data, analyzes them accordingly, and provides all the useful insights (e.g., optimal delivery route, accurate delivery time, and optimal module order time) along the supply chain in modular construction, project participants may have effective coordination and subsequently, better project performance.

Despite its promising potential for supply chain management, existing digital twin research is mainly found in the contexts of product operation and shop floor management [13,14]. There is thus untapped potential for using a digital twin for logistics, the process in which modules are produced in a factory, stored in a warehouse, and then delivered—one key component of supply chain management in modular construction. Recently, studies have indicated that a digital twin could enable efficient logistics management, but their application has been limited to logistics in factories and warehouses [9,15,16]. There is still a lack of knowledge about the digital twin's practical application in logistics for construction projects where materials are delivered from offsite to onsite through transportation. Many logistical uncertainties and risks have thus not been addressed, posing a major barrier to the widespread application of modular construction.

To address this issue, we aim to develop and test a digital twin framework that enables real-time logistics simulation in modular construction. The digital twin uses building information modeling (BIM) and geographic information system (GIS) as its backbone because BIM can include detailed geometry, scheduling, quantities, and module properties while GIS provides geospatial data with transportation information (e.g., traffic and regulation), all of which are important for logistics simulation. Then, the digital twin collects real-time IoT sensor data (e.g., GPS) from its physical asset (e.g., module), simulates and analyzes the data to predict potential logistics risks, and finds alternative delivery routes with accurate estimated times of arrival (ETA). Such proactive risk detection and accurate delivery estimation minimizes logistical uncertainties, thus facilitating effective supply chain coordination for more productive modular projects.

## 2. Literature Review

## 2.1. Supply Chain in Modular Construction

The supply chain of modular construction involves many interdependent parties (e.g., manufacturer, retailer, and assembler) thus supply chain coordination is essential for a successful modular project [3]. Such coordination requires efficient information sharing among project participants to achieve a project goal (e.g., schedule reduction). Over the last decades, BIM has been widely applied in construction supply chain management. Aram et al. [17] suggested a BIM-based information flow process model for a reinforced concrete supply chain. Magill et al. [18] suggested a 4D BIM-based supply chain model to optimize logistics and on-site production. They stated that 4D BIM, which includes 3D BIM geometry and project schedule information, can help communication among stakeholders with better visualization. Lu et al. [19] provided a BIM- and discrete event simulation-based supply chain management model for effective team coordination. Nissila et al. [20] and Getuli et al. [21] suggested a cloud-based BIM data sharing service to exchange project schedule and status information among project participants. Ocheoha et al. [22] argued that BIM helps supply chain integration and may enable 'just-in-time' delivery that reduces cost and waste in modular construction. Fitriawijaya et al. [23] suggested an integrated blockchain technology and BIM for more traceable and immutable data communication in supply chain process. These studies show that BIM facilitates information (e.g., schedule and cost) sharing for design, fabrication, transportation, and onsite work; thus it has good potential to improve overall supply chain coordination in modular construction.

However, BIM-based supply chain management is limited in the logistics stage. BIM barely supports the logistics process because it does not have geospatial data. For example,

to find logistics risks (e.g., road accessibility, accident zone, and curfew) or to find the optimal module delivery route, external geographic information is needed together with BIM. Recent studies have thus tried to combine BIM and GIS for more accurate and effective logistics monitoring and management. Deng et al. used BIM and GIS to select optimal suppliers considering their transportation distance and material unit price. Irizarry et al. [24] and Wang et al. [25] integrated BIM and GIS to visually track logistic statuses together with spatial data for material delivery time estimation. Despite the potential of integrated BIM and GIS for logistics management, existing approaches do not often take into account dynamic transportation conditions (e.g., traffic and regulations), which makes it hard to estimate accurate module delivery time. Furthermore, modules leaving the factory are often large and heavy which are more vulnerable to real-time transportation conditions. For example, when an accident occurs on a highway and an alternative route needs to be taken, a more elaborate plan is required because the routes a modular truck can enter are limited in terms of size. Also, there is often not enough space to store a large module on site, so 'just-in-time' delivery is particularly important in modular construction. Wuni et al. [26] have noted that module delivery delay is still one of the most critical risk factors that derails the benefits of modular construction in practice. Therefore, modular construction logistics require more sophisticated schedule management than previous stick-built construction methods; more accurate and reliable logistics monitoring and simulation techniques are thus necessary for more effective supply chain coordination.

### 2.2. Digital Twin for Real-Time Monitoring and 'What-If' Analysis

A digital twin is a virtual representation of a physical object or system used to understand and predict potential issues across its lifecycle. A digital twin consists of three main components: the physical object, the virtual object, and the linkage between them [27]. Together, these components allow real-time object monitoring, data visualization, data analysis, and 'what-if' simulation to head off potential issues before they occur, deducing useful insights and opportunities. The digital twin was first proposed in the context of product lifecycle management [12] and has been applied most prominently by aircraft and aerospace industries to mirror vehicle conditions, systems, or processes for simulation analytics [13,14]. Since then, the digital twin has been applied in many different areas such as robotics [28], health monitoring [29], and manufacturing [15].

One important potential benefit of the digital twin in construction is to complement BIM and GIS for more 'live' information sharing. Digital twins can use BIM and GIS as a backbone, but also includes entire assets such as workers, materials, equipment, systems, and processes. For example, a more detailed and interactive construction process can be visually simulated using 4D BIM, human, and equipment twins. Digital twins allow for real-time asset visualization, behavior and performance monitoring, and operation simulation and optimization-all of which are important pieces of information to be shared among project participants. Particularly, the IoT sensor, a device that detects one or more physical asset conditions, converts these conditions into human and/or machine-readable signals, connects to the internet to communicate with others [30,31], and enables digital twins to be synchronized with the status of physical assets. There are many different types of IoT sensors: GPS [32], image sensor [33], proximity sensor [34], radio frequency identification sensors [35], motion sensors [36], and biosensors [37]—all of which are widely used in construction. On the other hand, the digital twin can exploit artificial intelligence (AI) for rich data analytics-challenges of previous BIM and GIS applications [38,39]. Recently, digital twins have been applied widely in construction for different purposes such as information sharing among project participants [11], smart city level infrastructure management through linkage with GIS [40], sustainability (i.e., plan, design, operation, and maintenance) evaluation of railway station buildings [41], bridge construction management [42], collapse assessment [43], and real-time monitoring and anomaly detection for built assets [44]. These studies have shown that the digital twin can effectively monitor assets in near real-time and test 'what-if' scenarios to detect risks and

optimize operation in a dynamic construction environment. If the digital twin is applied in logistics together with BIM and GIS in modular construction, it can monitor and simulate different logistics scenarios in real-time to predict any potential logistics risks and to estimate more accurate delivery routes and arrival times for true 'just-in-time' delivery. In addition, the whole supply chain process (i.e., manufacturing, logistics, and assembly) can be simulated and integrated through the digital twin to find optimal operation strategies (e.g., optimal module ordering).

Despite this potential, digital twins have mainly been used in the construction research domain for the operation management of individual products (e.g., equipment, robots, and buildings), leaving untapped areas for logistics monitoring [16]. One critical reason for this untapped potential is that BIM and GIS should be combined on one platform for logistics simulation, but they are created by different tools with different data formats. Although recent research has integrated BIM and GIS with interoperable data formats such as industry foundation classes (IFC) and city geography markup language (CityGML), information loss during data transformation often occurs and has not yet been thoroughly addressed. If any important information (e.g., module delivery and ordering schedule, geometry, traffic condition, and weather condition) needed for logistics simulation is lost through data transformation in the digital twin, the data may not be reliable enough for logistics simulation. Therefore, a method is needed to do logistics simulation in a digital twin using BIM and GIS without worrying about information loss.

### 3. Digital Twin Framework for Logistics Simulation in Modular Construction

The objective of this study is to develop and test a digital twin framework that integrates BIM and GIS in the application level for real-time logistics monitoring and simulation in modular construction. The digital twin can represent modular construction assets (e.g., module, delivery truck, workers, and other transportation objects) in real time. The digital twin subscribes to real-time IoT (e.g., GPS) data from physical assets and updates its virtual assets in virtual space based on BIM. Then, the digital twin can test different 'what-if' logistics scenarios with the virtual assets to find potential risks and optimal delivery paths based on GIS. The proposed digital twin avoids the information loss issue because it does not integrate BIM and GIS at the data level, but selectively exchanges only the information necessary for logistics monitoring and simulation in the application level. We test if the suggested digital twin can predict logistics risks in near real-time and how it affects predicted ETAs (estimated times of arrivals) and subsequent project scheduling in modular construction.

#### 3.1. Framework Overview

The digital twin framework consists of three components as shown in Figure 1. This framework shows how real-time sensory data (e.g., GPS) is collected from the module and updates the virtual asset in the virtual space. This synchronized virtual asset shows the current project's progress (e.g., location of module and assembly status). Then, the asset can be used for what-if analysis to predict potential logistics risks and find alternative plans. This framework's core idea is to create a virtual asset based on BIM to monitor current progress and to selectively request the analytics needed for logistics simulation in an application outside the digital twin.

## 3.2. System Architecture

The suggested digital twin framework's system architecture is shown in Figure 2. The system architecture shows the overall outline of the system and its data transaction flow in detail; it also shows how data analytics for logistics simulation can be performed without combining BIM and GIS in one data format.



**Figure 1.** Digital twin framework for real-time logistics simulation in modular construction: (**a**) data collection; (**b**) virtual asset update; (**c**) what-if analysis.



Figure 2. System architecture of the digital twin platform for logistics simulation.

The digital twin is composed of a web front end and a back-end. The back-end contains a Unity (Unity; Unity Technologies, San Francisco, CA, USA) engine. Unity is a game engine that helps create interactive 3D content in real-time. Unity also supports BIM plug-ins, connecting all project members on one collaborative and immersive platform for real-time information sharing with visualization. Also, Unity is designed to test different 'what-if' scenarios, by running millions of physical simulations in parallel. Thus, many function modules needed for real-time logistics monitoring and simulation in modular construction can be made on Unity. First, the project manager inputs BIM data required for a modular project (e.g., module geometry, color, material properties, delivery, and assembly schedule) and simulation parameters (e.g., production rate, assembly speed, and transportation speed) into the back-end's system. Meanwhile, IoT sensors collect real-time sensory data (e.g., GPS) from the modules while they are in the logistics stage. The Unity engine creates a virtual asset in a virtual space by combining the BIM and IoT sensor data. The virtual asset includes all information (e.g., geometry, current location, and material properties) from the physical module. The virtual asset itself can be used to monitor conditions or test the performance of logistics. Information required for logistics route searches (e.g., weight, geometry, factory and site location, and location of modules) can be selectively extracted via JSON format, a standard text-based data format that can be

read in any programming language. The information is then transferred Bing Maps (Bing; Microsoft, Seattle, Washington, DC, USA), an application that exists outside of the digital twin, through the application gateway in real-time. Bing Maps provides a cloud-based web mapping service for tasks such as finding locations, vehicle routing, and route visualization. Bing also includes an application programming interface (API) which allows users to create different types of map-based applications on their own platforms. For example, when a digital twin requests Bing Maps to search for a delivery route that excludes highways, it returns coordinates for every turning point of the truck based on recently updated GIS. In addition, Bing Maps provides a key benefit to modular truck routing in being capable of incorporating search constraints such as maximum slope, minimum turning radius, height and width restrictions, and maximum load restrictions [45].

There are two simulators in the back-end. One simulator is for the module's offsite production and onsite assembly simulation in the Unity Engine. Unity allows detailed 3D simulation and data analytics (e.g., performance test) [46]. For example, module production time, assembly time, cost, and equipment idle time can be simulated in Unity with a 3D model in real-time. The other simulator is for logistics simulation that is connected to Bing Maps in real-time and is responsible for finding the optimal logistics scenario with alternative routes. For example, the logistics simulator sends the current location and geometry of the module to Bing Maps and requests a route which does not require any permissions or tolls for transit. Alternatively, the simulator can request the fastest route regardless of tolls to deliver the module as soon as possible if onsite teams are finished with prior work and waiting for the next module. Also, the module's ETA is calculated by performing logistics simulation according to the route provided by Bing Maps. By using these two simulators, it is possible to simulate all key modular construction supply chain processes, such as module production, logistics, and onsite assembly, at once. Such integrated supply chain simulation can provide important information for effective coordination and collaboration among interdependent project participants. For example, it is possible to plan a 'just-in-time' delivery by adjusting the production and delivery schedule of a new module based on the current location of the module and its accurate ETA. Then, various logistics scenarios derived through simulation can be reviewed quantitatively in the Alternative Evaluator module. Finally, the optimal scenario can be visualized through the web front end and delivered to the project's participants.

## 4. Case Study

To test the proposed digital twin framework that integrates BIM and GIS for real-time logistics simulation in modular construction, we conducted a case study with a virtual modular construction project. In this project, physical assets' (i.e., truck and module) locations and sizes were synchronized with virtual assets in the digital twin based on BIM and hypothetical IoT sensor data. Then, the virtual assets were used for predicting logistics risks and for finding alternative routes in real-time with ETA.

In this case study, the authors intended to validate that real-time logistics simulation for modular construction would be possible without worrying about data conversion between BIM and GIS based on the proposed digital twin framework. This validation would also confirm that a digital twin can help find potential logistics risks and more accurate routes in real-time with ETA than existing vehicle routing applications.

#### 4.1. Project Description

The case project was a 6-story apartment modular construction project that was erected over 8 calendar days with 80 modules [47]. The modules were manufactured and delivered from the factory to the construction site located near downtown Seattle area (Washington state, USA) by truck in 90% completed condition. The distance between the factory and the site was 156 miles. Trucks did not go through an intermediate warehouse or separate retailer. The Department of Transportation required pilot vehicles, which escort trucks with oversized loads, along its journey and requested limited speed. It took 80 trips to

transport 80 modules and single-trip permits were required every time a module left the factory. Delivery trucks with modules were 14 feet wide, 50 feet long, 13 feet 6 inches high, and weighed about 20 tons. All of this information was stored in the building information model. The shortest delivery routes were searched for based on a vehicle routing application. Once a module was delivered on-site, it was assembled by a mobile crane and plumbing, electrical, HVAC, and mechanical systems were completed by the assembly crews. Since the site was in an urban area without enough stockyard space, the modules had to be delivered 'just-in-time' via consideration of previous history data on assembly and delivery times. Moreover, in the urban area, there were various logistics risks that imposed constraints on the routes heavy trucks could take, so it was a good project to achieve the purpose of the case study.

#### 4.2. Test Scenarios

To find logistics risks and alternative routes based on the proposed digital twin framework, the authors performed a logistics simulation with the case project. First, we created a digital twin that represents the case project. The project's BIM data (e.g., module geometry, weight, and assembly schedule) was input to the back-end system in the digital twin. GIS data (e.g., traffic, geographic data, road accessibility, regulation, curfew, and accident area) was updated in real-time in the Bing Maps application. One important point to note is that BIM and GIS are stored in different platforms and they do not communicate at the data level. This scenario was thus intended to demonstrate logistics simulation without data conversion between BIM and GIS. IoT sensor data should be collected from the truck and module to create a virtual asset, but such a sensor has not yet been implemented. Thus, we created a virtual server that generates hypothetical IoT sensor data including the location of modules in real-time. The IoT sensor data was delivered to the digital twin platform which created a virtual asset in a virtual space based on BIM. The necessary information for logistics simulation in a virtual asset is the geometry and weight of the truck loading a module. These data were selected by Unity and delivered to the Bing Maps API through the application gateway in JSON format. Bing Maps then used input data and GIS to find an appropriate route requested by the simulator. The simulator requested two routes for the case project: one was the route used in the actual case project (baseline-route)-explored without considering logistics risks-and the other was accurately calculated by considering all logistics risks (DT-route). Then, the alternative route provided by the digital twin was found by comparing these two routes. The loss (idle) time that would have occurred in the actual logistics process for 80 modules was quantitatively estimated by comparing the ETA values of the baseline-route and DT-route.

On the other hand, in the case of DT-route, the module delivery route is continuously re-searched in near real-time until it leaves the factory and arrives at the installation site. If potential logistics risks occur along the expected route, the digital twin finds and presents an alternative route and continuously updates the ETA. Such near real-time logistics simulation is particularly important because unplanned events (e.g., accidents and road construction) may occur during transportation and, accordingly, the module's optimal delivery route and potential logistics risks change over time. It may take significant effort and time to search for a new route by reviewing module information, traffic conditions, and road regulations from scratch. In this regard, the digital twin can help to search for alternative routes and update the ETA in near real-time when such vulnerable transportation conditions occur. This capability is enabled by data from connected IoT sensors which collect information such as the real-time status (e.g., quality and location) of the module. This capability ultimately supports rapid decision-making for project stakeholders if and when unexpected issues occur during the logistics process. For example, if the digital twin detects module damage, such information can be shared in near real-time among stakeholders to set up an onsite repair schedule or to request that the manufacturer ship the damaged part for quick repair.

# 4.3. Results

As shown in Figure 3, 6 risk types and a total of 12 risk points were detected from logistics simulation in the digital twin. One important fact here is that it is not possible to show all possible logistics risks because risks vary depending on current traffic conditions which change over time. The risks shown in the results give examples of possible risks posed to the case project at a specific time on a particular day. Such hard to predict risks can occur after planning. These risks should be continuously identified and avoided through real-time logistics simulation. In order to indicate the moving direction of the truck, the starting point was marked as 'S', and the destination point was marked as 'D' in the Figure 3. The red line shows the baseline-route and the blue line shows the alternative route (DT-route) found by the digital twin.



Figure 3. Six risk types identified from the logistics risk assessment.

The first risk involved truck height restrictions. The module carrying truck was designed to be 13 feet 6 inches in height per Washington state's truck height standards and regulations, but there were cases where it could not pass due to bridge or tunnel height limitations. The second risk involved highway width. Because the modules' widths

exceed 14 feet and the standard lane width in the US is 12 feet, trucks needed to drive on two lanes at the same time. Although trucks can drive this way on most highways with permission from authorities, several ramps have only one lane, making it impossible for the trucks to enter. The third risk arose from bridge weight limits. A truck loaded with a module reaches a maximum weight of 20 tons and the maximum load for several bridges is 17–19 tons, making it impossible for the trucks to enter. The fourth risk was posed by a steep gradient. A dangerous accident may occur if a 20-ton truck enters a slope of more than 10 degrees and this road had a 19-degree slope, so an alternative road that bypasses the slope was searched for. The fifth risk involved the truck's minimum turning radius and a sharp curve. Since the length of the truck reaches a maximum of 50 feet, it cannot rotate unless the curve's inner radius is longer than 28 feet and the outer radius is longer than 40 feet. The digital twin requested an alternative route in which the truck could rotate. The sixth and last risk came from the highway's speed limit. The routing application calculates ETAs based on average travel speeds along the road from historic data, but modular trucks must often observe a different speed limit from normal vehicles. For example, several highways limit the speed of trucks driving in two lanes to 60 mph when it is otherwise 70 mph. Therefore, the digital twin corrected the ETA's value while the truck was driving this section of the route.

Both the baseline-route and DT-route were quantitatively compared with a metric of ETA. In both cases, the ETA calculation was performed within a short time of fewer than 2 s, so no comparison was made for ETA calculation time. Since ETA is affected by traffic, the ETA value was calculated according to the delivery start time and drawn as shown in Figure 4a. Since traffic may vary depending on the day of the week, an ETA graph was drawn based on a seven-day average. For the baseline-route, an average of about 156 miles and an ETA of 2 h and 33 min were estimated. For the DT-route, an average of about 173 miles and an ETA of 4 h and 8 min were estimated. (Figure 4a). Since the DT-route ETA was calculated considering potential logistics risks, it can be assumed that this ETA is close to the actual module delivery time. Thus, approximately 1 h and 36 min of delivery time error can be expected in the baseline-route compared to DT-route. Another important implication in Figure 4a is that the predicted ETA value changes over time. A main reason for ETA changes is that traffic conditions change in real time due to factors such as rush hour, temporary accidents, curfews, and construction zones. Therefore, to predict ETA more accurately, it is essential for a digital twin to collect the location of a module while Bing Maps collects traffic conditions in real-time. Figure 4b shows the total idle time in logistics simulation for a total of 80 modules. Idle time is a value calculated by comparing the actual module arrival time (ground truth) in the simulator and ETA. Since all 80 modules have different delivery start times, traffic conditions vary. Therefore, idle time was calculated based on the average traffic pressure (i.e., number of vehicles per hour) during the logistics process. Traffic pressure was set to change randomly from 1 to 1.9 and 100 logistics simulations were performed for both the baseline-route and the DT-route. A traffic pressure value of 1 means that traffic conditions can change, but their average traffic is same as normal condition while transporting 80 modules. The normal condition refers to the average traffic flow for the given route. If traffic flow is greater than 1, the truck's average speed may decrease depending on road conditions and vice versa. Since the digital twin updates its route (DT-route) in real time and calculates a new ETA considering changed traffic, it guarantees less idle time compared to the baseline-route. As a result, while transporting 80 modules, baseline-route showed an average of total idle time about 173.2 h (standard deviation: 33.5 h). DT-route showed an average of total idle time about 15.7 h (standard deviation: 13.0 h). On average, DT-routes showed less idle time by about 157.5 h compared to baseline-route. In addition, the idle time of DT-route and baseline-route differed from the standard deviation by about 20.5.



Figure 4. Results of logistics simulation: (a) Average ETA for a module; (b) Total idle time for 80 modules.

In addition, one important result to note is that logistics risks were explored in near real-time and delivery route and ETA were accurately updated accordingly throughout the logistics process. Also, Figure 4b shows that the DT-route spurs less idle time and standard deviation than the baseline-route in different traffic conditions, which implicates that idle time in logistics can be reduced when ETA is updated in real-time even though average traffic pressure changes.

## 5. Discussion

Schedule deviation along the supply chain is a critical risk factor in modular construction. Such deviation often occurs in the logistics process because modules are vulnerable to transportation uncertainties due to their complexity and large size. To address this issue, this study suggested a digital twin that connects IoT sensors, BIM, and GIS to predict various risks that may occur in the logistics process and calculate an accurate ETA based on different what-if scenarios. One important aspect of the suggested digital twin is that it does not require any data conversion between different data formats (e.g., BIM and GIS), rather it mediates them on demand to avoid any information loss in data conversion. This aspect is particularly important in modular construction where different interdependent stakeholders use a variety of tools and data formats. For example, a manufacturer may not know how transportation will be impacted or what logistics risks will occur during the logistics phase because they normally do not use GIS-implemented vehicle routing tools. Conversely, it may be difficult for a transporter to know the geometry, schedule, cost, and weight of the module they carry because they normally do not use BIM in their work. For such reasons, supply chain simulation across different phases (e.g., production, logistics, and assembly) has not been thoroughly tried or realized. If multiple stakeholders and their different work platforms can be integrated at their application level (not the data level) through a digital twin for project monitoring and information sharing, effective supply chain simulation can be possible.

Furthermore, Figure 3 shows that a digital twin can predict potential risks and find alternative routes. Figure 4a indicates that such risk prediction and alternative route searching can predict a more accurate ETA. Also, Figure 4b shows that a digital twin guarantees much less idle time and less standard deviation regardless of traffic conditions. This is because the digital twin uses IoT sensors to update the module's location in real time and re-search the route with potential risks, so it can predict the accurate schedule deviation regardless of traffic uncertainty. Sharing an accurate ETA among all project participants (e.g., manufacturer and on-site assembly teams) can improve team coordination along a modular construction supply chain. Specifically, the module production schedule in the

factory, module shipment schedule, and on-site assembly schedule can be coordinated based on an accurate ETA. For example, if an unexpected accident occurs along the planned route during module delivery and the ETA is delayed by 10 h, the manufacturer may adjust the next module's production and shipment schedules while the on-site assembly teams can perform other tasks (e.g., foundation work) first or adjust their assembly schedule to prevent worker and equipment idle time. Having such ETA information is especially important if the module's factory is far from the construction site (e.g., outside the country) or if the delivery truck has to pass through multiple warehouses or inventory centers during the logistics process. Meanwhile, based on the updated ETA, the digital twin can be used to simulate different supply chain scenarios for efficient coordination. For example, to minimize project schedule delay due to a delayed ETA, various module production, delivery, and on-site assembly scenarios can be simulated for coordinated scheduling. Overall, such flexible supply chain coordination based on a digital twin can help reduce losses from potential logistics risks, consequently maximizing the benefits of modular construction.

The ability to accurately predict potential risks in a supply chain also can help widespread applications of modular construction. Presently, many construction players such as general contractors and sub-contractors may not be willing to participate in modular construction projects because of uncertain risks issues. Nobody wants to have liability for the uncertain risks such as schedule deviation and quality degradation in their supply chain. If such risks can be accurately predicted or detected in real-time, they can be clarified, allocated, and shared fairly or prevented altogether.

This paper focused only on predicting schedule deviation risks in the logistics process. Further research should be conducted for predicting overall supply chain risk (e.g., quality issues and cost overrun) management. First, offsite module manufacturing processes and onsite module assembly processes should be modeled in detail in a digital twin. For example, we can allow the digital twin can monitor the module manufacturing progress, or perform onsite module quality inspections (e.g., alignment checking and surface quality inspection). Then, such detailed models should be linked to the logistics scenario to enable overall supply chain simulation. Second, various IoT sensor data should be obtained for richer risk management. For example, this paper only considered the module's location data for logistics simulation. To consider overall supply chain coordination in modular construction other important data (e.g., module production status, geometrical quality, surface quality, and equipment schedule) should be obtained with different sensors in the future study. Lastly, when a risk occurs as predicted, the burden or loss due to the risk must be shared fairly among related stakeholders. For example, if the delivery of a module is delayed because of an unexpected weather change, the onsite assembly schedule may also be delayed, resulting in a large cost overrun. By sharing the loss due to such risk among related stakeholders, the negative impact of the unexpected event will be absorbed. In a future study, we will investigate how risks in modular construction can be fairly shared among stakeholders with aid of the digital twin.

#### 6. Conclusions

We developed a digital twin framework for real-time logistics monitoring and simulation in modular construction. The digital twin created a virtual asset based on BIM and simulated different logistics scenarios based on a GIS-enabled routing application. We tested the suggested framework in a case project and the results indicate that the digital twin can predict various risks that may occur in the logistics process and calculate an accurate ETA. Accurate ETA prediction reduced a total of 157.5 h in idle time loss. The main contribution of this study is the development of a new data framework which mediates IoT, BIM, and GIS without data format integration for reliable logistics simulation. A digital twin can predict potential logistics risks and accurate ETA based on reliable simulation. Furthermore, accurate risk prediction and ETA calculation can facilitate effective supply chain coordination among project participants and enable 'just-in-time' module delivery. Finally, 'just-in-time' delivery can help reduce scheduling and cost in modular construction, ultimately helping modular construction become more widespread in the industry.

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