Integrating 4D BIM and GIS for Construction Supply Chain Management

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Abstract: Construction supply chain management (CSCM) requires the tracking of material logistics and construction activities, an integrated platform, and certain coordination mechanisms among CSCM participants. Researchers have suggested the use of building information modeling (BIM) technology to monitor construction activities and manage construction supply chains. However, because material warehousing and deliveries are mostly performed outside construction project sites, project information from a single BIM model is insufficient in meeting the needs of construction supply chain management. In this research, an integrated framework was developed based on four-dimensional (4D) BIM and a geographical information system (GIS) for coordination of construction supply chains between the construction project sites and other project related locations, such as supplier sites and material consolidation centers. The proposed integration was used to solve three common tasks in CSCM, namely (1) supplier selection, (2) determination of number of material deliveries, and (3) allocation of consolidation centers, using information from 4D BIM and GIS. The proposed 4D BIM-GIS framework was demonstrated via case studies. The results of the case studies indicated that determinations of supplier and number of deliveries need to take into account both the transportation distance and material unit price. Mathematical solutions were also generated to support decision making for the allocation of consolidation centers in congested regions with long transportation distances. The outcomes of this paper serve as a decision support base for a more efficient CSCM in the future. **DOI: 10.1061/(ASCE)CO.1943-7862.0001633.**

Author keywords: Building information modeling; Construction supply chain management; Coordination mechanism; Geographical information system; Lean construction.

Introduction

A supply chain is a network of organizations that are involved, through upstream and downstream linkages, in different processes and activities that produce value in the form of products and services in the hands of the ultimate customers (Christopher 2008). Supply chain management (SCM) is to recognize the interdependency in supply chains and improve the performance of supply chains by minimization of inventory, cost, or waste (Vrijhoef and Koskela 2000). The construction industry is one of the largest industries in any country. For example, the US construction industry contributed $1,072 billion and accounted for 7.5% of the gross domestic product in 2008 (Bureau of Economic Analysis 2009). The construction industry has become more reliant on its supply chains, and statistical figures have shown that 75% of a main contractor's turnover is contributed by construction supply chains (Scholman 1997). However, the high fragmentation and one-off project-based nature of the construction industry pose a significant challenge to the efficient management of construction supply chains (Cheng et al. 2010). A closer look at the construction industry shows that a considerable amount of the waste produced in the construction industry is rooted in poor management of material supply chains (e.g., delivery services, inventory, and communications) (Omar and Ballal 2009). Therefore, the construction industry has an increasing need for tools and studies on efficient construction supply chain management (CSCM).

The keys to an efficient CSCM are to allow transparency of information and to develop coordination mechanisms for the participating entities involved in a construction supply chain. Shin et al. (2011) introduced a service-oriented integrated information framework to deal with frequent changes in the construction supply chain and improve time efficiency by about 32% compared with using traditional supply chain management tools. Cheng et al. (2010) proposed a prototype service-oriented web-based system that provides a single point of access to the distributed information, applications, and services among scattered supply chain members. Although these interfaces among stakeholders involved in construction supply chains facilitate information sharing and promote transparency, a coordination mechanism among the stakeholders also needs to be developed in order to make construction supply chains more reliable and cost-effective. Said and El-Rayes (2014) developed a multiobjective construction logistics optimization system to automatically retrieve project and supplier data for optimizing the material supply and site decisions toward the least CSCM costs. Some studies (Gan and Cheng 2015; Xue et al. 2005) have also attempted to integrate construction organizations into the construction supply chain and the negotiation model into a multiagent system (MAS), providing efficient communication and

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Note. This manuscript was submitted on April 12, 2018; approved on September 24, 2018; published online on February 12, 2019. Discussion period open until July 12, 2019; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Construction Engineering and Management***, © ASCE, ISSN 0733-9364.

coordination among the entities involved in construction supply chains.

Although there is abundant literature on the design, application, and evaluation of CSCM, the effective use of geographic data in CSCM has not been fully explored. Thöni and Tjoa (2017) argued that planning systems often make use of geographical information systems (GIS) that could help improve sustainability of production activities and of transportation links. Li et al. (2003) pointed out that location-related information plays an essential role in all kinds of business activities, including e-commerce systems for construction activities. Jadid and Idrees (2013) presented a framework to implement GIS in construction supply chain modeling, incorporating geographic data to locate the material suppliers so as to enhance the supply chain process. If detailed information on building projects (such as material demand) can be obtained and applied with geospatial data in GIS, CSCM has a more efficient mechanism to manage supply chains (Jadid and Idrees 2013). Building information modeling (BIM) technology provides detailed geometric and semantic information through the life cycle of buildings; hence, integrating BIM and GIS can utilize the advantages of both the detailed building information and large geospatial data in order to achieve more efficient CSCM.

During the last 10 years, integration of BIM and GIS has been studied and applied to the construction industry. Kim and Chai (2017) showed that information sharing is considered useful for promoting collaboration and cooperation in the supply chain. Information sharing builds better partnerships and promotes integration between suppliers and manufacturers in the supply chain, leading to better performance. Different integration methods have been proposed, such as the extraction of BIM data to the GIS context, extraction of GIS data on BIM platform, and integration of BIM and GIS on a third-party system (Ma and Ren 2017). A literature analysis carried out by Song et al. (2017) indicated that extracting BIM data to GIS [such as in the studies done by de Laat and Van Berlo (2011) and Liu et al. (2014)] is the mainstream of the integration methods. In these studies, Industrial Foundation Class (IFC) and City Geography Markup Language (CityGML) are two most comprehensive standards for exchanging semantic information and three-dimensional (3D) geography for BIM and GIS, respectively (Gröger and Plümer 2012). To avoid information losses between BIM and GIS during the integration process, different methods were used to enhance the information transformation. For example, a semantic extension called Urban Information Modeling was proposed to cover information on both the BIM and GIS models (Mignard and Nicolle 2014). Deng et al. (2016) applied an instance-based method to achieve seamless mapping of coordinate systems and geometry information between BIM and GIS in different levels of detail.

Integration of BIM and GIS opens up a new way to solve the issues in the construction industry. For example, Irizarry et al. (2013) and Wang et al. (2017) integrated BIM and GIS to visualize and monitor the status of construction supply chains. The developed system took advantages of rich data and visualization capability in BIM and GIS to support the supplier selection. Mignard and Nicolle (2014) used semantic graphs and ontologies defining relations to model the information in BIM and GIS so as to manage urban facilities (including urban proxy elements and buildings) in an interoperable way. Rafiee et al. (2014) and Wu and Zhang (2016) applied methods to integrate the geometric and semantic information of BIM models with geospatial models in order to support spatial planning in an urban environment, such as view and shadow analyses. Salimzadeh et al. (2016) reviewed recent approaches to perform urban energy assessment using computer modeling tools including BIM and GIS. Salimzadeh et al. (2016) also illustrated how to perform energy mapping and discover the spatial patterns of energy consumption using recent computer modeling tools. Aram et al. (2013) developed an information flow process model based on the detailed building element information in BIM in order to support the procurement of construction materials over the supply chain. The building element information in BIM was used with the geospatial analyses in GIS to manage the location planning process during the design and preconstruction stages (Karan and Irizarry 2015). Isikdag et al. (2008) investigated the applicability of high level semantic and geometric information acquired from BIM to the geospatial environment in GIS, focusing on the selection and analysis of the building construction site. The proposed building plan is taken from BIM to guide the site selection analysis in GIS, aiming at identifying the most suitable site for the building construction (Isikdag et al. 2008). Through transforming the BIM model and scheduling data into GIS, Elbeltagi and Dawood (2011) developed a visualization system to monitor the repetitive construction progress and evaluate the overall construction performance.

Integrated BIM-GIS methods have also been used to address logistic issues during construction. For example, Wang et al. (2017) transformed detailed and accurate building information in BIM to its corresponding geolocated model in order to provide strong support in supplier selection. The elements of a building and corresponding production details (e.g., model and manufacturers) were extracted from BIM for further use in GIS-based spatial analysis so as to provide an optimal solution for supplier selection. Irizarry et al. (2013) attempted to integrate BIM and GIS into a third-party system that supports monitoring of the supply chain status and provides warning signals to ensure the required deliveries of materials. Similarly, Zheng et al. (2015) employed BIM to conduct quantity take-off in the early procurement stage and used GIS to analyze the material deliveries in a CSCM system for monitoring the supply chain status. In addition to building construction, integration of BIM and GIS has been moved to wider applications, such as the management of highway construction (Fu et al. 2012) and cost estimation of a national road system (Park et al. 2014).

Even though BIM-GIS integration for CSCM has been studied, previous studies mainly focused on either the improvement of on-site construction activities (e.g., reduce the costs or duration of site activities) or the supply chain network itself (e.g., reduce logistics costs, lead time, and inventory). There has not been much success with the full integration of the two technologies in providing sufficient construction information and real-time analysis for CSCM. For construction projects nowadays with more complex configurations, it is a big challenge to manage the dynamic changes in materials and delivery orders in construction and to achieve the project completion timetable. Four-dimensional BIM (4D BIM) provides schedule-related and cost-related data of construction projects in addition to the geometric and material information. A deep integration of detailed building information in 4D BIM with the large geographic data in GIS can provide comprehensive analysis and understanding on the inventory and deliveries of materials for work-in-progress over the different construction phases, as well as for finished building elements and materials, from various suppliers to the construction site. Based on the information obtained from 4D BIM and GIS, mathematical optimizations can be performed to enhance the traditional CSCM process by addressing common logistic tasks such as (1) supplier selection, (2) determination of the number of deliveries, and (3) allocation of consolidation centers.

The primary objective of this study is to develop an integrated framework based on 4D BIM and GIS for efficient coordination between construction project sites and other project-related entities (such as suppliers and consolidation centers) in order to enhance the CSCM process. The proposed integrated 4D BIM-GIS framework provides information sharing and construction supply chain coordination for project managers using detailed project information (e.g., material demand) stored in BIM and the geographic information of suppliers and consolidation centers in GIS. Information from the 4D BIM is used to determine the construction activities and their material demands. A bidding and requisition module is developed based on GIS to allow suppliers to bid for material orders. The proposed framework applies the strength of both BIM and GIS technologies to evaluate and minimize costs in construction supply chains by generating optimized mathematical solution for the three aforementioned common CSCM tasks, i.e., (1) selecting suppliers, (2) determining the number of deliveries, and (3) allocating consolidation centers. The proposed framework serves as a decision support base for project managers to achieve the goal of on-time deliveries of material at the minimal supply chain cost. The structure of the paper is organized as follows: section "Literature Review on Common Tasks for CSCM" provides a review on the three common tasks in CSCM. Section "Proposed Integrated 4D BIM-GIS Framework for CSCM" describes the 4D BIM-GIS framework including mathematical solutions to the three CSCM tasks. Two case studies are presented, followed by the section "Conclusions."

Literature Review on Common Tasks for CSCM

There are three common tasks for CSCM. The first task is related to the material supplier selection; this becomes more critical when the supplier offering the lowest price is not the nearest in distance. The second task is related to the determination of the number of material deliveries, considering a balance between the material delivery charge and the on-site inventory cost. For example, reducing the number of deliveries will decrease the delivery charge, but will increase the need for on-site inventory and hence holding costs. The third task is related to the allocation of consolidation centers for the material supply to multiple construction project sites. Sections "Supplier Selection and Determination of Number of Deliveries" and "Allocation of Consolidation Centers" will provide a detailed review on the three common tasks for CSCM. Supplier selection and determination of the number of deliveries are highly interactive, and therefore will be discussed together in section "Supplier Selection and Determination of Number of Deliveries." Previous studies on the allocation of consolidation centers will be reviewed and discussed in section "Allocation of Consolidation Centers."

Supplier Selection and Determination of Number of Deliveries

Aissaoui et al. (2007) identified two major decisions that are related to supplier selection and number of deliveries problems. The first decision is to determine the type of material to be ordered as well as the suppliers for purchasing the order. Around half of the relevant studies considered cases in which suppliers are selected for only one type of product. In addition, it was assumed that all the suppliers in the construction industry can fully meet the contractor's requests in terms of quantity, quality, and deliveries, among others. Consequently, the actual concern is to identify the most appropriate supplier with relatively lower material cost and transportation distance. The second decision is to determine the optimal number of deliveries required, which is also related to the inventory lot-sizing. Incorporating the decision on supplier selection to schedule the number of deliveries over time can significantly reduce costs over the planning horizon.

There have been some studies on the synergy effect of supplier selection and number of deliveries. Kasilingam and Lee (1996) examined the development of a chance-constrained integer programming formulation to address the supplier selection problem and determined the number of deliveries to be placed. However, the unit cost of each item in their model already included the transportation cost and did not change irrespective of the delivery distance. Jayaraman et al. (1999) also presented a mixed-integer programming formulation for supplier selection, with a model that helps choose an optimal set of suppliers, taking into account quality requirements, restrictions in storage and production capacity, and production lead time. However, that study did not consider the delivery cost of the products, but it was estimated that the transportation costs accounted for 10%–20% of construction costs (Shakantu et al. 2003). In this regard, the locations of suppliers and project sites and transportation distances need to be retrieved. Thus, GIS can be introduced in the CSCM process to support the wide range of network spatial analyses used in the supply chain coordination process. Jadid and Idrees (2013) leveraged geographic data in GIS to locate the suppliers for construction materials and thereby enhanced the CSCM.

To acquire accurate data on the amounts and types of materials, Wang et al. (2017) and Volkov and Sukneva (2013) applied geometric and material information from BIM to the geospatial environment in GIS, aiming to provide strong support for the selection of material suppliers. Irizarry et al. (2013) also attempted to develop a unique system using BIM and GIS, enabling an efficient tracking for the supply chain status and providing signals for the deliveries of materials. However, previous studies on BIM-GIS for CSCM did not take into account the project completion timetable and did not provide sufficient and varying construction information for CSCM. As construction projects nowadays have become more complex, it is challenging to manage the dynamic changes of materials and delivery orders over different construction phases. The use of 4D BIM can provide time-related and schedule-related data on construction, thereby supporting supplier selection and determination of number of deliveries for work-in-progress over different construction phases.

Allocation of Consolidation Centers

Consolidation centers are regional stocking points where construction materials can be stored before distribution to the site in order to avoid congestion of materials at the site loading area. Implementation of a consolidation center solves problems due to the lack of storage space on construction sites. Kasim (2008) studied the benefits of establishing consolidation centers in an airport terminal and airfield modification project. It was revealed that establishing consolidation centers in a supply chain provides improved site security and safety, reduces congestion from construction traffic within the airport, improves delivery reliability and workforce efficiency, enhances environmental benefits, and reduces materials losses. In addition, establishing consolidation centers ensured that correct construction materials are efficiently delivered to the correct construction sites at the right time (Kasim 2008). Although there have been studies on the consolidation centers for construction projects, there is still a lack of studies on the details of allocation of consolidation centers for CSCM. Most of the previous studies focused on the design and operation of consolidation centers for the manufacturing industry. For example, Song et al. (2008) developed coordination mechanisms for shipments while considering (1) product release times at the source locations, (2) latest arrival times at the destinations, (3) routes and options used for the transportation,

(4) storage cost at the consolidation center, and (5) consolidation policies.

However, there is limited literature concerning the design and allocation of consolidation centers in the construction industry. Isikdag et al. (2008) implemented a BIM-GIS integration framework to select the optimal site location for constructing a specific building considering the building shape and different material suppliers, the concept of which is related to the setup of consolidation centers. Shigute and Nasirian (2014) studied the coordination mechanism among consolidation centers, material suppliers, and construction sites. Although there has been some research on the coordination mechanism among various supply chain participants, studies on optimal allocation of the consolidation centers are still lacking. A primary objective of this study is to determine the optimal locations of the consolidation centers in CSCM in order to minimize the costs for material inventory and deliveries. In this regard, the project information can be retrieved from 4D BIM, and the allocation problem can be solved using the network analysis functions in GIS, which will be discussed in section "Proposed Integrated 4D BIM-GIS Framework for CSCM."

Methodology: Proposed Integrated 4D BIM-GIS Framework for CSCM

The CSCM process requires information from different data sources (e.g., construction projects and logistics) as well as reliable analytical functions in order to support management decision making. As such, the proposed integrated 4D BIM-GIS framework will have three layers: (1) data storage and retrieval layer, (2) analysis layer, and (3) application layer. As Fig. 1 shows, the data storage and retrieval layer extracts necessary information to support the analysis layer and application layer. The data used in the analysis layer are retrieved from 4D BIM (via project files), user input, and GIS (via a geodatabase). The 4D BIM provides a full range of construction project information (such as construction schedule, material quantity, and on-site inventory), whereas GIS provides the logistic information (such as location, transportation distance, and traffic network). The retrieved data are then used by the analysis layer (e.g., cost analysis or network analysis) in order to support CSCM tasks in the application layer.

The use of 4D BIM and GIS provides opportunities to minimize the manual effort for data input, and all data can be stored in the geodatabases in GIS with customized analytical functions. A detailed quantity take-off of the construction project is executed at the early stage of procurement from BIM, and GIS is used to support a wide range of analysis functions to provide decision making in the CSCM process. The data from BIM are exported to databases linked to GIS, which are used for analysis. The manual-input data are mostly related to the quotations for materials from multiple suppliers and changes in the current project plans. It is possible that some of the construction activities, for example scaffolding, are not present in the 4D BIM. In this case, manual inputs of such activities along with their material demand and time duration are needed. In the proposed CSCM framework, data storage, analysis, and decision making are performed in a GIS system. GIS has the capacity to store massive amounts of data and the ability to access fundamental analysis tools such as route finding for delivery cost analysis.

Data Storage and Retrieval Layer: Using BIM Data in a GIS Environment

There are a number of data exchange standards to address how 3D geometry information can be used within the architectural, engineering, and construction (AEC) industry. The open BIM standard, namely IFC, is considered to be a nonproprietary data standard supported by most BIM tools. Therefore, a schematic extension that enables seamless mapping between IFC and the input data formats used by GIS (i.e., CityGML) was developed for the proposed CSCM system, with reference to Deng et al. (2016). A parser was developed to read related information for CSCM from the IFC file using Java. The customized parser can retrieve information from 4D BIM files and pass to the geodatabase for CSCM. The parser also ensures that changes in the 4D BIM can be retrieved

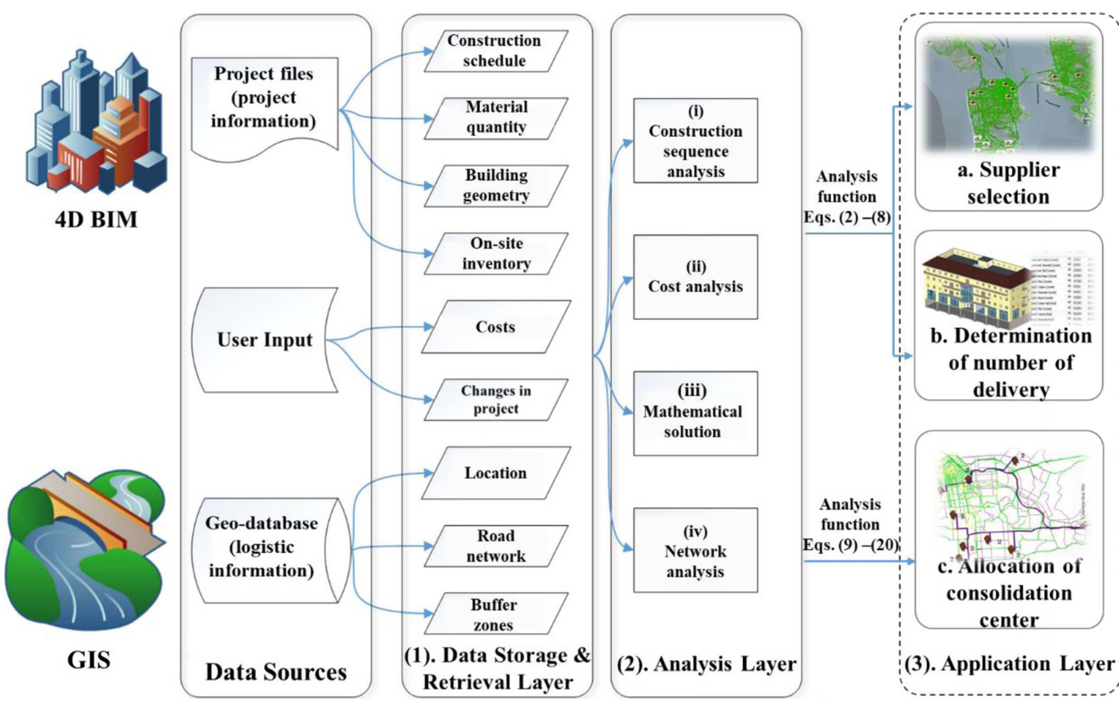


Fig. 1. Framework overview.

and that the geodatabase is updated. The data storage of the proposed CSCM framework is achieved in the GIS using a geodatabase. Entity families in the IFC standard are extended to store information for supply chain management and for spatial analysis in GIS, namely the *project*, *supplier site*, and *ordering*. The *project* entity stores information retrieved from BIM along with the geolocation of the project site. The *supplier site* entity stores the location of the supplier site, the material supplied, and the price of the material and delivery fee ratio. The *ordering* entity links the *supplier site* and *project* entity. It stores information about ordering cost, inventory cost for a certain order and penalty cost. The notation used in subsequent sections are given in the "Notation" section, and the schema design of the database is shown in Fig. 2. Time-related and schedule-related information on construction projects are taken from 4D BIM to support supplier selection and determination of number of deliveries over different phases.

The duration of a construction activity i (retrieved from BIM), denoted by $D_{a,i}$, is calculated

$$D_{a,i} = \mathrm{ET}_{a,i} - \mathrm{ST}_{a,i} \tag{1}$$

where $\mathrm{ET}_{a,i}$ = completion time of a construction activity i in site CS_a (from BIM); and $\mathrm{ST}_{a,i}$ = starting time of a construction activity i in site CS_a (from BIM).

Similarly, this study assumes that a consolidation center z was built and located with a delivery distance of DD^l_{sz} from a material supplier SS^l_s and a distance of DD^l_{za} to a project site CS_a (transportation distances are measured from GIS). The inventory capacity of consolidation center z for material l is I^l_z.

It is noticeable that the system provides a quotation function that enables user to input different instances of *supplier site*. Given different quotations of unit price of materials and delivery fee ratios, the framework computes the total cost for each supplier site considering delivery cost, inventory cost, ordering cost, and material price. This computing process also generates the optimal number of deliveries and material delivery plans. The analyses and mathematical solutions are provided in sections "Analysis Layer" and "Application Layer."

Analysis Layer

The proposed CSCM framework utilizes several fundamental analysis tools from both 4D BIM and GIS to help generate mathematical solutions for supplier selection, number of deliveries, and allocation of consolidation centers. Four analysis tools are essential to the proposed CSCM framework, namely (1) construction sequence analysis, (2) cost analysis, (3) mathematical solution generator, and (4) network analysis tools.

The construction sequence analysis tool aims to establish the interdependency of activities in a construction project. It is mainly achieved by using 4D BIM software such as Navisworks version 2015. The interface of the data input in Navisworks is shown in Fig. 3. The construction sequence analysis is helpful when there are changes in the project plans or material delivery plans. For example, when some activities are delayed, the construction sequence analysis can be used to determine the subsequent activities and the impact of the delay on the final delivery of the construction project.

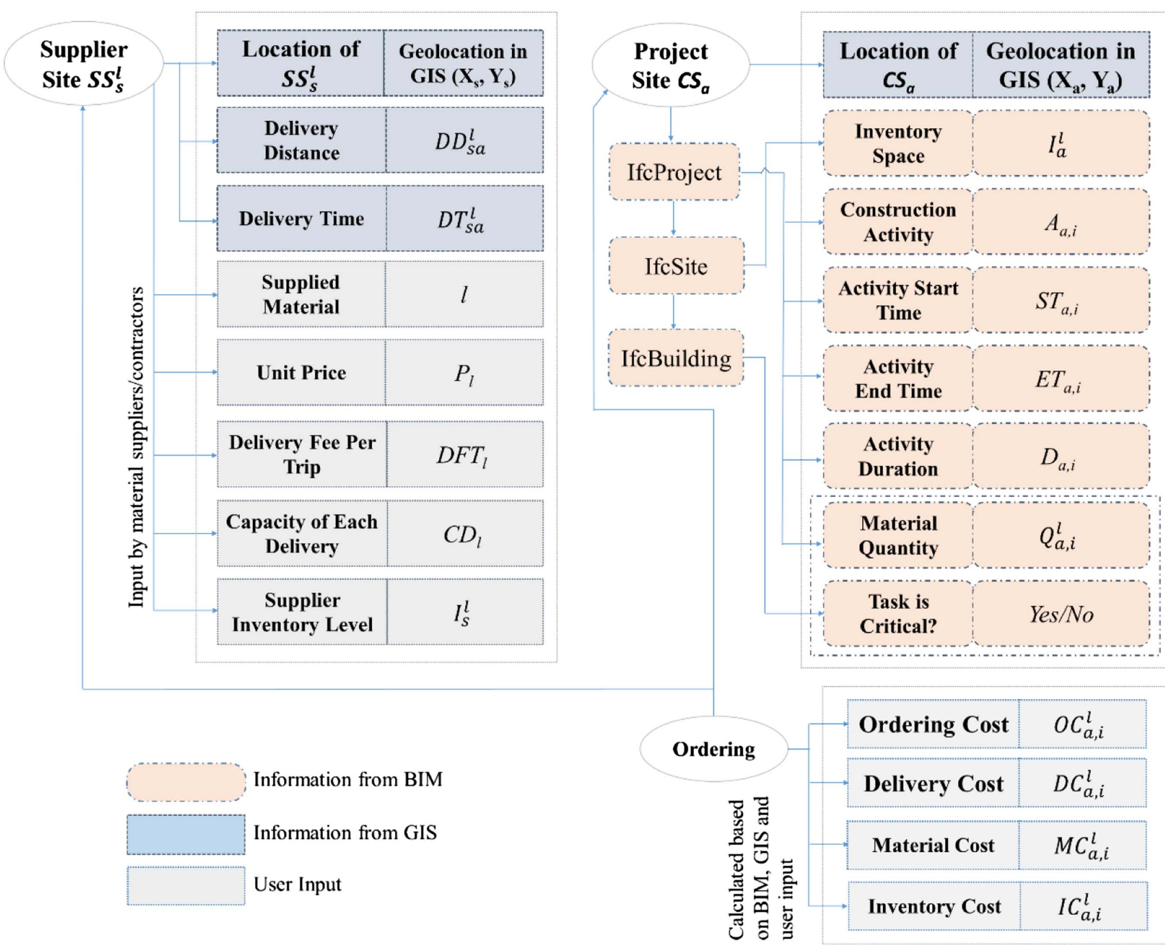


Fig. 2. Database design for the proposed BIM-GIS based CSCM framework.

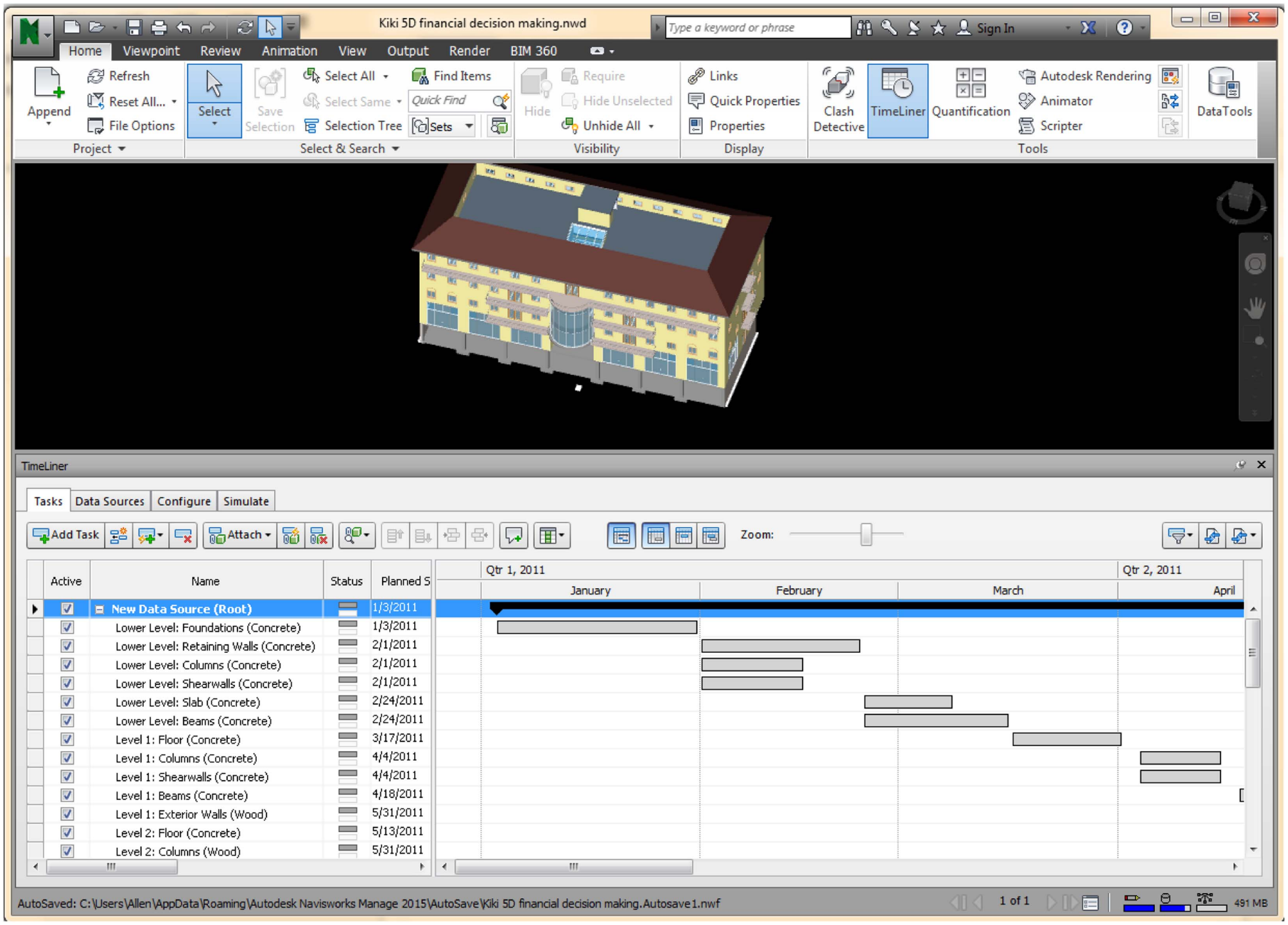


Fig. 3. Data input in Navisworks.

A customized program (also known as a plug-in) was developed in the ArcGIS version 10.1 system. The program uses data stored in the geodatabase in order to compute the costs incurred during the procurement process for subsequent analyses. In this study, ordering cost, delivery cost, and inventory cost are considered for generating optimal solutions to CSCM common tasks. The mathematical solution generator in the proposed BIM-GIS framework could adopt Monte Carlo simulation to compute the solution and tackle stochastic issues such as different choices of suppliers or uncertainty in traveling time among others.

The network analysis tool computes routes from one location to another in a given network. A network is a system of interconnected elements, such as edges (lines) and connecting junctions (points) that represent possible routes from one location to another. The network analysis in GIS allows computing of the shortest paths from the supplier sites to the project sites, which are the basis for computing delivery fees. With the data obtained from the four analysis tools, specific mathematical solutions are generated to support decision making, which will be discussed in section "Application Layer."

Application Layer

With the results obtained from the analysis layer as described in section "Analysis Layer," mathematical solutions are generated in order to support decision making in terms of three aspects: (1) supplier selection, (2) determination of number of deliveries, and (3) allocation of consolidation centers. The supplier selection and number of deliveries are solved together, whereas the allocation of consolidation centers is solved by another set of mathematical functions.

Proposed Mathematical Solutions for Supplier Selection and Determination of Number of Deliveries

It was assumed that all the materials are delivered right on time in the ordered amount. Therefore, in a case where only one order is needed, the normal ordering time will be related to the lead time of the material deliveries. An arrangement of material ordering needs to be identified based on information from BIM (e.g., material demand and scheduling information) and GIS (e.g., geolocations and travel distances) in order to

- Determine the optimal supplier site SS_s^l via GIS for each construction activity $A_{a,i}$ obtained from BIM (because the ordering cost, delivery cost, and material cost will change considerably for different supplier sites); and
- Compute the optimal number of deliveries $N_{a,i}$ for each construction activity $A_{a,i}$ considering the ordering cost, delivery cost, and inventory cost.

Following the principle of just-in-time, the ordering cost can be calculated

$$OC_{a,i}^l = OCR \times Q_{a,i}^l \tag{2}$$

where $OC^l_{a,i}$ = ordering cost; OCR = ordering cost rate proportional to the quantity of materials being ordered; and $Q^l_{a,i}$ = quantity of required materials obtained from BIM.

The delivery cost can be calculated

$$DC^l_{a,i} = N \times DD^l_{sa} \times DFT_l \tag{3}$$

where $DC^l_{a,i}$ = delivery cost; N = optimal number of deliveries ($N \geq Q^l_{a,i}/CP_l$, where CP_l is the capacity of one delivery, i.e., the amount of material l that can be delivered each time); DD^l_{sa} = delivery distance from a material supplier to the project site taken from GIS; and DFT_l = delivery fee per trip for material l.

The material cost can be calculated as the product of material quantity and unit price

$$MC^l_{a,i} = Q^l_{a,i} \times P_l \tag{4}$$

where $MC^l_{a,i}$ = material cost; $Q^l_{a,i}$ = quantity of material l; and P_l = unit price for material l.

Following the rule of just-in-time delivery, the inventory level on project sites for materials is shown in Fig. 4. In an ideal case, the on-site inventory is replenished when the inventory level hits zero. Assuming that the inventory level drops at a constant rate, for each delivery, the inventory cost can be calculated

$$ICC^l_{a,i} = \frac{Q^l_{a,i}}{N} \times \frac{D_{a,i}}{N} \times \frac{1}{2} \times ICR \tag{5}$$

Considering N times of deliveries, the total inventory cost can be calculated

$$IC^l_{a,i} = \frac{Q^l_{a,i} \times D_{a,i}}{2N} \times ICR \tag{6}$$

where ICR = inventory cost rate, proportional to the inventory level.

Thus, the optimization problem becomes finding the supplier site SS^l_S and the optimal number of deliveries N in order to minimize the total logistic cost, as follows:

$$\text{miminize } OC^l_{a,i} + DC^l_{a,i} + MC^l_{a,i} + IC^l_{a,i} \tag{7}$$

subject to

$$Q^l_{a,i}/N \leq I^l_a \tag{8}$$

$$Q^l_{a,i}/N \leq CD_l \tag{9}$$

Eq. (8) refers to the on-site inventory level, and Eq. (9) stands for the capacity of deliveries for suppliers. Only a finite number of suppliers and a finite discrete number of delivery orders are considered in the solution. If the unit price of construction materials varies significantly, Monte Carlo simulation could be used to solve Eq. (7) for identifying the appropriate supplier site SS^l_s and the optimal number of deliveries N.

Proposed Solution for Allocation of Consolidation Centers

Although there were studies on the consolidation centers for construction projects (Kasim 2008), there is a lack of studies on the details of allocation and setup of consolidation centers which will be discussed in herein. In Eq. (6), the ordering cost ($OC^l_{a,i}$) and material cost ($MC^l_{a,i}$) are known for a given amount of a particular material. The unknown cost items, namely the delivery cost ($DC^l_{a,i}$) and the inventory cost ($IC^l_{a,i}$), are related to the locations of the project and supplier sites, which can be further expressed

$$\text{Location-related cost} = DC^l_{a,i} + IC^l_{a,i} \tag{10}$$

or alternatively as follows:

$$\text{Location-related cost} = N \times DD^l_{sa} \times DFT_l + \frac{Q^l_{a,i} \times D_{a,i}}{2N} \times ICR \tag{11}$$

In a congested project site where on-site inventory level (I^l_a) is low, then

$$I^l_a = Q^l_{a,i}/N \tag{12}$$

Eq. (11) becomes

$$\text{Location-related cost} = \frac{Q^l_{a,i}}{I^l_a} \times DD^l_{sa} \times DFT_l + \frac{I^l_a \times D_{a,i}}{2} \times ICR \tag{13}$$

As Fig. 5 shows, the on-site inventory level where the location-related cost is at minimum is equal to

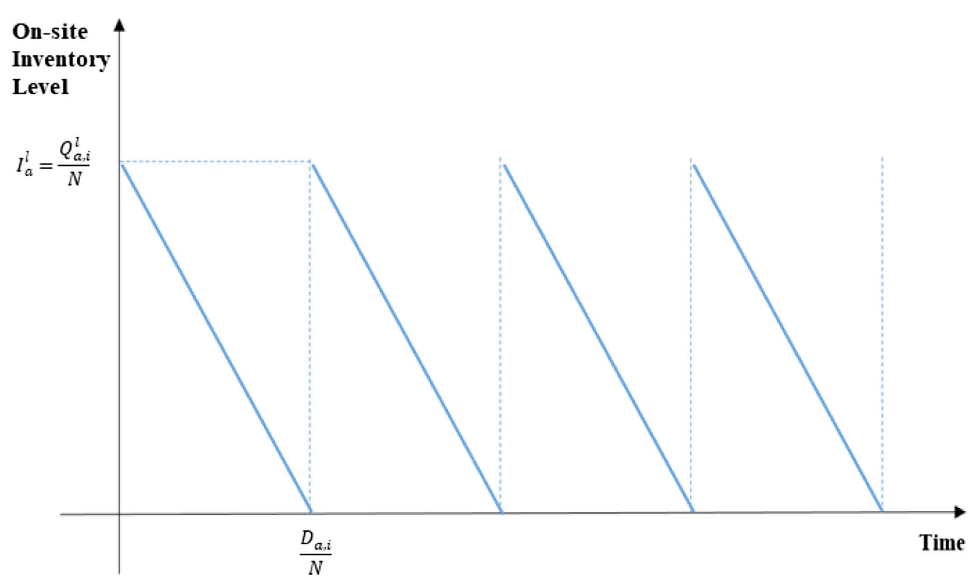


Fig. 4. Computation of the inventory cost.

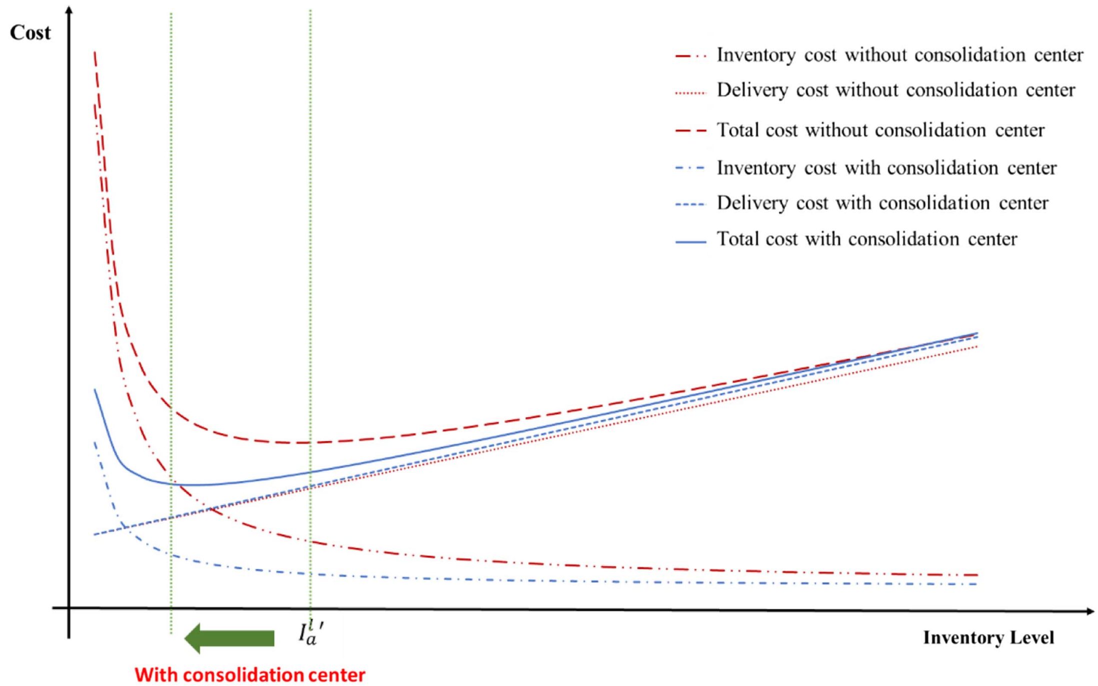


Fig. 5. Relationship between location-related cost and on-site inventory level.

$$I_a^{l\prime} = \sqrt[4]{\frac{8 \times Q_{a,i}^l \times \mathrm{DD}_{sa}^l \times \mathrm{DFT}_l}{D_{a,i} \times \mathrm{ICR}}} \tag{14}$$

Eq. (14) reveals the relationship between on-site inventory level and location-related cost; $I_a^{l\prime}$ can be regarded as the critical threshold. As Fig. 5 shows, if the on-site inventory level (I_a^l) is less than the critical threshold ($I_a^{l\prime}$), the location-related cost will increase rapidly. If material supplier sites are close to the project site, the critical threshold of on-site inventory level ($I_a^{l\prime}$) is small, and the on-site inventory can be set at a low level. However, if the supplier sites of a particular material are far away from the project site, the value of $I_a^{l\prime}$ becomes large, implying that the on-site inventory must be set at a high level to guarantee the supply reliability. In such a case, allocating consolidation centers becomes beneficial in reducing the location-related cost.

Searching for the optimal location for a consolidation center is related to the location of the project site and supplier sites, as well as the traffic network itself. Suppliers will deliver materials to a consolidation center, from which the materials are further shipped to the project site. Assume that a consolidation center z is located with a distance of DD_{sz}^l from a supplier site SS_s^l and with a distance of DD_{za}^l to a project site CS_a. The site locations (i.e., SS_s^l and CS_a) and transportation distances (i.e., DD_{sz}^l and DD_{za}^l) can be obtained from GIS. The inventory capacity of z for material l is I_z^l. In general, a consolidation center has larger inventory capacity that of a project site

$$I_z^l > I_a^l \tag{15}$$

The total cost for material deliveries and inventory as well as the setup cost of a consolidation center can be expressed

$$\text{Total cost} = \left(\frac{Q_{a,i}^l}{I_Z^l} \times \mathrm{DD}_{sz}^l \times \mathrm{DFT}_l + \frac{I_z^l \times D_{a,i}}{2} \times \mathrm{ICR}\right) + \left(\frac{Q_{a,i}^l}{I_a^l} \times \mathrm{DD}_{za}^l \times \mathrm{DFT}_l + \frac{I_a^l \times D_{a,i}}{2} \times \mathrm{ICR}\right) + \mathrm{ZC} \tag{16}$$

where ZC = cost to set up a consolidation center; $(Q_{a,i}^l/I_Z^l) \times \mathrm{DD}_{sz}^l \times \mathrm{DFT}_l + (I_z^l \times D_{a,i}/2) \times \mathrm{ICR}$ = total logistic cost for transporting material from the consolidation center to the construction; and $(Q_{a,i}^l/I_a^l) \times \mathrm{DD}_{za}^l \times \mathrm{DFT}_l + (I_a^l \times D_{a,i}/2) \times \mathrm{ICR}$ = total logistic cost for transporting material from the supplier site to the consolidation center.

Because a consolidation center usually obtains materials from different suppliers and delivers the materials to multiple construction project sites, the objective function for finding an optimal location of a consolidation center can be derived from Eq. (16), as follows:

$$\text{minimize} \sum_{s\in S} F_{sz} \times \mathrm{DD}_{sz}^l + \sum_{a\in A} Fza \times \mathrm{DD}_{za}^l + F_z \tag{17}$$

subject to

$$F_{sz} = \frac{Q_{a,i}^l}{I_Z^l} \times \mathrm{DFT}_l \tag{18}$$

$$F_{za} = \frac{Q_{a,i}^l}{I_a^l} \times \mathrm{DFT}_l \tag{19}$$

$$F_z = \frac{I_z^l \times D_{a,i}}{2} \times \mathrm{ICR} + \frac{I_a^l \times D_{a,i}}{2} \times \mathrm{ICR} + \mathrm{ZC} \tag{20}$$

where F_z = cost constant; and F_{sz} and F_{za} = cost ratios proportional to the transportation distances of DD_{sz}^l and DD_{za}^l, respectively. Eq. (17) was used to evaluate different candidate locations for setting up consolidation centers. If a specific area is designated for the location of consolidation centers, the problem will become a discrete simulation issue using point sampling in that area. An illustrative case study is used to show the workflow for finding the optimal location of a consolidation center.

Case Studies

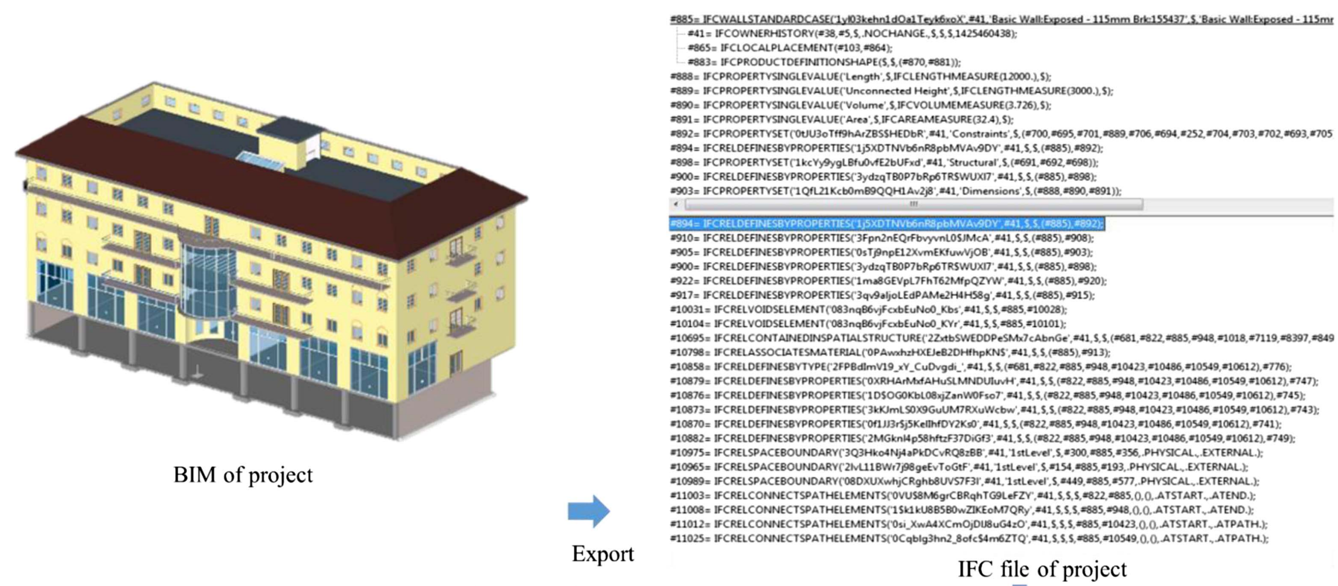
A 5-story building project and the road network data for San Francisco, California have been used to demonstrate the proposed 4D BIM-GIS framework and its mathematical solutions for supplier selection and determination of number of deliveries in a construction supply chain. Because selection of the material supplier cannot rely solely on the unit prices or the nearest delivery distances, another case study considering a network with five project sites and 15 suppliers is used to demonstrate the problem of allocating consolidation centers.

Determining the Supplier and Number of Deliveries

For the first case study, a 3D model of the building was created using BIM software Autodesk Revit version 2015. The schedule information was added to the BIM later by linking to project databases using Navisworks. The generated 4D model was exported to IFC format, which was then parsed by the developed parser. All the relevant information for CSCM was finally exported to data tables in the GIS system, which is based on ArcGIS. The data input process is shown in Fig. 6.

Here, 230-mm-thick brick was used for the construction of interior walls in order to demonstrate the material selection process. The potential suppliers willing to supply this material and their location, along with the location of the project site, are shown in Fig. 7. The GIS network analysis function allows route finding with the shortest distance, which is used for delivery fee estimation, and the results are shown in Fig. 7. The manual input function is used to enter the information on different potential suppliers. The delivery distances are obtained from the network analysis to represent the actual delivery distances. All the information regarding different suppliers is given in Table 1. Based on the information given in Table 1 and Fig. 6, the cost analysis function in the framework computes the delivery cost and on-site inventory cost for every potential supplier, considering different numbers of deliveries. It is noticeable that every possible solution is computed for the selection of suppliers and the number of deliveries because the total number of suppliers and construction sites considered in the case study is relatively seldom. Table 2 provides the result for the cost analysis. It is clear that with the increased number of deliveries, the on-site inventory cost decreases while whereas the delivery cost increases. In order to find the suppler with the lowest cost, the total costs were analyzed. The results are presented in Table 3 and Fig. 8.

It can be seen in Fig. 8 that when selecting supplier SS_2 and setting delivery time to four, the total cost is minimized. It is noticeable that supplier SS_2 is neither the supplier with the lowest unit price, nor the supplier with the shortest delivery distance to the project site. This proves that the selection of suppliers is not solely based on the unit prices or the distance of suppliers. Moreover, supplier SS_6 has the lowest unit price, but because a relatively large delivery distance is involved, the total cost is still high.



Active	Name	Status	Planned Start	Planned End
	Lower Level: Columns (Concrete)		2/1/2011	2/15/2011
	Lower Level: Shearwalls (Concrete)		2/1/2011	2/15/2011
	Lower Level: Slab (Concrete)		2/24/2011	3/8/2011
	Lower Level: Beams (Concrete)		2/24/2011	3/16/2011
	Level 1: Floor (Concrete)		3/17/2011	4/1/2011
	Level 1: Columns (Concrete)		4/4/2011	4/15/2011
	Level 1: Shearwalls (Concrete)		4/4/2011	4/15/2011
	Level 1: Beams (Concrete)		4/18/2011	5/12/2011
	Level 1: Exterior Walls (Wood)		5/31/2011	6/21/2011
	Level 2: Floor (Concrete)		5/13/2011	5/30/2011
	Level 2: Columns (Wood)		5/31/2011	6/13/2011
	Level 2: Shearwalls (Wood)		5/31/2011	6/13/2011
	Level 2: Beams (Wood)		6/14/2011	6/21/2011
	Level 2: Joists (Wood)		6/14/2011	7/5/2011

Adding schedule and cost to BIM

Activity ID	Activity Name	Material ID	Material Name	Material Quantity	Start Time	End Time	Onsite Inventory
Level 1: Interior Wall	4	120	**Brick (230mm)**	1600	4/19/2014	6/25/2104	1200
Level 1: Interior Wall	4	121	Wood	26	4/27/2014	6/30/2104	2
Level 1: Interior Wall	4	122	Glazed tile	1500	05/041/2014	6/26/2104	150

Data table in CSCM framework

Fig. 6. Data storage and retrieval from project files.

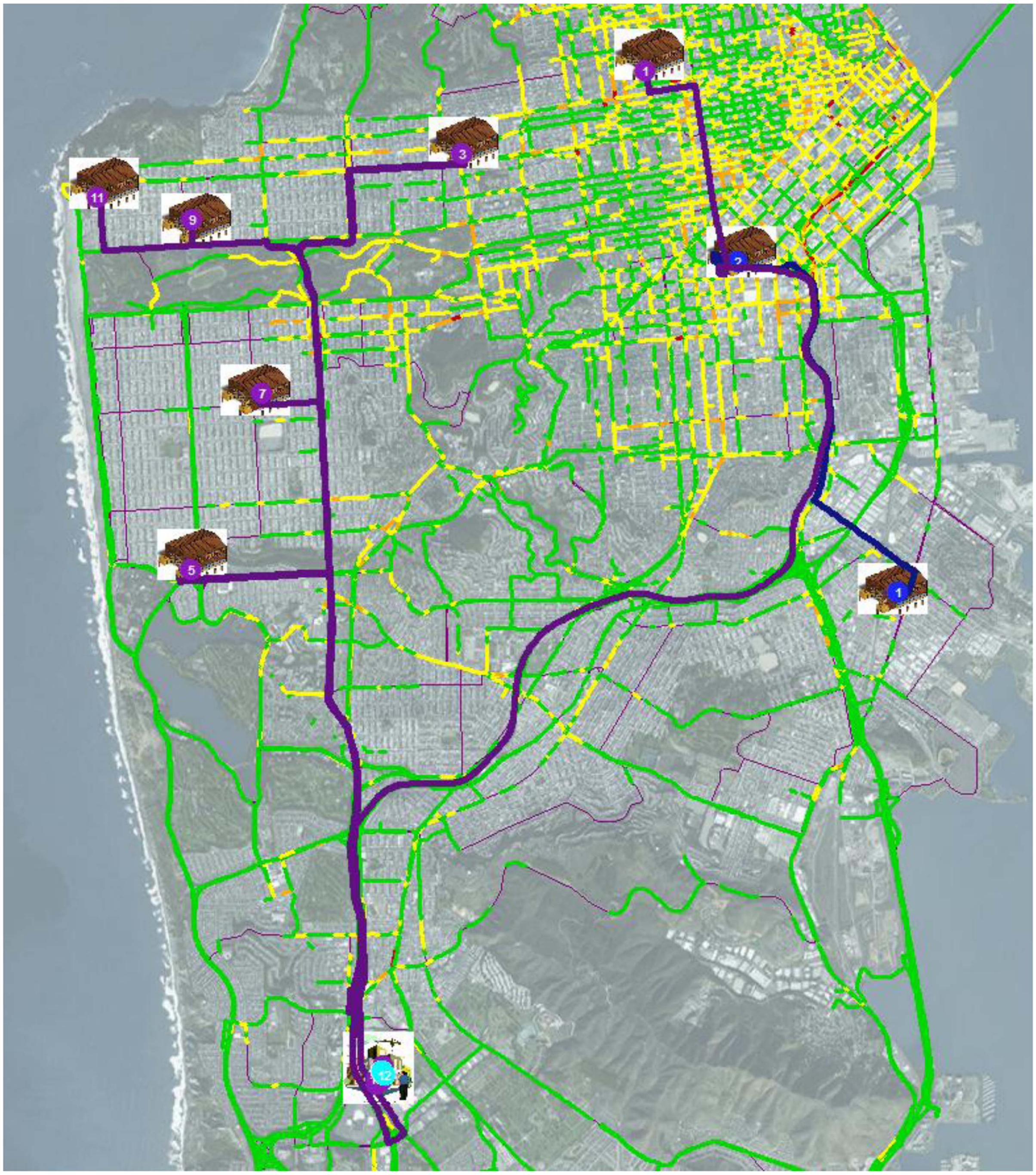


Fig. 7. Route finding for determination of the delivery fee. (Map data © OpenStreetMap contributors.)

Allocating the Consolidation Centers

The second case study considers a supply chain network consisting of five project sites and 15 suppliers in different locations supplying different materials. The locations of the project sites and suppliers are shown in Fig. 9. Road network data for San Francisco are used here to calculate delivery costs. The first step of the consolidation allocation problem is to determine the cost ratios F_{Za} and F_{ZS} using Eqs. (18) and (19) with data from these five projects. The budget for each cost item is given in Table 4. With the calculation of F_{Za} and F_{ZS} from the project data, the allocation problem of the consolidation center has been transformed to a location-allocation problem in GIS. The process of consolidation center allocation starts from generating unified distributed sample points on the base map. Here, the resolution of the sample points was set as 100 m. After acquiring the sample points, the cost for each sample point is calculated using Eq. (16). After each sample point is calculated, it is possible to generate a cost map which represents the cost of setting up a consolidation center in a given location, as shown in Fig. 10. The location with the lowest cost after setting up the consolidation center is shown by a star symbol in Fig. 10. Fig. 10 also provides the setup cost of a consolidation center in different areas, serving as a guideline for project managers to find the optimal location of a consolidation center. It is noticeable that near the optimal location in Fig. 10, there is a zone with a high consolidation center cost. The reason is that the traffic network and the transportation infrastructure in this area are not sufficient, and the transportation cost will increase dramatically in this area.

Table 1. Suppliers' information and delivery distance from GIS analysis

Supplier ID	Unit price ($)	Order processing time (days)	Delivery fee per trip per kilometer ($)	Delivery capacity	Delivery distance (km)	Inventory cost per unit per day ($)	Ordering cost per order ($)
SS_1	0.65	1	1.5	1,000	**8.7**	0.004	10
SS_2	0.63	1	1.6	1,200	**9.9**	0.004	12
SS_3	0.62	1	1.8	800	**12.4**	0.004	14
SS_4	0.64	2	1.2	600	**16.3**	0.004	12
SS_5	0.625	2	1.7	1,200	**12.4**	0.004	10
SS_6	0.625	2	1.4	1,000	**19.1**	0.004	14
SS_7	0.64	1	1.5	1,000	**14.2**	0.004	10
SS_8	0.63	1	1.6	800	**14.2**	0.004	10

Note: The bold font highlights the actual delivery distance calculated from GIS.

Table 2. Delivery and inventory cost analysis for different suppliers and different number of deliveries

	Number of deliveries								
Supplier ID	2	3	4	5	6	7	8	9	10
SS_1	26.1	39.2	52.3	65.3	78.4	91.4	104.5	117.6	130.6
SS_2	31.6	47.5	63.3	79.1	94.9	110.7	126.6	142.4	158.2
SS_3	44.8	67.2	89.6	112.0	134.4	156.8	179.2	201.6	224.0
SS_4	39.2	58.8	78.4	98.0	117.6	137.2	156.7	176.3	195.9
SS_5	42.3	63.5	84.6	105.8	127.0	148.1	169.3	190.5	211.6
SS_6	53.4	80.1	106.7	133.4	160.1	186.8	213.5	240.2	266.8
SS_7	42.5	63.8	85.0	106.3	127.5	148.8	170.0	191.3	212.5
SS_8	45.6	68.3	91.1	113.9	136.7	159.4	182.2	205.0	227.8
Onsite inventory cost	107.2	71.5	53.6	42.9	35.7	30.6	26.8	23.8	21.4

Table 3. Total cost analysis for different suppliers and different number of deliveries

	Number of deliveries								
Supplier ID	2	3	4	5	6	7	8	9	10
SS_1	1,183.3	1,160.7	1,155.9	1,158.2	1,164.1	1,172.1	1,181.3	1,191.4	1,202.1
SS_2	1,158.8	1,138.9	**1,136.9**	1,142.0	1,150.7	1,161.4	1,173.4	1,186.2	1,199.7
SS_3	1,158.0	1,144.7	1,149.2	1,160.9	1,176.1	1,193.4	1,212.0	1,231.4	1,251.5
SS_4	1,182.4	1,166.2	1,168.0	1,176.8	1,189.3	1,203.8	1,219.5	1,236.2	1,253.4
SS_5	1,159.5	1,145.0	1,148.2	1,158.7	1,172.7	1,188.8	1,206.1	1,224.3	1,243.1
SS_6	1,174.6	1,165.5	1,174.3	1,190.3	1,209.8	1,231.4	1,254.3	1,278.0	1,302.3
SS_7	1,183.7	1,169.2	1,172.6	1,183.2	1,197.3	1,213.4	1,230.8	1,249.1	1,268.0
SS_8	1,170.8	1,157.8	1,162.7	1,174.8	1,190.4	1,208.1	1,227.0	1,246.8	1,267.2

Note: The bold font highlights the minimum cost.

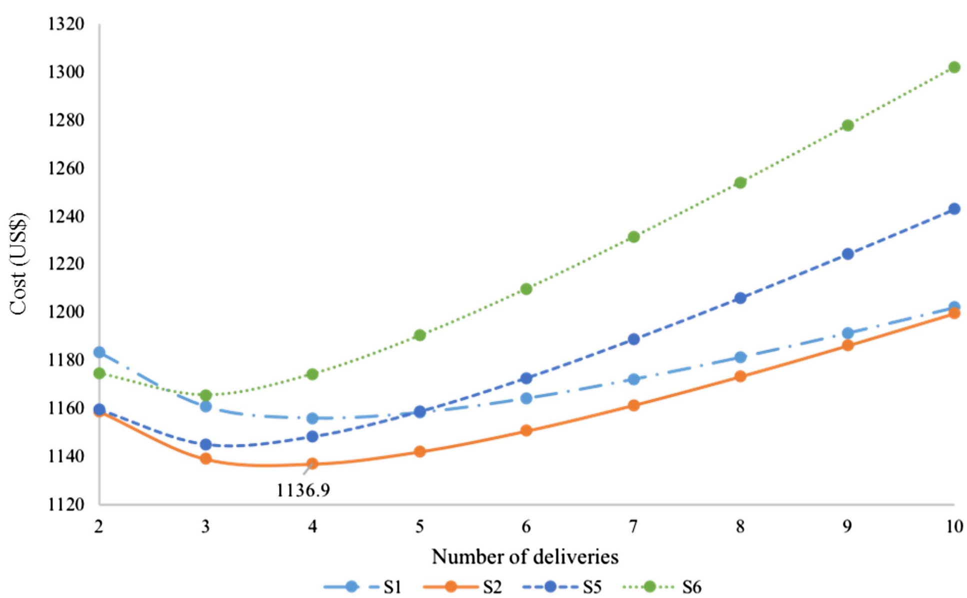


Fig. 8. Analysis of total logistic cost for different supplier sites and number of deliveries.

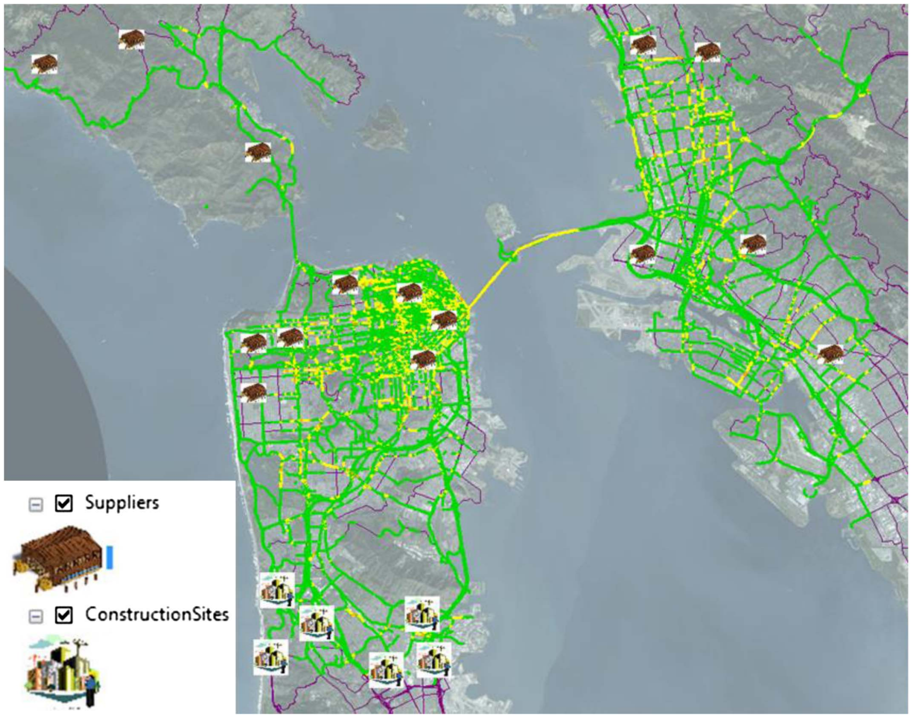


Fig. 9. Location of facilities. (Map data © OpenStreetMap contributors.)

Table 4. Project information and costs with consolidation centers

Construction site ID	Budget ($)	Supply chain cost without consolidation centers ($)	F_{za}	F_{sz}	Supply chain cost with consolidation centers ($)
CS_1	2,531,470	1,164,476	974,667	108,296	1,082,963 (−7%)
CS_2	1,893,690	1,098,340	929,196	103,244	1,032,440 (−6%)
CS_3	2,154,780	1,120,486	927,762	103,085	1,030,847 (−8%)
CS_4	2,254,780	1,059,747	867,932	96,437	964,369 (−9%)
CS_5	1,963,510	1,099,566	930,232	103,359	1,033,592 (−6%)

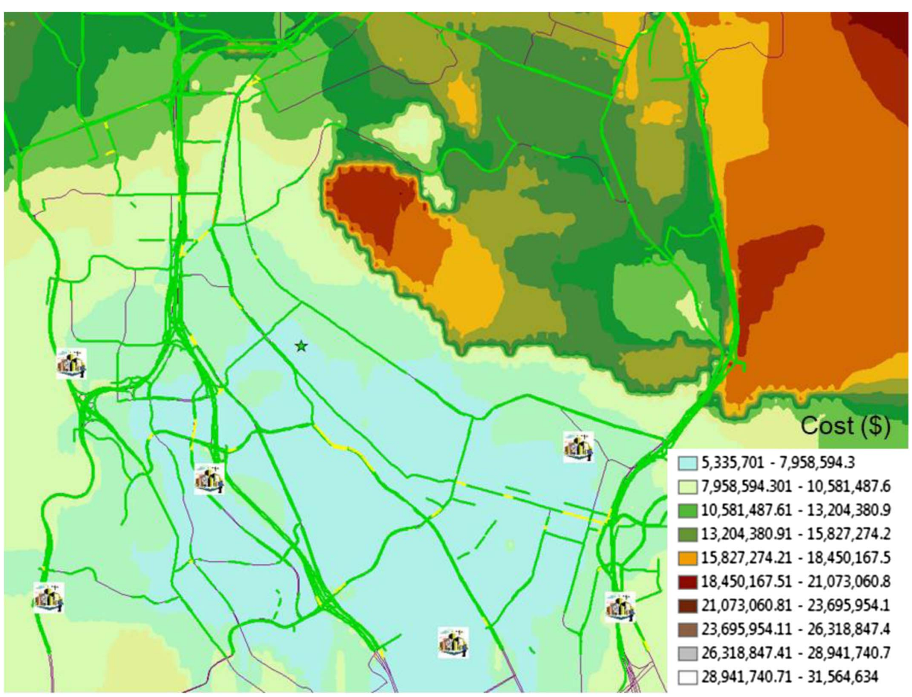


Fig. 10. Finding an optimal consolidation center location.

This is further evidence that GIS network analysis is necessary in calculating delivery costs. As indicated in Table 4, setting up a consolidation center will reduce the inventory and delivery cost by 6%–9%.

Conclusions

This paper presented an integrated framework based on 4D BIM and GIS to support CSCM. The framework consists of three layers, namely (1) data storage and retrieval layer, (2) analysis layer, and (3) application layer, which have been discussed in detail. The framework can support decision making for the three common tasks in CSCM: (1) supplier selection, (2) determination of the number of deliveries, and (3) allocation of consolidation centers. With data from 4D BIM and GIS, the three CSCM tasks are formulated mathematically and solved to support decision making.

The results of the study indicated that selection of suppliers needs to consider both the delivery distance and unit price. The combined effect due to the delivery distance and unit price needs to be considered in selecting the optimal supplier. Second, the number of material deliveries has impacts on the total cost of the supply chain, and mathematical method was proposed to solve the problem. Third, mathematical modeling was used to prove the necessity of locating consolidation centers in congested regions with long delivery distances. A solution was provided to the allocation problem regarding the location of consolidation centers. The proposed framework enhances CSCM using the data inputs and analysis functions in BIM and GIS. With application of BIM increasing in the construction industry, data in BIM nowadays are capable of providing information for the analysis functions introduced in this paper.

The proposed BIM-GIS framework can be modified to consider more real-life conditions. For example, the quality of materials as well as the trust of suppliers may also play important roles in supplier selection, which can be considered in the proposed framework in the future. In addition, the illustrative case study considers that consolidation centers serve only one construction project. The situation of consolidation centers serving multiple construction projects can also be considered in the future work. It is noticeable that uncertainties in the construction supply chain, such as variations in the consumption rate of construction material, were not considered in this study because the focus of the study is the integration of BIM and GIS. Uncertainty in the construction supply could be considered in future work.

Data Availability Statement

All data generated or analyzed during the study are included in the published paper. Information about the *Journal*'s data-sharing policy can be found here: http://ascelibrary.org/doi/10.1061/(ASCE)CO.1943-7862.0001263.

Acknowledgments

The authors would like to acknowledge support by the Hong Kong Research Grants Council (Grant No. 622812), the China Postdoctoral Science Foundation (Grant No. 2016M592498), the State Key Laboratory of Subtropical Building Science (Grant No. 2017KB12), and the Guangdong Science Foundation (Grant No. 2017A030313393).

Notation

The following symbols are used in this paper:

$A_{a,i}$ = specific construction activity i in site a;
CD_l = capacity of each delivery for material l;
CS_a = location of a specific project site a;
$D_{a,i}$ = duration of a construction activity i (retrieved from BIM);
$\mathrm{DC}^l_{a,i}$ = delivery cost for material l;
DD^l_{sa} = delivery distance of material l from a supplier site SS^l_s to a project site CS_a;
DD^l_{sz} = delivery distance of material l from a supplier site SS^l_s to a consolidation center z;
DD^l_{za} = delivery distance of material l from a consolidation center z to a project site CS_a;
DFT_l = delivery fee per trip for material l;
DT^l_a = delivery time of material l to project site a;
$\mathrm{ET}_{a,i}$ = completion time of a construction activity i in site a;
F_{sz} = cost ratio proportional to distance between a consolidation center and a supplier, $\mathrm{DD}_{\mathrm{ZS}}$;
F_z = cost constant;
F_{za} = cost ratio proportional to distance between a consolidation center and a project site, DD_{Za};
I^l_a = on-site inventory of a project site for material l;
I^l_z = inventory capacity of a consolidation center for material l;
$\mathrm{IC}^l_{a,i}$ = inventory cost for material l;
ICR = inventory cost rate, proportional to the inventory level;
l = specific type of construction material;
$\mathrm{MC}^l_{a,i}$ = material cost for material l;
N = optimal number of deliveries for activity $A_{a,i}$;
$\mathrm{OC}^l_{a,i}$ = ordering cost (e.g. setup of the material ordering) for material l required for a construction activity i in site a;
OCR = ordering cost rate proportional to the quantity of material $Q^l_{a,i}$;
P_l = unit price of construction material l;
$Q^l_{a,i}$ = quantity of material l required for a construction activity i in site a;
SS^l_s = location of a supplier site s that provides construction material l;
$ST_{a,i}$ = starting time of a construction activity i in site a; and
ZC = setup cost for a consolidation center.

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