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LIST OF ABREVIATIONS

A/E	Architects and engineers
BIM	Building information modeling
BLE	Bluetooth low energy
CAD	Computer-aided design
CSC	Construction supply chain
CSCM	Construction supply chain management
GA	Genetic algorithms
GC	General contractor
GIS	Geographical information system
IoT	Internet of Things
IT	Information technology
RFID-RTLS	Radio frequency identification
SC	Supply chain
SCM	Supply chain management
SLD	Site layout design
SLP	Systematic layout planning
Subs	Subcontractors
TPL	Third party logistics
VBA	Visual basic

INTRODUCTION

Introduction to the research context

The construction industry is a basic and important sector for the world-wide economy; however, it is known as a complicated and often underperforming segment. The industry is regarded as high fragmentation, low productivity, cost and time consumption, and conflicts. Many construction projects are recorded with overdue schedules, overrun budgets, and poor quality, which pave the way for problems to plague in the industry (Aloini et al., 2012). In construction networks, clients, consultants, contractors, designers, subcontractors, and suppliers are key nodes that are connected by interfaces embracing knowledge transfer, information exchange, financial, and contractual relationships. Yet, these networks are noted with inefficient collaborations; for instance, the splitting up design and construction, absence of integration and coordination between different functional disciplines, as well as poor communication (Behera et al., 2015). Major problems occurring in relationships among stakeholders of construction projects are summarized in **Figure 0.1**.

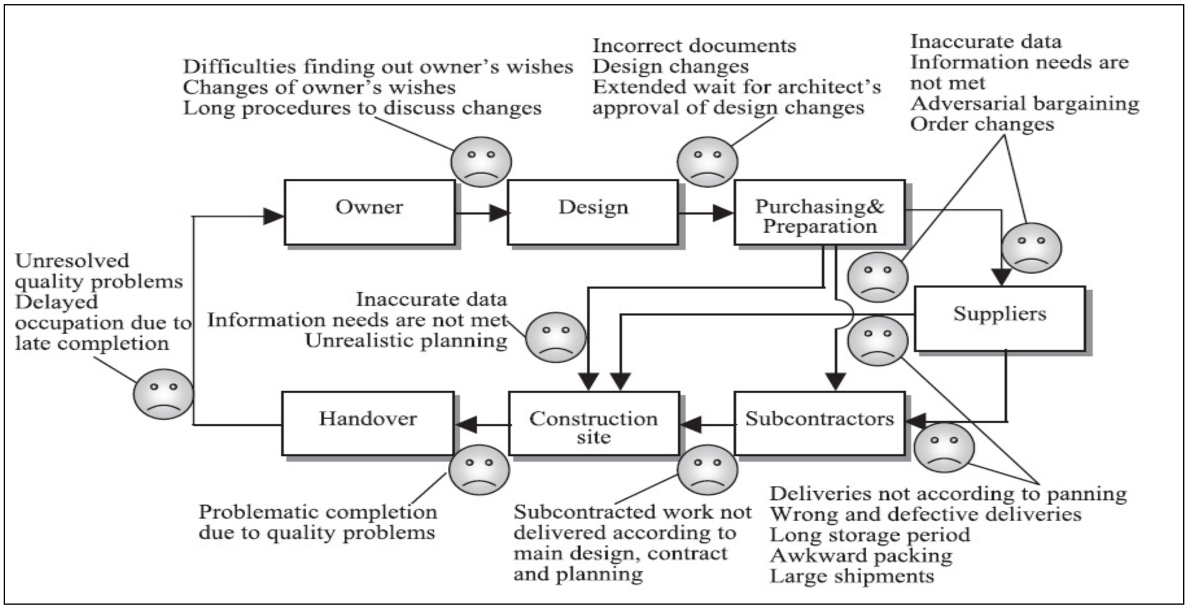

Figure 0.1 Major problems in construction relationships

(Source: Xue et al., 2005; Behera et al., 2015)

Table 0.1 Inefficiencies in sharing information in construction projects
(Adapted from Validyanathan, 2009)

	General contractor (GC)	Subcontractor	Supplier
Business model	• Typically focus on coordinating all stakeholders in each construction project	• Typically focus on managing business across multiple construction projects	• Typically apply approaches of manufacturing sectors
Work coordination	• Work is usually coordinated through phone/fax leading to translation errors and omissions	• Non-integrated business processes within the firm leading to manual recreation of data (CAD, estimation, design, engineering)	• Direct incentives to improve operational efficiency within an organization
Incentives and tools in information sharing	• Lack of incentives to share information with others, leading to duplication of data creation • Unavailability of compatible tools for communicating with subcontractors • Lack of visibility and incentives to aggregate procurement across projects	• Lack of tools and technologies to aid business process management • Inadequate scheduling tools to address multi-project interactions • Trade subcontractors lack mobile collaboration tools that simplify communication between field workers and office	• Lack of integration data standards with GCs and subcontractors • Unable to gain visibility into demand for equipment investment to reduce lead time

As shown in **Figure 0.1**, stakeholders in the construction industry normally focus on their benefits, which cause many problems in communication and information sharing with others. Sharing information in a construction network is a critical problem, which is a major source of delays, errors, and duplications on projects. Validyanathan (2009) claim that no single stakeholder has motivations in improving the whole construction network since it is not clear who will gain the benefits of the improvement of the network relationships. Stakeholders, such as GC or Subcontractor, are concurrently managing several projects; thus, they have incentives to focus on enhancing the efficiency of their own business to realize immediate economic advantages rather than to improve the network performance. It is, therefore, definitely noticed that the nature of construction networks is decentralized and multi-enterprise oriented. **Table 0.1** presents inefficiencies in sharing information in construction projects.

Table 0.2 Differences in characteristics between construction and manufacturing (Source: Azambuja and O'Brien, 2009)

Characteristics	**Manufacturing**	**Construction**
Network structure	Highly combined High obstacles to entry Static locations Great interdependency Largely global markets	Greatly fragmented Low obstacles to entry Transitory locations Little interdependency Largely local markets
Information flow	Greatly integrated Greatly shared Quickly Using tools (factory planning and scheduling, procurement, SC planning)	Reconstructed some times between trades Absence of sharing across firms Slowly Inadequate tools to support SC
Collaboration	Long-term relations Shared benefits, motivations	Oppositional practices
Product demand	Highly uncertain Advanced forecasting tools	Fewer uncertain
Production variability	Greatly automated environment, standardization, production methods are defined - less variability	Open environment, absence of tolerance and standardization management, space availability, material flows are complicated - greater variability
Buffering	Available inventory models (EOQ, safety inventory, etc.)	No models Buffers on-site to decrease risks Use of floats for scheduling
Capacity planning	Aggregate planning Optimization models	Independent planning Infinite capacity assumptions Reactive approach (react to unexpected situations, for instance, overtime)

In comparison to manufacturing, construction industry characteristics differ significantly. For many products, the manufacturing procedure is usually the same from order to order; thus, processes and stakeholders remain the same. This explains why various stakeholders often keep long relationships with others in the manufacturing sectors. In contrast, the short-term and prototype nature of construction projects results from short-term relationships among the stakeholders in the construction sector. **Table 0.2** presents the differences in many characteristics between the manufacturing and construction sector. These differences are barriers to implementing many concepts from manufacturing to construction, such as Supply chain management (SCM). The concept of SCM has been increasingly applied to many industrial sectors to improve business performance, such as faster response to the variety of customer demands, lower cost, and better quality. In construction, the application of the SCM concept is frequently used to guide project managers in strategic planning to achieve partnerships with suppliers, and obtain more efficiency in operational construction (Azambuja and O'Brien, 2009). However, the importance of SCM in improving construction management has been recognized since the 1990s. Papers in this specific period mostly discussed the controversial issue about whether SCM should be applied or not for the construction industry due to its different characteristics from the manufacturing sector. Until the 2000s, research studies focused on the analysis and the exploration of the relevant aspects of SCM in construction, especially after Vrijhoef and Koskela (2000) introduced four roles of SCM in construction that motivated many scholars in studying the field.

Meanwhile, BIM (Building Information Modeling) is defined as an intelligent 3D model-based technology that supports architecture, engineering, and construction specialists with tools and data to improve the efficiency of construction planning, designing, constructing, and controlling (Azhar, 2011; Rowlinson, 2017). In terms of construction design, BIM adoption can improve relations among clients, architects, and contractors. The design team is responsible for making innovations in the design processes and integrating design procedures into BIM (Elmualim and Gilder, 2014). BIM encourages the designers' activities with visualization, automatic generation of drawings, code reviews, construction sequencing (Azhar, 2011). Moreover, in large-scale complex projects, BIM is believed to not only improve design coordination but also facilitate knowledge sharing when being combined with team co-location (Bektas, 2013). Such benefits create the fame of BIM utilization, which in turn leverages its effective implementation for construction design (Son et al., 2015).

Additionally, BIM leverages the construction execution through its built-in features, such as visualization for clash detections, monitoring, and scheduling capabilities. The integration of BIM with emerging technologies creates communication and feedback mechanisms among the supply chain (SC) stakeholders on site. Also, the BIM application for workspace management can support the optimization of the construction activities on site (Moon et al., 2014). BIM models are considered plentiful sources of data used for decision making in construction management. Material and spatial data from BIM can be integrated with activity data from the project schedule and related costs from the financial budget to create an extended-BIM platform called 5D-BIM (Ding et al., 2014).

Through understanding the concepts, we recognize that both SCM and BIM focus on SC integration, which leverages information sharing among related construction actors. While BIM contributes to the construction industry with rich sources of building data, the SCM concept consists of a set of practices for SC integration: partner sourcing, logistics control, quality management, information management, and cultural alignment. Thus, this project aims to apply both SCM and BIM to solve the problems existing in the construction industry and enhance the construction logistics planning and performances. Improving the performances of logistics activities is an important reason for applying the terms of SCM and BIM in construction since it helps to reduce the total cost and lead time of the whole CSC (Polat et al., 2007; Liu and Tao, 2015). Up to date, research into logistics planning for SCM in construction has focused on enhancing construction performance through efficient material purchasing, transportation, storage and handling to the site regarding multiple echelons in the SC network to promote the interactions between relevant actors (Vidalakis et al., 2011; Said and El-Rayes, 2014).

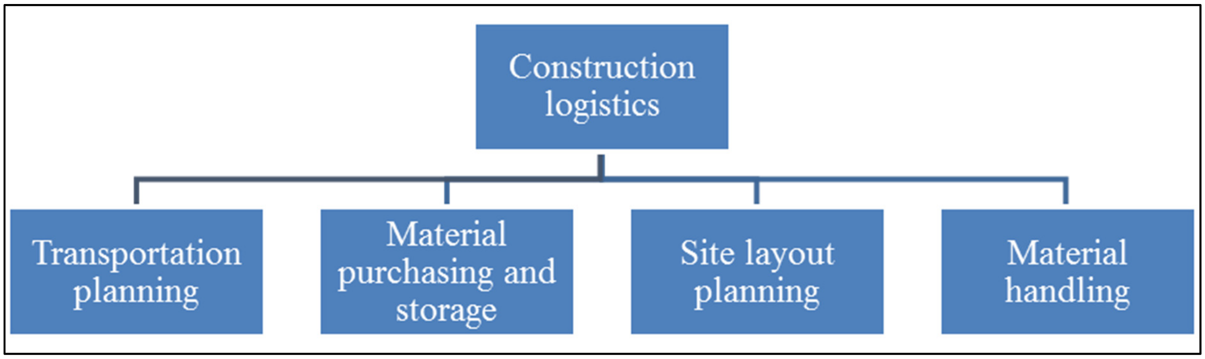

Figure 0.2 Main focuses of construction logistics

As shown in **Figure 0.2**, in order to achieve efficiency in construction logistics, the four analyzes are commonly conducted: transportation analysis, material purchasing and storage analysis, site layout analysis, and material handling analysis (Polat et al., 2007; Liu and Tao, 2015). Transportation accounts for a high proportion of the logistics cost in several industries, often between one-third and two-thirds. In the construction industry, transportation costs may be considerably greater because of high-volume and low-value raw materials. Therefore, it causes an increase in requests for transportation capacity, but it does not essentially come with proportional income. It is suggested to employ an efficient method for controlling transportation means and creating a load consolidation of shipped goods to decrease the transportation cost. Material purchasing and storage take into account the search for efficient solutions in the determination of purchasing material quantity for each planned period and the storage of the purchasing materials to avoid the risks of shortage due to the supply delay or changes in demand. Site layout planning is conducted to look for the best arrangement of temporary facilities on the sites to minimize the transportation distances of on-site personnel and equipment. Material handling should be effectively planned and executed to avoid the negative influences of material shortage or too much material inventory on-site. It is related to many activities such as conveying, elevating, positioning, transporting, packaging, and storing of materials.

In the scope of this research, transportation planning and material purchasing and storage are taken into account to model and optimize the integrated CSC network, which minimizes the total SC costs, including transportation cost, material purchasing cost, and material storage cost (presented in **Chapter 2**). Meanwhile, site layout planning and material handling are closely interrelated. The construction of a building or an infrastructure facility requires intensive efforts for transporting, storing, assembling, and placing the building materials in a site space through using appropriate construction technology. Thus, a construction site is normally considered as a system of material handling. The efficiency of this system cannot be obtained without an efficient site layout planning. A productive site layout facilitates the material handling in the construction site with smooth material and equipment flows, thereby enhancing the safety and effectiveness of construction project execution (Sadeghpour and Andayesh, 2015). Thus, site layout planning and material handling are concurrently considered to generate an efficient layout of temporary facilities in the construction site, which aims to minimize the material handling cost and maximize the adjacency score between the facilities (presented in **Chapter 3**).

Research problem description

CSCs are very complex systems in which the performance relies on a set of hundreds of decisions delivered by multiple independent firms. In construction networks, owners, contractors, designers, subcontractors, and suppliers are the key players connected by interfaces embracing knowledge transfer, information exchange, financial, and contractual relationships. **Figure 0.3** simplifies a CSC process with relevant actors. In a construction project, GC is considered as a representative of the owner for the construction execution. According to the owner's directives, the GC contacts the selected suppliers for material procurement, and then the materials are transported to the storage points. Then, raw materials are supplied to the contractors for their fabrication. The semi-fabricated units produced by the contractors are then shipped to the GC. In the end, the GC finishes the construction project and delivers it to the owner. The designer plays a consulting role in determining the material requirements. The designer provides and checks the requirements and possible changes of materials with contractors, and then confirms this information with the owner (Liu et al., 2017).

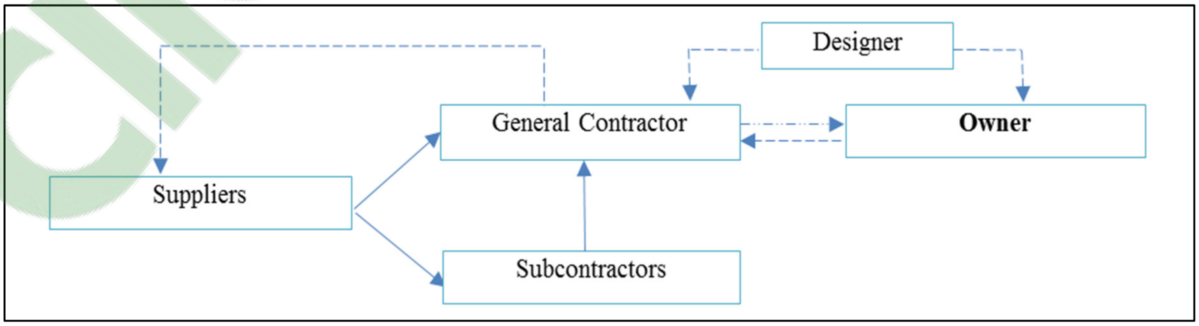

Figure 0.3 Construction supply chain processes

CSC networks are still characterized by inefficient collaboration. For instance, the splitting up design and construction, the absence of integration and coordination between different functional disciplines, as well as the poor communication are some of the challenges that construction management is facing (Behera et al., 2015). Stakeholders in the construction industry usually focus on their benefits. Thus, the lack of collaboration causes many problems in communication and information sharing with others. The lack of information sharing in construction networks is a critical problem, and it is a significant source of delays, errors, and duplications in construction project management (Xue et al., 2005). Stakeholders, such as GC or subcontractor, are concurrently managing several projects; thus, they have incentives to focus on enhancing the efficiency of their own business to achieve immediate economic advantages rather than to improve the network performance.

CSC operations begin with the raw material procurement and finish with the project delivery (Liu et al., 2017). It is estimated that 60–80% of the workload in construction projects involves the material and service procurement from suppliers and subcontractors (Ekeskär and Rudberg, 2016); thus, these supply chain (SC) actors have significant impacts on the performance of construction projects (Miller et al., 2002). The inefficiency in managing the complex network is one of the main reasons those cause low productivity and the cost increase for the industry (Vrijhoef and Koskela, 2000; Love et al., 2004). Meanwhile, SCM principles are not wholly adopted in the construction industry (Fernie and Tennant, 2013), and yet realized for their benefits by construction companies (Sundquist et al., 2018). One reason for this issue is the lack of collaboration among the actors in the SC network, which is a significant source of delays, errors and duplications in construction projects (Xue et al., 2005). In terms of CSC planning and operations, there is a lack of SC driver who plays a role as the focal coordinator to integrate the associated actors across the construction network (Sundquist et al., 2018; Le et al., 2018).

Lack of SC integration is the critical issue of construction logistics management (Sundquist et al., 2018). As a result, construction logistics practice and performance are considered to be lagged in comparison with other industries (Segerstedt and Olofsson, 2010). Building materials need for large storage capacity and require an efficient coordination system to ensure the quality as well as reduce the logistics costs. There are many problems associated with poor material management such as unqualified materials are delivered, the material purchasing is conducted too late, or wrong quantity orders are decided. These cause the disturbances for onsite assembly, delays in material delivery, or cost increase due to wastes (Sundquist et al., 2018). These problems can be improved by employing efficient plans and coordination systems of materials delivery, storage, and handling, as well as resource utilization (Ying et al., 2014; Sobotka and Czarnigowska, 2005). Productive construction logistics can facilitate the organization of materials delivery, storage, and handling as well as the allocation of spaces and resources to support the labor force and eliminate inefficiencies due to the congestion and the excess material movement (Almohsen and Ruwanpura, 2011; Thomas et al., 2005). As the construction industry has increasingly applied the approach of SCM, logistics management is considered as the core of such an application (Hamzeh et al., 2007).

Previous studies support "SC integration" to become the key enabler that contributes to CSC performance (Briscoe and Dainty, 2005; Bankvall et al., 2010). Once conducted properly, SC integration can facilitate the full information sharing, and long-term trust among the SC actors (Lönngren et al., 2010; Meng et al., 2011), which in turn enhances material flows throughout the whole SC (Akintoye et al., 2000; Liu et al., 2017). In large CSC projects, to deal with the challenges of temporary and complex nature of the industry as well as increase the SC integration, construction firms have thought of TPL (Third-party logistics) providers to increase productivity at the construction site, reduce logistics costs and enhance the utilization of site assets (Ekeskär and Rudberg, 2016; Tommelein et al., 2009). TPL partnership is based on the idea that a construction firm hires logistics professionals to manage all the logistics activities (transportation, material procurement, and storage). Using TPL, an interface is formalized to connect the SC network to the construction site (Le et al., 2018).

Lack of SC integration also impacts the efficiency of site layout planning since the required data are reserved in many organizations as internal knowledge. Therefore, it is necessary to facilitate a platform that supports information sharing among the construction actors. Although BIM leverages optimal conditions for the generation of building models, the site layout planning for temporary facilities is not supported due to the existing limitations of computer-based tools. For example, some of the required data for site layout planning (such as the material quantity of columns, walls or beams) can be extracted from the modeling software; however, other data (such as frequency of these materials or schedule data) require a custom design (Hammad et al., 2016a; Schwabe et al., 2019). Schedule data are stored in a separate file and can be integrated with the building data in a 4D-BIM software.

Similarly, material frequency between facilities can be calculated from BIM-based data and integrated into the database for site layout planning. Thus, it is suggested to develop an integrated data collection and processing system to generate the required data for site layout planning based on the data from BIM and other sources. In other words, a productive site layout plan of temporary facilities requires the SC integration to deal with the multi-objective problems and a BIM-based platform that facilitates the data collection and processing from multiple sources.

Research questions

In this thesis, the separation of the construction process into three phases (Planning and Design; Procurement; and Construction and delivery) follows the proposition of Azambuja and O'Brien (2009)**.** The first phase (Phase I), Planning and Design, consists of the functions related to the construction conceptualization and SC configuration planning. The second phase (Phase II), Procurement, embraces the relevant functions of partner selection and material procurement. The third phase (Phase III), Construction and delivery, includes inventory control, material handling for on-site construction, and the delivery of the final construction project. It is suggested that CSC actors should consider the global efficiency of the whole CSC network for their decision-making during the construction phases. However, recent researches in construction management have not proposed any framework to classify CSC decisions made in each construction phase or suggest when they should be integrated along with the construction phases (Azambuja and O'Brien, 2009).

To have clear understandings of CSC and logistics management, it is important to identify the present focuses, which consist of critical decisions in construction management. It is also essential to highlight the crucial evolution steps in the development of SCM decision-making in general and makes a comparison with the evolution of SCM decision-making in the construction industry. This comparison indicates the gaps observed in the implementation of SCM in the construction industry when being compared to other sectors, especially in the manufacturing and the service industries. Based on this comparison, future directions of decision making in construction SCM are proposed with a more detailed specification of methods and tools that meet new requirements of construction management practices and technological progress. Thus, the first research question (RQ) of this thesis is presented as the following, which is answered in **Chapter 1**:

[RQ1]: What are the present focuses and future trends of decision-making in construction logistics and SCM during the major construction phases?

As mentioned, previous studies support "SC integration" to become the key enabler that contributes to construction logistics performance. In large CSC projects, TPL (Third-party logistics) providers can be hired to take over the logistics activities and integrate the participation of associated actors across the CSC network. Under the owner's directives, the GC selects the suppliers and TPL provider who is responsible for material purchasing, storage, and transportation. In this CSC process, the TPL provider plays a central role in coordinating all materials necessary for the construction work and equipment necessary for the materials handling on site (Ekeskär and Rudberg, 2016). The TPL provider creates the regulations for material procurement, delivery, and storage, which are agreed by the GC and the owner. The regulations are informed to all contractors through official documents and reminded in periodical meetings held by the TPL provider. The TPL solution is mandatory for all contractors. Since all the materials are coordinated and handled by the TPL provider; thus, the CSC network with TPL partnership becomes the integrated SC network in which the TPL provider takes the role of a SC integrator (Fabbe-Costes et al., 2009). Being different from a normal decentralized construction logistics network, the integrated CSC with the TPL partnership leverages the cooperation between different SC actors (Ekeskär and Rudberg, 2016), as well as the information and risk-sharing (Liu et al., 2017b). The integrated CSC is modeled as a focal network in which the construction owner, the GC, and the TPL provider are treated as focal decision-makers. In terms of construction logistics, the focal decision-makers need to identify the optimal values of relevant costs: material ordering cost, checking cost, transportation cost, and storage cost (Fang and Ng, 2011). Thus, the second research question (RQ) of this thesis is presented as the following:

[RQ2]: How to model and optimize the integrated CSC network regarding the TPL partner as the focal coordinator for the SC operations?

The answer for the research question 2 **[RQ2]** is presented in **Chapter 2**, which presents the modeling and optimization for the integrated CSC network with the TPL partnership regarding the logistics activities of transportation planning and material purchasing and storage.

The other important logistics activities, which are site layout planning and material handling, are taken into account for the next research question. In practice, site space in urban construction projects is a restricted resource that must be wisely utilized to deal with issues of approachability, safety, and congestion (Kumar and Cheng, 2015). It is critical to focus on developing a BIM-based framework for site layout planning to solve multi-objective problems occurring in congested construction sites: data requirement (updated and correct data provision for practical site layouts), productivity (layout cost), and layout safety. Practically, site layout planning is dynamic (various facilities required for different construction phases) and complex (multi-objective needed to achieve in constraints of limited space in an urban area). Presently, dynamic site layout planning models are created on the required information: number and types of associated facilities, related costs, workflow, and construction phases (to identify required facilities for each stage) (Lien and Cheng, 2012; Xu and Li, 2012; Akanmu *et al.*, 2016). One of the realistic requirements of site layout planning is data correction and update. However, such data in previous studies are mostly predetermined by planners and added to layout programs in manual. The manual determination of layout data may be significantly inefficient and incorrect, mainly when there are unexpected changes in project schedules (Kumar and Cheng, 2015). These changes should be updated automatically for site layout planning instead of being entered manually into layout software by planners. Thus, automation for data update is needed for a practical plan to eliminate errors and inefficiency causing by manual work as well as ease the use of layout plans for different phases and various projects (Said and El-Rayes, 2014). This can be feasible through developing a BIM-based framework that uses BIM models as rich sources of information to automate the data update for mathematical models in dynamic site layout planning.

The other practical requirements of site layout planning are cost optimization and safety insurance for congested sites (Xu and Li, 2012). It is meant to develop a multi-objective mathematical model to optimize the material handling cost and improve the adjacency between facilities (including safety and environmental issues). In order to provide required data for the first objective (material handling cost), data from the BIM model and construction schedule are extracted to compute the material trip frequencies, location distances and identify temporary facilities required for different phases of the project. The use of BIM ensures that changes in design and construction are automatically updated to feed the site layout models and reduces the laborious work for planners (Akanmu *et al.*, 2016). BIM implementation for providing inputs to mathematical models has been reported in previous studies (Inyim *et al.,* 2015; Irizarry and Karan, 2012).

Nevertheless, previous studies have mostly integrated BIM models and construction schedules for visualization of the construction process instead of using data for estimation and planning purposes (Hammad *et al.,* 2016a). For the second objective (adjacency between facilities), knowledge-based reasoning is applied to collect the data for the mathematical model. For this aspect, expertise from managers is used to evaluate adjacency scores between facilities based on the combined conditions of three aspects: workflows, safety/environmental concerns, and manager preferences. The usage of managers' expertise can improve the safety and reliability of site layout planning (Elbeltagi and Hegazy, 2001; Schwabe *et al.,* 2019). Thus, the third research question (RQ) of this thesis is presented as the following, which is answered in **Chapter 3**:

[RQ3]: How to use data from BIM and knowledge-based reasoning to create the required quantitative data (material trip frequency, location distances, and related costs) and qualitative data (workflows, safety/environmental concerns, and manager preferences) for the optimal multi-objective site layout plan?

Thesis objectives

This thesis aims to answer three above mentioned research questions. For the first research question *[RQ1]*, a systematic literature review of construction logistics and SCM (presented in **Chapter 1**) is conducted to analyze the relevant body of knowledge identified in 123 articles published from 2000 to the present and to determine the SC decisions made in each construction stage. The period from 2000 to the present is thought to be sufficient to cover the most significant changes and the evolution of decision-making in logistics and SCM in the construction industry. Thus, the following research objectives need to be achieved:

Thesis objective 1.1: *Identifying the present focuses of decision-making in construction SCM and the relationships existing between the SC actors during the major construction phases.*

Thesis objective 1.2: *Proposing the future trends of SCM applications in the construction industry to meet the new requirements of construction practices and technological progress.*

The research objectives 1.1 and 1.2 are obtained to formalize a background for research question 2 *[RQ2],* which reveals that SC integration is suggested as the critical strategy for SCM application in the construction industry. Meanwhile, the TPL partnership is also proposed to improve the logistics performances for construction companies, in which the TPL partner plays a focal role as the SC coordinator for construction logistics activities. Thus, the construction network becomes the integrated CSC with the participants of the relevant actors, and the TPL becomes the SC driver under the agreement of the construction owner and contractors. In practice, suppliers can offer low prices and low transportation costs for the purchased materials but require a high purchasing quantity. These materials can be purchased with high volumes and need for the warehouse to be stored; otherwise, they should be purchased with smaller quantities to be sent directly to the construction site. Besides, due to the contractors' demands, some materials should only be delivered directly to the construction site to reduce the relevant risks. Therefore, it is essential to employ a focal actor who takes into account these issues for SC planning and coordination. In order to fill the research gaps (presented in **Chapter 2**) as well as meet the practical requirements of construction logistics, the following research objectives need to be achieved:

Thesis objective 2.1: *Developing an optimal decision-making model for CSC operations with the TPL partnership. The proposed model leverages the TPL provider as the focal decision-maker who coordinates the logistics activities: material purchasing, transportation, and storage. The model takes into account the two kinds of materials. Type-1 materials can be transported to a warehouse or directly sent to the construction site. Type-2 materials must be sent to the construction site only).*

Thesis objective 2.2*: Using the proposed model to assess the efficiency of the TPL employment through the comparison between the total logistics costs calculated for the CSC with the TPL provider and without the TPL provider.*

For the third research question *[RQ3],* this thesis proposes an innovative BIM-based framework for multi-objective and dynamic temporary construction site layout planning, which uses a hybrid approach of systematic layout planning and mathematical modeling. Systematic layout planning is a procedural method that is widely utilized to generate effective layouts for the facility arrangement in manufacturing and service sections (Flessas et al., 2015; Lin et al., 2015). This method systematically facilitates the application of knowledge-based rules for qualitative evaluation of relationships between facilities (Ali-Naqvi et al., 2016).

However, to the best of the author's knowledge, systematic layout planning has not been used for temporary facility layout planning in construction sites. Moreover, in site layout planning, construction managers normally select a final layout solution based on multi objectives (Hammad et al., 2016b). Some objectives, such as closeness rating or safety rating, can be achieved through qualitative analysis of facility relationships. Other objectives, such as productivity (cost or distance), can be optimized through mathematical modeling. Therefore, the combination of the two methods (systematic and mathematical layout planning) is expected as a great solution to respect construction managers' requirements (cost, safety, closeness, etc.) during the project execution. The hybrid approach, which follows a step-by-step process for site layout planning, is designed to facilitate both qualitative and quantitative data collection and processing. BIM platform is utilized to facilitate the determination of the required quantitative data while the qualitative data are generated through knowledge-based rules. Therefore, in order to fill the research gaps (presented in **Chapter 3**) as well as meet the practical requirements of site layout issues, the following research objectives need to be achieved:

Thesis objective 3.1: *Proposing a systematic approach that combines both systematic and mathematical layout modeling to solve the multi-objective problems in site layout planning. The approach consists of a step-by-step procedure that details how to achieve site layout optimization and selection.*

Thesis objective 3.2: *Developing a BIM-based data collection and processing system which enables the data extraction and integration from various sources (quantitative data from BIM, project schedule and cost budget; qualitative data from the expertise of related actors). The system facilitates the creation of a BIM-based database that can be updated and shared among the construction actors.*

Thesis 3.3: *Detailing the calculation and the integration of all necessary data (location distances, trip frequencies between facilities, layout costs, project schedule, and actors' assessments of facility relationships) used for the optimization of the site layout model.*

Methodological design

To achieve the thesis objectives as mentioned above, the methodological approach includes four main steps. In step 1 called *problem identification*, the process for the problem identification is highlighted. The outputs of this step are the identifications of research questions and the thesis objectives. In step 2, called *identifying present focuses and future directions in construction logistics and SCM,* the method of a systematic literature review is conducted to address the current focuses and future trends for decision making in construction logistics and SCM. This second step ensures the thesis objectives 1.1 and 1.2 are achieved. In step 3 called *optimization modeling for CSC with TPL partnership,* a research procedure including CSC modeling and optimization, model validation, and managerial implications is presented. This third step contributes to the achievement of the thesis objectives 2.1 and 2.2. Finally, in step 4, called *developing a BIM-based framework for site layout planning,* a hybrid site layout framework is developed to facilitate data collection and processing. Based on this framework, the site layout modeling and optimization are performed, and then validated with a case example, as well as compared to previous studies. Based on the result validations, managerial implications are proposed for the construction managers to improve logistics performance. This final step contributes to the achievement of the thesis objectives 3.1, 3.2, and 3.3.

Problem identification: Literature review, which is the basis of every research, for which it shows how connected research is to previous studies and sets criteria for readers to assess the quality of research. Thus, it helps to identify research focuses and stimulate new research directions. A thorough review of the literature leads to a better choice of theories, which helps the research to be carried out properly (Bell et al., 2018). In this thesis, to identify the research gaps, we conduct a preliminary literature review of related studies in decision making in construction logistics and SCM, issues in construction logistics and SCM, CSC optimization, site layout planning, and BIM for construction logistics. Material collection of this study aims at the academic papers and books published by reliable peer-reviewed journals, internationally honorable conferences, or book publishers. To reach the credibility of the literature review, trustful databases are chosen such as Emerald, Science Direct, Springer Link, Wiley as well as international scientific conferences: IEEE-Xplore, and IGLC.

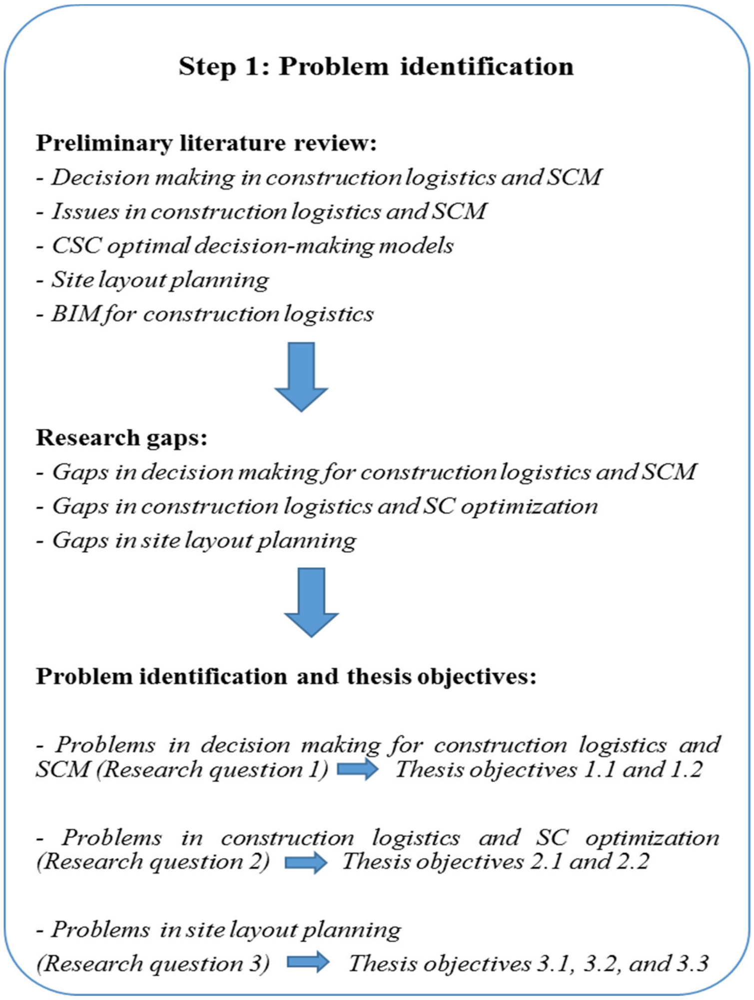

Figure 0.4 Process of step 1

As presented in **Figure 0.4**, after the preliminary literature review, we address three kinds of research gaps in (1) gaps in decision making for construction logistics and SCM (chapter 1), (2) gaps in construction logistics and SC optimization (chapter 2), and (3) gaps in site layout planning (chapter 3). Based on these gaps, the research problems are identified for this thesis. The problems are stated as the research questions: problems in decision making for construction logistics and SCM (Research question 1), problems in construction logistics and SC optimization (Research question 2), and problems in site layout planning (Research question 3). Based on these research questions, we set the corresponding thesis objectives 1.1 and 1.2 for the research question 1, thesis objectives 2.1 and 2.2 for the research question 2, as well as thesis objectives 3.1, 3.2 and 3.3 for the research question 3.

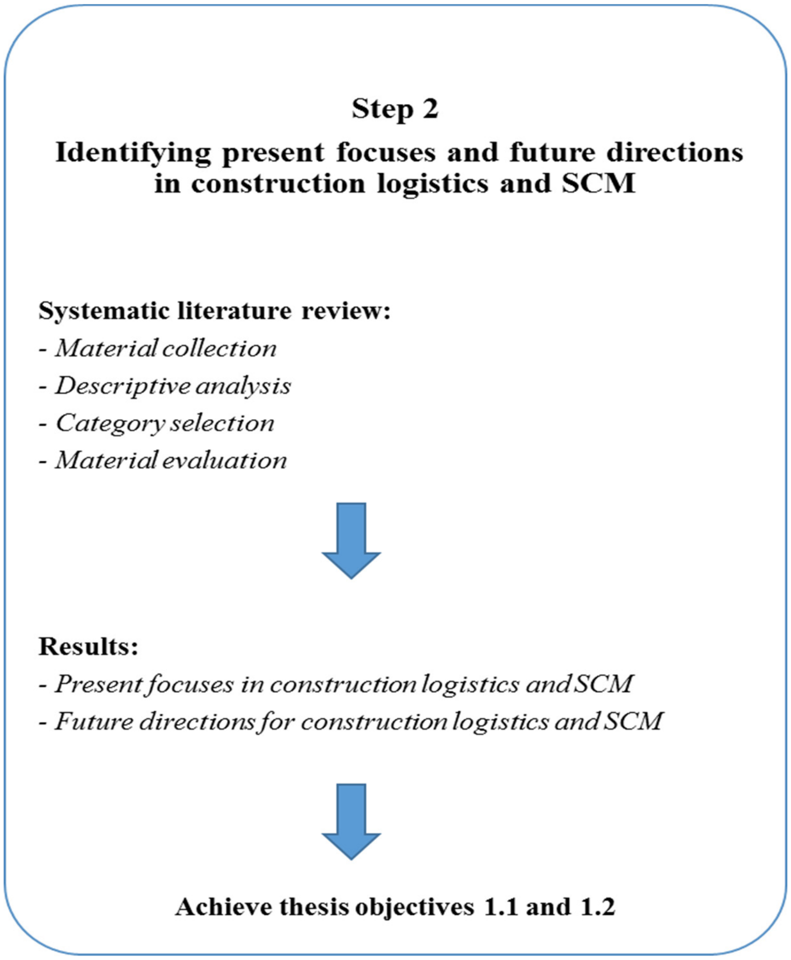

Figure 0.5 Process of step 2

Identifying present focuses and future directions in CSCM: In order to achieve thesis objectives 1.1 (identifying present focuses in construction logistics and SCM) and 1.2 (proposing future directions for construction logistics and SCM), we conduct an in-depth literature review process called a systematic literature review. The systematic literature review is performed by following the process of content analysis provided by Seuring and Gold (2012), consists of four steps: (1) material collection; (2) descriptive analysis; (3) category selection; and (4) material evaluation. Both types of qualitative and quantitative content analysis are used to support each other to get research results efficiently (Bell et al., 2018). The process of this step is presented in **Figure 0.5**. The details of the systematic literature review and results are presented in **Chapter 1**.

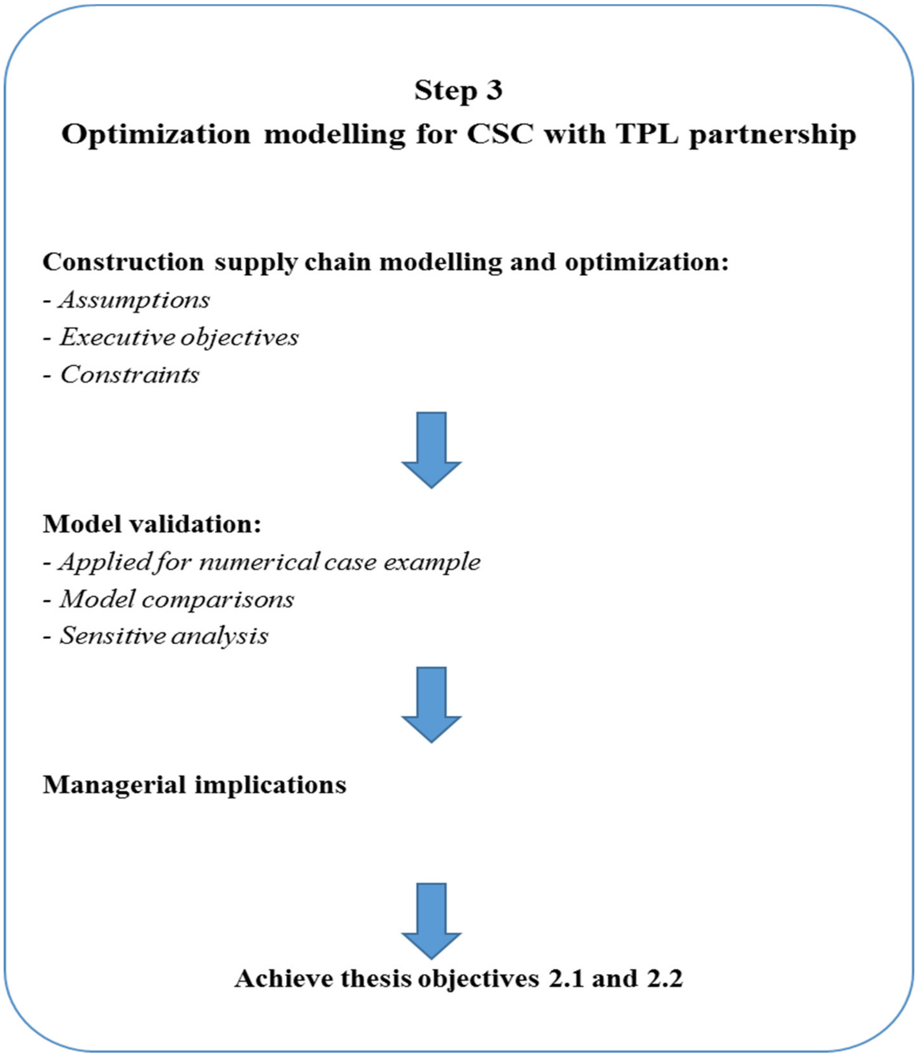

Figure 0.6: Process of step 3

Optimization modeling for construction supply chain with third-party logistics partnership: In order to achieve thesis objectives 2.1 (developing an optimization model for CSC operations with TPL partnership) and 2.2 (using the proposed model to assess the efficiency of the TPL employment), we apply a process including three minor steps: (1) CSC modeling and optimization, (2) model validation, and (3) managerial implications. The process of this step is presented in **Figure 0.6**.

Construction supply chain modeling and optimization: For the first step, we define the relevant issues: assumptions, executive objectives, and constraints. The assumptions for modeling and optimization of the operations of the CSC network with TPL partnerships are made to define a scope that the model works for. The executive objective of the model takes into account the optimization for the construction logistics costs. The logistics costs can be estimated by considering the componential costs: ordering cost, transportation cost, storage cost, and material checking cost. In this model, we consider the following constraints: uncertain price, safety stock, inventory status, and SC trade-off issues. The details of this step are structurally presented in **chapter 2**.

Model validation: For the second step, in order to validate the proposed model, a hydropower construction project is illustrated. Besides, in order to consider the efficiency of the proposed model, we compare the results obtained from three models: the TPL model with price discounts, the TPL model without price discounts, and the model without TPL. Then, the analyzes of impacts of uncertainties (delivery lead-time, demand, and price) on total SC costs are conducted to provide managerial implications for SC improvement. The sensitive analyzes are also done to consider how the total SC cost is sensitive to changes in price discounts offered by suppliers. The details of this step are presented in **chapter 2**.

Managerial implications: Finally, for the third step, the managerial implications are given for CSC operations with the TPL integration in order to enhance the logistics performance. We have relevant recommendations for the key SC actors: the owner, the TPL provider, the contractors, and suppliers. The details of the managerial implications are presented in **chapter 2**.

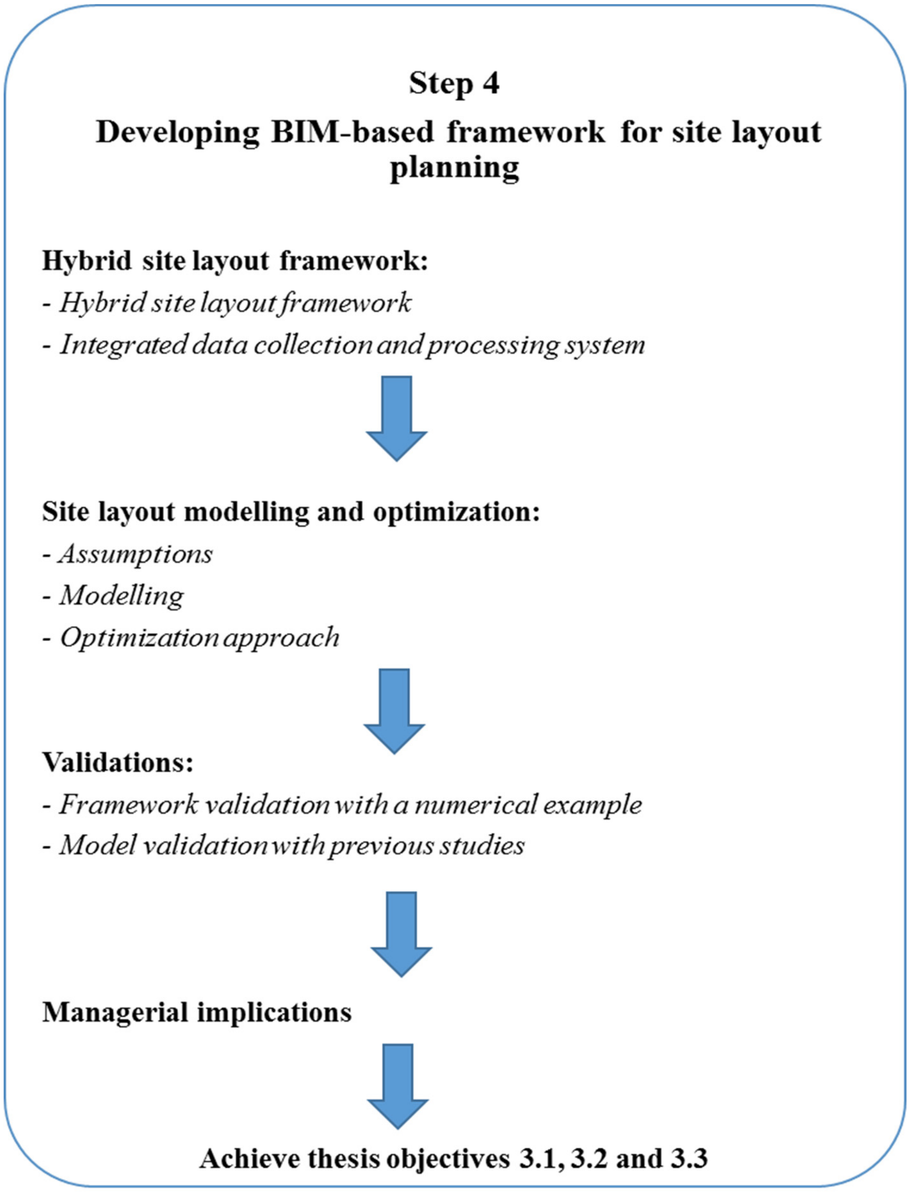

Figure 0.7: Process of step 4

Developing BIM-based framework for site layout planning: In order to achieve thesis objectives 3.1 (proposing a systematic approach which combines both systematic and mathematical layout modeling), 3.2 (developing a BIM-based data collection and processing system which enables the data extraction and integration from various sources) and 3.3 (detailing the calculation and the integration of all necessary data), we apply a process including four minor steps: (1) proposing a hybrid site layout framework, (2) site layout modeling and optimization, (3) validations, and (4) managerial implications. The process of this step is presented in **Figure 0.7**.

Proposing a hybrid site layout framework: For the first step, we propose a hybrid framework for construction site layout planning, which includes four main components: systematic layout process, input data, output data, and mathematical programming. Systematic layout planning (SLP) is a procedural layout method, which facilitates knowledge-based rules for data creation and analysis. In this thesis, the systematic site layout process consists of six steps, as presented in **chapter 3**. The database and the knowledge-based rules provide the input data for the systematic site layout process. The output data of each step of the systematic site layout process will be identified in **Figure 3.2**. The mathematical modeling consists of the components: defining objective functions (total layout costs and adjacency scores), developing constraints, and defining the multi-objective optimization method. In order to create the BIM-enabled database for the above-mentioned systematic site layout process, an integrated data collection and processing system is proposed, as shown in **Figure 3.3**. The system comprises five modules: (1) data collection, (2) data sharing, (3) data processing, (4) data storage, and (5) systematically dynamic site layout.

- Module 1 - Data collection encompasses three components: BIM software, cost, and project schedule.
- Module 2 - Data sharing: The cloud-enabled platform is established to leverage data sharing among the construction participants.
- Module 3 - Data processing: Through a middleware using VBA (Visual Basic) programming, Excel-based macros are designed to extract and process the data. The middleware is responsible for computing: (1) material trip frequencies between facilities, (2) distances of available locations, and (3) closeness ratings between facilities.
- Module 4 - Data storage: The related data of cost (transportation cost and setup cost) and project schedule (construction phases and activities with required facilities) are prepared and tabulated by the project manager and saved into the database in forms of the spreadsheet.

- Module 5 - Systematically dynamic site layout: The step-by-step systematic site layout process is detailed in the previous section. This process uses the input data shared by the cloud-enabled platform, which facilitates a project manager to proceed with the site layout at any time and place.

Site layout modeling and optimization: For the second step, we define the relevant issues: assumptions, modeling, and optimization approach. In this thesis, construction site layout planning is assumed as tactical planning, which arranges a set of temporary facilities on the site in order to satisfy the constraints and optimize layout objectives and adjacency scores. The total layout cost includes two components: material handling cost and set-up cost for each stage of the construction project. The adjacency scores among all facilities are evaluated by the relevant construction actors with different levels: absolutely necessary = 5, especially important = 4, important = 3, ordinarily close = 2, unimportant = 1. We ensure the constraints in which each facility is allocated to only one location, and each location contains only one facility. The $\boldsymbol{\varepsilon}$-constraint method is used to reformulate a multi-objective optimization problem into a single-objective optimization problem. $\boldsymbol{\varepsilon}$-constraint method bases on the idea that one of the objectives is kept and the other objectives are constrained by values identified by users. The proposed site layout optimization model can be solved by some soft-wares, which support the optimal calculation with mathematical algorithms. However, those soft-wares require much mathematical programming or coding. In this thesis, an evolutionary algorithm provided by Microsoft Excel Solver is used to solve the multi-objective site layout problem to reduce the complexity in mathematical programming for construction managers. The details of this step are structurally presented in **chapter 3**.

Validations: For the third step, in order to validate the proposed framework and the proposed mathematical model, the following actions are performed:

- The site layout planning for temporary facilities of the medium-size housing project is presented to validate the proposed framework. The project uses BIM from initiation until construction. The optimal values of the selected solution are used to compare to the current solution prepared by the site managers.

- In order to validate the solution method proposed by the framework, the mathematical model is applied for the site layout planning problem mentioned by Li and Love (2000). Then, a comparison of results is conducted to previous studies: Li and Love (2000), Lien and Cheng (2012), and Papadaki and Chassiakos (2016). All these previous studies adopted the same medium-sized project to test optimal site layouts by using different mathematical solution methods.

The details of this step are structurally presented in **chapter 3**.

Managerial implications: Finally, for this step, the distinctive and important implication of this thesis is the integration of systematic site layout process, BIM technology, and actors' expertise for a smooth and productive site layout plan. This triad supports the site planners to analyze the resources, collect and estimate the data, develop the site layout models, share and update the data, as well as select the optimal solution. Based on the research implications, we give recommendations to the site planners to deliver a productive and safe site layout plan. The details of the managerial implications are presented in **chapter 3**.

Thesis outline

The rest of this thesis is structured to present how the research objectives are achieved as follows:

Chapter 1 presents the results of the identification of the present focuses and discusses the future directions of decision-making in construction logistics and SCM. The results highlight that SC integration is the future trend in SCM application for the construction industry. Besides, the application of technology, such as BIM, is also suggested for the improvement of construction logistics and SC performances. To enhance CSC integration, a TPL partnership is proposed for CSC operations.

Chapter 2 develops an optimal model for CSC with a TPL partnership, which takes into account the two kinds of purchased materials: type 1 (materials can be transported to a warehouse or directly sent to the construction site), and type 2 (materials can be directly sent to construction site only). The optimal solution provided by the model can assist the decision-makers in determining the operational strategies for common tasks in construction SCM: supplier selection, determination of order quantity, and consideration of the efficiency in using TPL. The proposed model also facilitates the construction managers to take advantage of the TPL warehouse to order a larger quantity to obtain lower prices and transportation costs per unit offered by suppliers.

Chapter 3 details an innovative BIM-based framework for multi-objective and dynamic temporary construction site layout planning, which uses a hybrid approach of systematic layout planning and mathematical modeling.

Finally, the conclusions summarize all the achievements of this thesis: research contributions, main findings, managerial implications, research limitations, and further researches.

Research contributions

Article 1 (presented in Chapter 1): This paper utilizes a systematic literature review methodology to identify the present focuses and discuss the future directions of decision-making in construction SCM. The results show that, at present, the construction SCM applications are still focusing on material and resources management with internal SC integration. Strategic decisions related to building partnerships, IT-based planning, and logistics-based planning are not conducted at the early stage of planning and design. For future trends in construction SCM application, a framework is proposed to leverage the three important points: the collaborative planning and design with advanced techniques; the lean procurement with BIM and TPL; and the application of BIM in construction operations and delivery. The original contribution of this paper is the attempt to identify CSC decisions and suggests how they should be delivered during the phases of a construction project with the use of appropriate SC methods and tools.

Article 2 (presented in Chapter 2): Previous studies confirm the benefits of using Third-party logistics (TPL) for efficient management of construction logistics. Nevertheless, there is a lack of decision-making models and tools to evaluate the exact role that can play a TPL provider as a driver for the supply chain (SC) integration and optimization. Therefore, this study aims to develop a decision-making model for construction supply chain (CSC) optimization with possible TPL integration. The proposed model takes into account two types of purchased materials. Type-1 materials can be transported to the warehouse owned by the TPL or directly sent to the construction site. Type-2 materials are sent to the construction site only. In this case, the optimization model assists decision-makers in determining the operational strategies in construction supply chain management (CSCM), including supplier selection, TPL integration, and inventory policy determination. The proposed model assists construction managers to take advantage of the TPL warehouse and order larger quantities if necessary, to obtain lower prices offered by suppliers and reduce the transportation cost. Using the numerical case example, we find that the proposed model performs better results in total SC cost in comparison with the CSC model without TPL. This implies that the optimization model for the integrated CSC operations with TPL partnership can be used to improve the construction logistics performance and deal with the practical requirements of the current issues in the construction industry.

Article 3 (presented in Chapter 3): This paper proposes an innovative BIM-based framework for multi-objective and dynamic temporary construction site layout design, which uses a hybrid approach of systematic layout planning and mathematical modeling. BIM (Building information modeling) platform is utilized to facilitate the determination of the required quantitative data while the qualitative data are generated through knowledge-based rules. The multi-objective layout model represents two important aspects: layout cost and adjacency score. The result shows that the model meets construction managers' requirements not only in saving cost but also in assuring the preferences of temporary facility relationships. The proposed framework is expected to serve as a solution for practical application, which takes advantage of technologies in data collection and processing. Besides, this paper demonstrates, by using numerical experimentation and applying Microsoft Excel Solver for site layout optimization, how to reduce the complexity in mathematical programming for construction managers. The original contribution of this paper is the attempt to develop a framework in which all data used for the site layout modeling are collected and processed using a systematic approach, instead of being predetermined as in many previous studies.

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CHAPTER 1

PRESENT FOCUSES AND FUTURE DIRECTIONS OF DECISION-MAKING IN CONSTRUCTION SUPPLY CHAIN MANAGEMENT: A SYSTEMATIC REVIEW

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Abstract

This paper utilizes a systematic literature review methodology to identify the present focuses and discuss the future directions of decision-making in construction supply chain management (CSCM). The results show that, at present, the CSCM applications are still focusing on material and resources management with the internal SC (supply chain) integration. Strategic decisions related to building partnerships, IT-based planning, and logistics-based planning are not conducted at the early phase of planning and design. For future trends in CSCM application, a framework is proposed to leverage the three important points: the collaborative planning and design with advanced techniques; the lean procurement with BIM and 3PL; and the application of Lean and BIM in construction operations and delivery. The original contribution of this paper is the attempt of identifying CSC decisions and suggests how they should be delivered during the phases of a construction project with the use of appropriate SC methods and tools.

Keywords: construction supply chain management; present focuses; future directions; decision making.

1.1 Introduction

The concept of Supply Chain Management (SCM) has been increasingly applied to many industrial sectors to improve business performance such as faster response to the variety of customer demands, lower cost, and better quality. In construction, the application of SCM concepts is frequently used to guide project managers in strategic planning to achieve partnerships with suppliers, and obtain more efficiency in operational construction (Azambuja and O'Brien 2009). However, the importance of SCM in improving construction management has been recognized since the 1990s. Papers in this specific period mostly discussed the controversial issue that whether SCM should be applied or not for construction industry due to its different characteristics from the manufacturing sector. Until the 2000s, research studies focused on the analysis and the exploration of the relevant aspects of SCM in construction, especially after Vrijhoef and Koskela (2000) introduced four roles of supply chain management in construction that motivated many scholars in studying the field.

The last decades have witnessed changes in the awareness of applying SCM in construction management. At the beginning of the 2000s, researchers in CSCM focused on the examination of some aspects such as proposing perspectives on construction supply chain integration (Dainty et al. 2001). They also explore skills, knowledge, attitudinal requirements for construction supply chain partnerships (Briscoe et al. 2001); and how to adopt SCM in the construction industry (Saad et al. 2002). From the middle of the 2000s, many authors were interested in developing in-depth frameworks for solving and applying managerial problems of CSCs. For instance, an agent-based framework for supply chain coordination in construction (Xue et al. 2005), a conceptual framework for mature CSC (Vaidyanathan and Howell 2007), and dynamic reputation incentive model in CSC (Chen and Ma 2008) are only a few examples of application attempts. In recent years, researchers have paid attention to many methods and tools that are integrated to CSC to achieve the efficiency in performance: Lean concept is adopted to improve CSC collaboration (Eriksson 2010); Logistics modeling using simulation (Vidalakis et al. 2011); Logistics optimization using meta-heuristics algorithms (Said and El-Rayes 2014; Kumar and Cheng 2015). Recently, CSC integrated with Building Information

Modeling (BIM) is another proof that the adoption of logistics and SCM in the construction sector continues to evolve with the technological progress (Papadonikolaki et al. 2015).

Construction supply chains (CSCs) are very complex systems in which the performance relies on a set of hundreds of decisions delivered by multiple independent firms. In construction networks, clients, consultants, contractors, designers, subcontractors, and suppliers are the key players connected by interfaces embracing knowledge transfer, information exchange, financial and contractual relationships. These networks are still characterized by inefficient collaboration. For instance, the splitting up design and construction, the absence of integration and coordination between different functional disciplines, as well as the poor communication are some of the challenges that construction management is facing (Behera et al. 2015). Stakeholders in construction industry usually focus on their benefits. Thus, the lack of collaboration causes many problems in communication and information sharing with others. They tend to push certain data and documents to others in the network. The lack of information sharing in construction networks is a critical problem, and it is a significant source of delays, errors, and duplications in construction project management (Xue et al. 2005). Stakeholders are not motivated in improving construction networks since it is not clear who will gain the benefits of the improvement of the network relationships (Vaidyanathan 2009). Stakeholders, such as General Contractor (GC) or Subcontractor, are concurrently managing several projects; thus, they have incentives to focus on enhancing the efficiency of their own business to achieve immediate economic advantages rather than to improve the network performance.

It is suggested that the stakeholders should consider the global efficiency of whole CSC network for their decision-making during the construction phases. An integrated CSC can solve the existing problems in the construction industry that is known as a decentralized SC. However, recent researches in construction management have not proposed any framework to classify construction supply chain decision-making or suggest when they should be integrated along the construction phases (Azambuja and O’Brien 2009). To fill this gap, this paper conducts a systematic literature review of construction logistics and CSCM to analyze the relevant body of knowledge identified in 123 articles published from 2000 to 2017, and to determine the SC decisions made in each construction phase. The period of seventeen years is thought to be sufficient to cover the most significant changes and the evolution of decision-making in logistics and supply chain management in construction management.

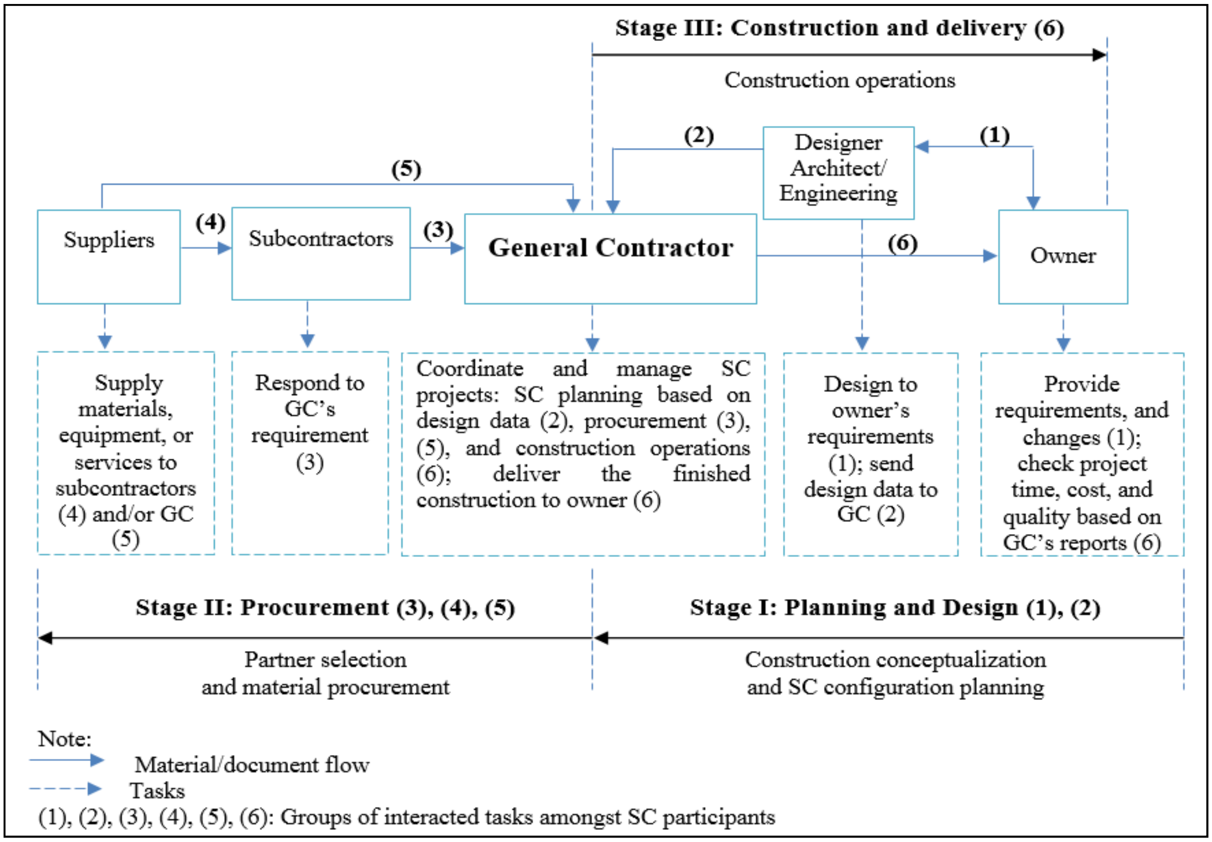


Figure 1.1 Phases of the CSC process with participants' tasks

In this paper, the separation of construction process into three phases (Planning and Design; Procurement; and Construction and delivery) follows the proposition of Azambuja and O'Brien (2009) with the tasks presented in **Figure 1.1**. The first phase (Phase I), Planning and Design, consists of the functions related to the construction conceptualization and SC configuration planning. The second phase (Phase II), Procurement, embraces the relevant functions of partner selection and material procurement. The third phase (Phase III), Construction and delivery, includes inventory control, material handling for on-site construction, and the delivery of the final construction project.

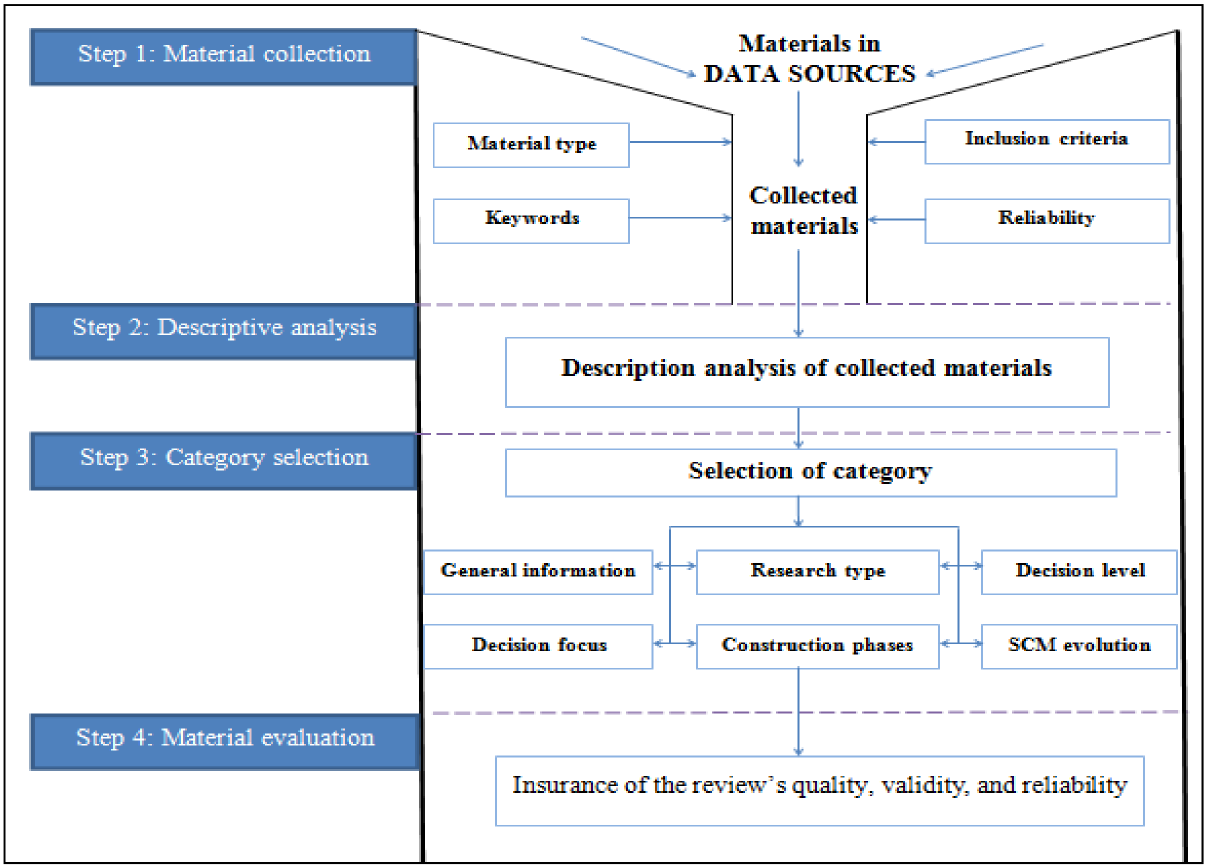


Figure 1.2 Phases of the CSC process with participants' tasks

Based on the reviewed results, a systematic analysis and discussions of decision focus in CSCM are conducted. The paper also highlights the crucial evolution steps in the development of SCM decision-making in general and makes the comparison with the evolution of SCM decision-making in the construction industry. This comparison indicates the gaps observed in the implementation of SCM in the construction industry when being compared to other sectors, especially in the manufacturing and the service industries. Based on this comparison, future directions of decision making in CSCM are proposed with a more detailed specification of methods and tools that meet new requirements of construction management practices and the technological progress. Thus, the specific objective of this paper is to answer the following research questions (RQ):

- [RQ1]: What are the present focuses of decision-making in CSCM and the relationships existing between the SC participants during the major construction phases mentioned in the reviewed literature?

- [RQ2]: What are the future trends of SCM applications in the construction industry to meet the new requirements of construction practices and technological progress?

1.2 Review Methodology

This paper utilizes a systematic literature review, which is performed by following the process of content analysis provided by Seuring and Gold (2012), consists of four steps: (1) material collection; (2) descriptive analysis; (3) category selection; and (4) material evaluation. This process of content analysis is utilized for this study with the aim to achieve the research objectives. Both types of qualitative and quantitative content analysis are used to support each other to get research results efficiently (Bryman and Bell 2015). The process of the systematic literature review is presented in **Figure 1.2**.

1.2.1 Material collection

To perform this study, academic papers published in reputable peer-reviewed journals and internationally important conferences are used. The other sources (editorial papers, practitioner journals, assessment reports, professional guidelines, and standards) are not selected for this study since the reliability of these materials is not easily validated. To reach the credibility of the literature review, trustful databases are chosen: Emerald, SCOPUS, Springer Link, Wiley, as well as, international scientific conferences in the field of construction management: IEEE-Xplore, International Group for Lean Construction (IGLC), International Conference on Management Science and Engineering Management (ICMSE), and International Symposium on Automation and Robotics in Construction (ISARC). Articles published from 2000 to 2017 are collected for this study. As mentioned in the introduction, the period from 2000 to the present has witnessed the publication of many academic papers focusing on the implementation of SCM in construction. The period of the past seventeen years covers most of the significant changes and updates in the field of CSCM. The detailed criteria for material collection are presented in **Table 1.1**.

Table 1.1 Criteria for material collection

	Inclusion	**Exclusion**	**Reliability**
Material source	Trustful databases: Emerald, SCOPUS, Springer Link, Wiley; International scientific conferences in construction	Non-academic and unreliable data sources	Assurance of academic and reliable requirements of material sources
Material type	Academic papers published in reliable peer-reviewed journals, and internationally honorable conferences	Editorial papers, practitioner journal articles, assessment reports, professional guidelines, and standards	Ease of validation for material's reliability
Publication period	From 2000 to 2017	Out of the period	Covering all changes and updates in terms of construction SCM
Keywords (construction SCM, CSC logistics, CSC modeling, construction SCM trend, SCM evolution)	Articles mention, describe and analyze the keywords' content	Articles only mention the keywords	Assurance of the articles' contents in terms of suitability and reliability.

To achieve the research objectives, the keywords chosen for paper search are “construction supply chain management,” “construction supply chain logistics,” “construction supply chain modeling,” “construction supply chain management trend,” and “supply chain management evolution.” These keywords are used for the advanced searches (searching for anywhere of the articles including title, keywords, abstract, and content; searching for articles published from 2000 – 2017) to find the suitable articles which mention, describe, and analyze the contents of these keywords. For the combined keywords, construction supply chain logistics, construction supply chain modeling, construction supply chain management trend, and supply chain management evolution, the functions “AND” of the “advanced search” option are used. For example, the keyword “construction supply chain logistics” is searched by “construction supply chain” AND “logistics.” The keywords related to construction (construction supply chain management, construction supply chain logistics, construction supply chain modeling, construction supply chain management trend) are utilized to search for present focuses and trends of SCM application in the construction industry. Meanwhile, the keyword “supply chain management evolution” is used to search for academic articles, which analyze the evolution of SCM in general during the period. Articles that do not describe nor analyze the contents of these keywords are removed. Specifically, articles which only mention the terms of “construction supply chain management, construction supply chain logistics, construction supply chain modeling, construction supply chain management trend, and supply chain management evolution” without describing and analyzing these terms for their contents, are eliminated from this study. After removing inappropriate documents, there are 123 journal and conference articles remaining for the further analysis and discussions. These documents are fully listed in the references.

1.2.2 Descriptive analysis

The descriptive analysis for general information of collected documents (years of publication, publications by country, and journals/conferences/publishers) is conducted in the below section. The descriptive analysis is also responsible for analyzing important contents of chosen documents. In this study, along with general information of collected articles, the other contents that focus on the descriptive analysis are research type, decision levels, and construction phases. The details of description analysis are presented in the next section.

1.2.3 Category selection

The collected documents are categorized using five groups (dimensions) of classification criteria: (1) General information; (2) Research type; (3) Decision level; (4) Decision focus; and (5) Construction phases. **Figure 1.3** shows the classification framework for reviewed papers. Each group of the category selection reflects each critical aspect of the contents presented in all collected documents. The base for each category group is explained in details as in the following.

- General information - In this category, publisher title (journals and conferences), publication year, and publication by country are presented. Leiras et al. (2013) also use this criterion for the systematic literature review.

- Research type - The collected documents are classified based on their research type as adopted by Bygballe et al. (2010). Papers are organized as action research, case study, conceptual, document analysis, literature review, quantitative study, qualitative study, survey, or their possible combinations. It is probable that a study in CSCM can either only employs one kind of research method or utilizes many research methods to achieve its objectives.

- Decision level - Leiras et al. (2013) claim that decisions in SCM should be divided according to the three levels because an efficient allocation of resources in supply chain networks requires efficiently strategic (long-term), tactical (medium term), and operational (short term) decisions. This paper follows this approach to classify the documents regarding decision level. In the construction industry, strategic decisions are taken for a long-term horizon and identify the SC configuration (construction participants, locations, and relationships), plan for construction capacities, information systems, and risk mitigation strategies. Tactical decisions in construction formalize a set of policies that apply for a period (production planning, inventory control, and material handling). Operational decisions focus on weekly and daily operations for the construction sites after the SC configuration is fixed, and the tactical plans are already approved.

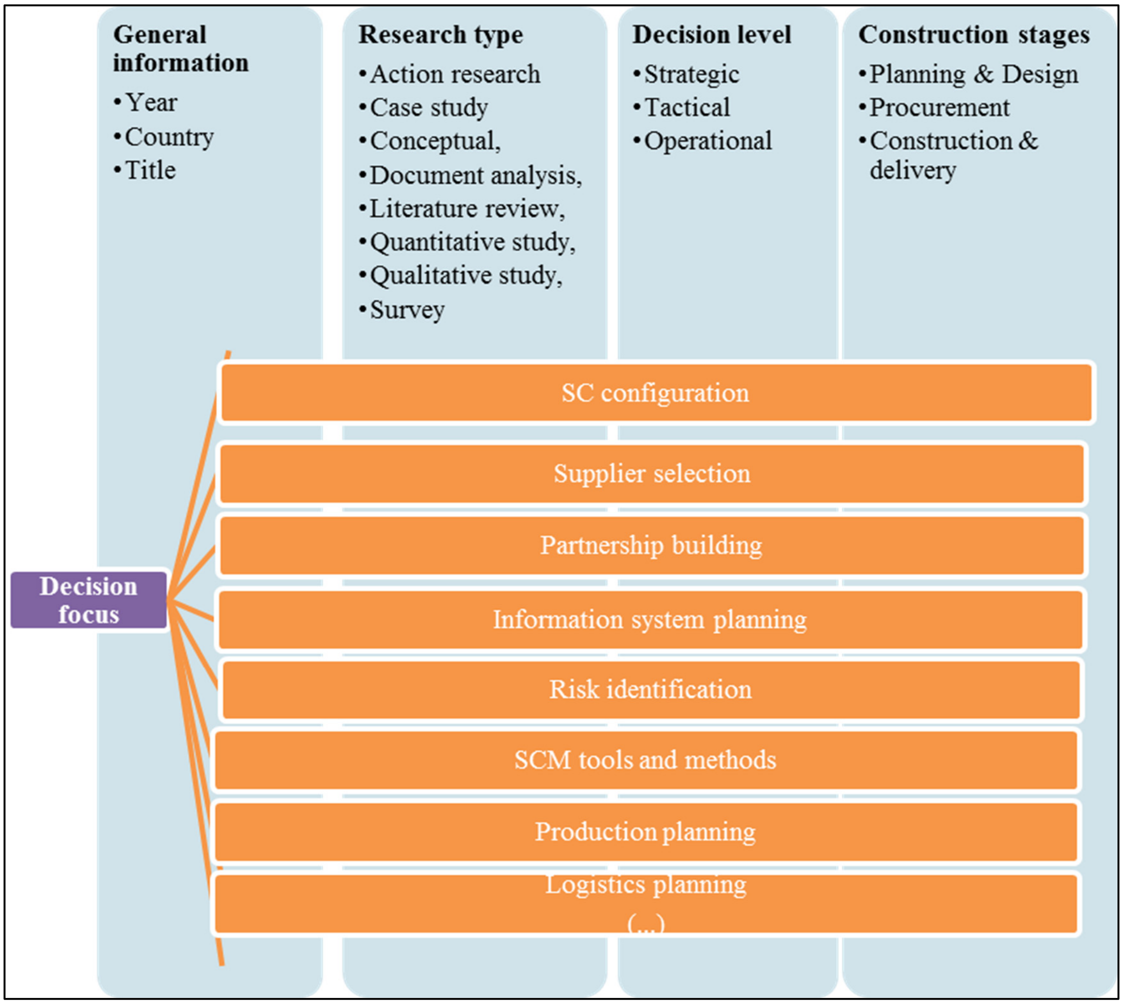


Figure 1.3 Classification framework for reviewed papers

- Decision focus – With the objective of identifying decisions made in each phase of CSCM, the papers are classified into different decision focuses based on the content analysis. Azambuja and O'Brien (2009) have already proposed that the most critical decisions to be made in each phase of a construction project are: SC configuration, supplier selection; information system planning; risk identification; and developing tools and methods for CSC planning. These decisions are significant for CSCM and focused by many studies in the field. Besides, the decisions for CSC logistics are also critical for the performance of CSCM. Specifically, logistics in construction focus on material procurement, site layout planning, transportation routing, and material handling (Vidalakis et al. 2011; Said and El-Rayes 2014; Ying et al. 2014). The specific details for each of these decisions are presented in the next sections.

- Construction phase - Azambuja and O'Brien (2009) divide a project in CSCM into three (3) phases: Planning and design, Procurement, and Construction and delivery. The first phase deals with the decisions regarding project's SC configuration and systems' specifications design. The second phase focuses on the decisions of supplier assessment and purchasing. The final phase is responsible for the decisions of operational activities in construction. Based on the content analysis, the collected papers are categorized based on these phases. The details of phase description are already presented in **Figure 1.1**.

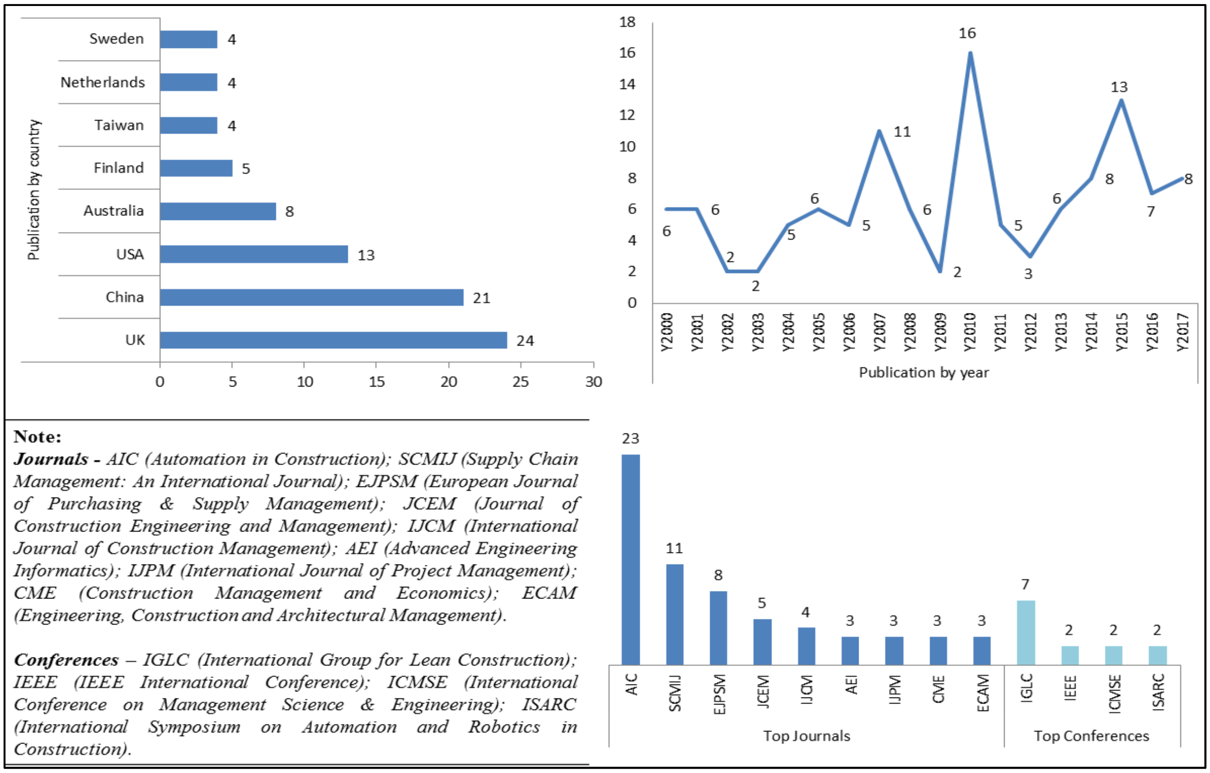
1.2.4 Material evaluation

The collected sample of documents is reviewed following the five classification criteria mentioned in the above section. To guarantee the quality, the validity, and the reliability of the review, a crosschecking process is conducted for the document classification. In this process, two authors are required to read carefully the category criteria as well as the content of collected papers. Then, the sample is classified independently by the two authors based on their understanding of the documents. After finishing the classification, the two authors discuss together to get the agreement. For papers with different classification results between the two authors, the content analysis of the documents must be reviewed again by them until a consensus is achieved. Later, the classification list of the sample is presented to the third author who has academic and practical experiences in the field of logistics and CSCM. The third author is responsible for a quick reading of all the documents to check the validation of the classification. The third author gives the corrections for cases that are thought to be unsuitably classified. The discussion among all authors is conducted for these cases to make sure that the classification is unbiased. The cross-checking process is performed until a final agreement is achieved. This process plays an essential role in improving the quality of academic judgment for content analysis within the systematic literature review process.

1.3 Descriptive analysis

1.3.1 General information of the literature sample

The distribution of the reviewed literature sample with general information is presented in **Figure 1.4**. Top countries of paper publications are UK (24), China (21), and USA (13); followed by Australia (8), Finland (5), Taiwan (4), Sweden (4), and The Netherlands (4). Among the top journals and conferences referred by the sample are Automation in Construction (AIC), Supply Chain Management: An International Journal (SCMIJ), European Journal of Purchasing and Supply Management (EJPSM), and IGLC conference.



Note:
Journals - *AIC (Automation in Construction); SCMIJ (Supply Chain Management: An International Journal); EJPSM (European Journal of Purchasing & Supply Management); JCEM (Journal of Construction Engineering and Management); IJCM (International Journal of Construction Management); AEI (Advanced Engineering Informatics); IJPM (International Journal of Project Management); CME (Construction Management and Economics); ECAM (Engineering, Construction and Architectural Management).*

Conferences – *IGLC (International Group for Lean Construction); IEEE (IEEE International Conference); ICMSE (International Conference on Management Science & Engineering); ISARC (International Symposium on Automation and Robotics in Construction).*

Figure 1.4 General information about the sample

1.3.2 Research types

The research type plays a vital role in ensuring the reliability and validity of a study. **Figure 1.5** shows that in the field of construction SCM, top research methods are exploited by researchers are a case study (25 publications), quantitative study (23), literature review (17), and conceptual (7). This result reflects the reality that construction SCM is a new and evolving area of study in which researchers are trying to adapt SCM approaches to the construction industry, which have been applied with success previously in the manufacturing and the service sectors, more specifically for construction logistics with quantitative models and applicable case studies. In recent years (from 2010 to 2017), many authors have proposed diversified their methods in the field aiming at increasing the applicability of their models in construction practice. As shown in **Figure 1.5**, there are several papers that used mixed research methods. For example, seven (7) publications combine the quantitative study with an example; ten (10) publications adopt mixed-methods of quantitative and case study methodologies; two (2) publications utilize mixed-methods of qualitative, interview and survey methodologies.

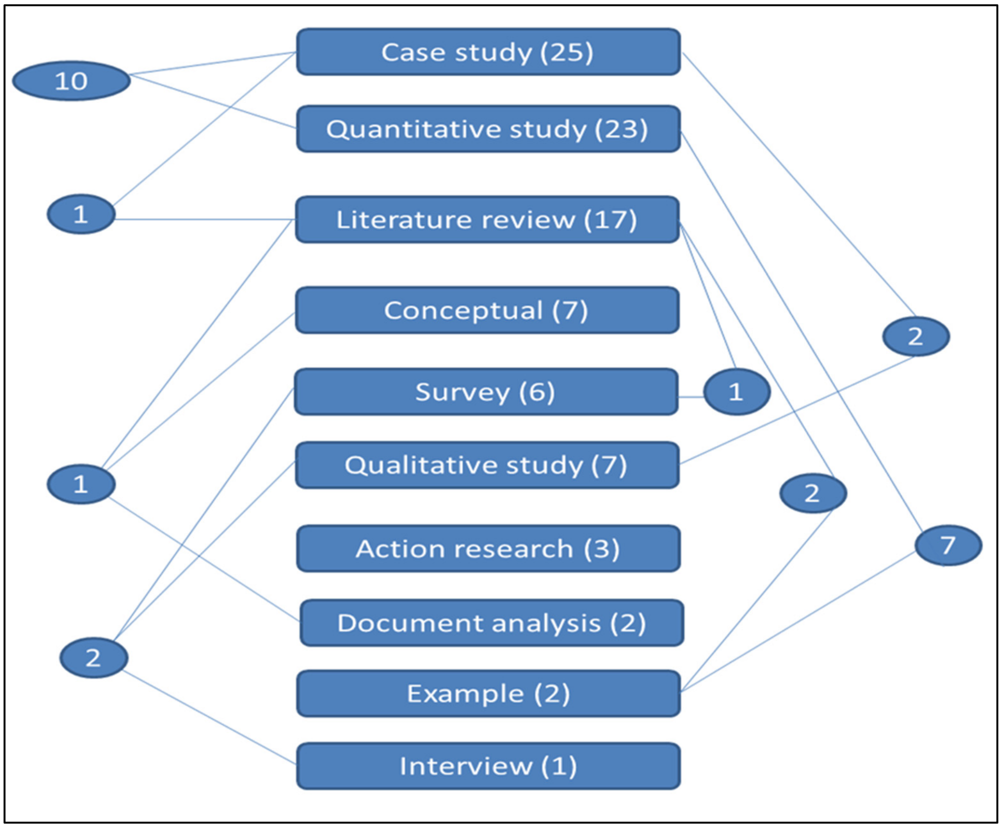


Figure 1.5 Paper distribution of research type

1.3.3 Decision levels and construction supply chain phases

For the sample, only twenty two (22) papers discuss the involvement of decision-making in the planning and design stage of CSC. Fifty (50) papers focus on decisions related to the procurement stage. There are sixty-one (61) papers that cover the decision process within the construction and delivery stage. In the stage of planning and design, strategic decisions such as CSC configuration and developing of the detailed drawings of engineering and architecture are conducted. Because of the project-based oriented perspective and the short-time relationships in construction, important strategic SCM decisions are not released in the planning and design stage. One of the most important decisions is building a strategic relationship that is usually deployed in the procurement stage. The other important strategic decision, for example, building the construction information system is often set up for the construction and delivery stage.

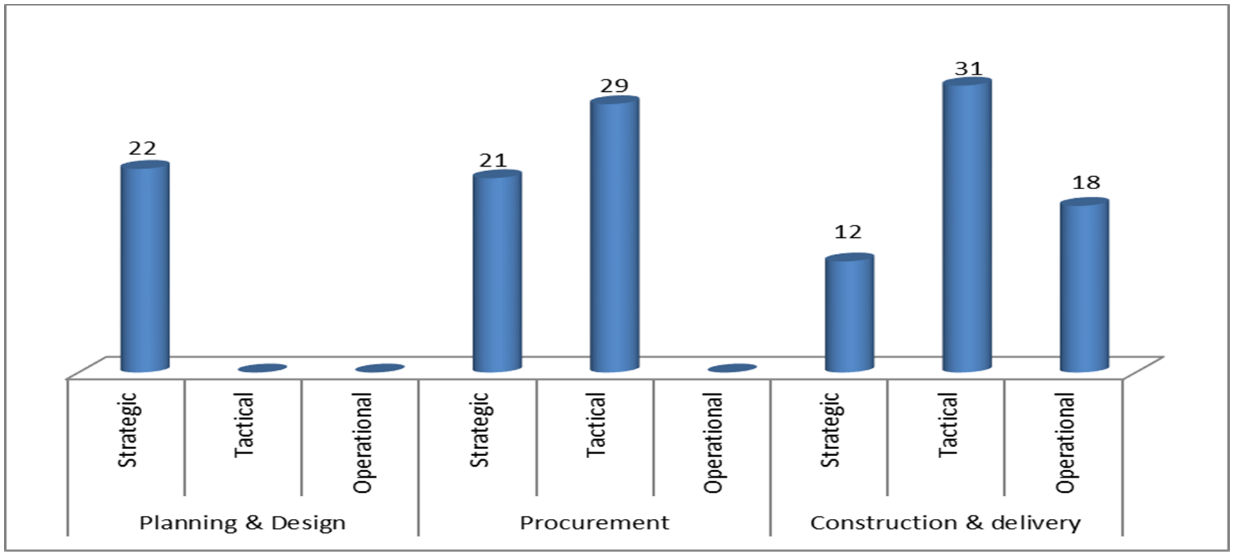


Figure 1.6 Decision levels across different CSC phases

Figure 1.6 shows the decision levels across different phases of CSC. There are twenty two (22) papers focusing on strategic decisions at the first stage of planning and design. At this early stage, no tactical and operational decisions are discussed. For the second stage of procurement in which most of the suppliers and subcontractors are selected, twenty one (21) papers mention strategic decisions problems at this stage. Tactical decisions studies are proposed by twenty-nine (29) papers. In the construction stage, 12, 31, and 18 papers, respectively deploy strategic, tactical, and operational decisions. It is noted that a publication can be classified into more than one category. This result supports the idea of Azambuja and O'Brien (2009) and Shi et al. (2016) who claim that most of the studies in construction SCM focusing on decisions at the tactical level. The foundations and the nature of SCM decisions in the CSC are detailed in the following section.

1.4 Present focuses of decision-making in CSCM

This section contributes to the illustration and discussion about the present focuses of decision making in construction SCM for the reviewed papers. It answers the research question "*What are the present focuses of decision-making in construction SCM and the relationships existing between the SC actors during the major construction phases mentioned in the reviewed literature?*" **Table 1.2** shows the decision focuses on construction SCM across three major construction phases mentioned by recent scholars.

Table 1.2 CSC decision-making across the construction phases

	Planning and design	**Procurement**	**Construction and delivery**
Strategic decisions	• CSC Configuration ***(8)*** • Tools and methods development for CSC planning and management ***(9)*** • Identifying CSC risks ***(5)***	• Building partnerships ***(22)***	• Building construction information system ***(12)***
Tactical		• Production planning ***(9)*** • Supplier selection ***(3)*** • Purchasing materials ***(15)***	• Identifying transportation system ***(7)*** • Site layout planning ***(15)*** • Controlling information flow ***(9)*** • Material handling ***(9)***
Operational			

At the strategic level, eight (8) papers aim at the decision of identifying CSC configuration, nine (9) papers focus on the decision of developing tools and methods for CSC planning and management, and five (5) papers consider the identification of CSC risks as an important decision at the stage of planning and design. Other strategic decisions, building partnerships and building construction information system, which are respectively focused by 22 and 12 papers, are deployed at the phases of procurement, and construction and delivery.

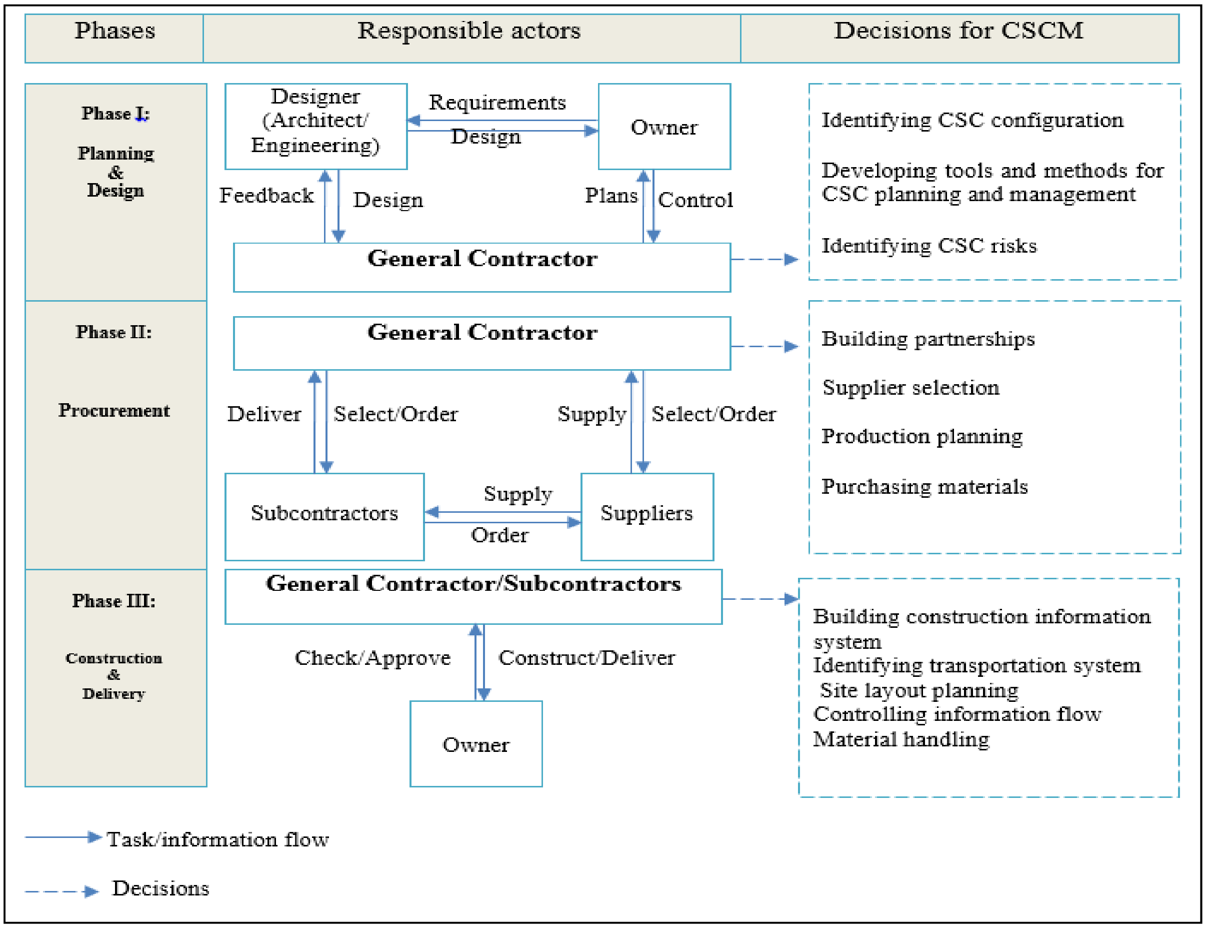


Figure 1.7 Decision focuses on each stage of construction project

Table 1.2 also shows the main decisions that have been proposed for tactical and operational planning in CSC. These decisions are made at the phases of procurement, and construction and delivery including: production planning (9 papers), supplier selection (3 papers), purchasing materials (15 papers), transportation system identification (7 papers), site layout planning (15 papers), controlling information flow (9 papers), and material handling (9 papers). **Table 1.3** presents the detailed descriptions of CSC decisions.

Figure 1.7 presents the summary of focused decisions, for construction SCM in accordance with each stage of the construction project, which are proposed by the reviewed literature. At the stage of planning and design, in order to design an efficient CSC network, it is essential to have the corporation of the owner, the designer (architect and engineering), and the GC. In such combination, the owner delivers the requirements in terms of construction design to the designer. The designer makes the design based on the owner's requirements and changes and sends it to the owner for approval and to the GC for planning and execution. In terms of SCM, the GC makes plans in the association with the strategic decisions (identifying CSC configuration; developing tools and methods for CSC planning and management; and identifying CSC risks) based on the design. The GC gives the feedback to the designer and calls for the designer's contributions during the stage of CSC network planning. The owner plays an important role in checking and controlling the GC's plans in terms of time, cost, and quality of construction. In reality, there is a lack of integration amongst the GC, the designer, and the owner for the planning and design; thus, it results in the inefficiency in construction planning and design. Therefore, a proposition is made as follows:

P1- During the planning and design stage, the integration between the General Contraction, the Owner, and the Designer contributes to the efficiency of CSC network planning and design through the decisions focused on identifying CSC configuration; developing tools and methods for CSC planning and management; and identifying CSC risks.

Table 1.3 Descriptions of CSC decisions

Decision level	Decision	Descriptions	Typical papers
Strategic	CSC configuration	- To configure and allocate CSC factors, SC participants, procedures, tasks, material flow, information flow, inventory strategies, and organizational resources of the SC network. - To establish the relations between participants and procedures together with their suitable sequence of procedures.	Vrijhoef and Koskela (2000); Chen et al. (2011); Cutting-Decelle et al. (2007); Azambuja and O'Brien (2009); Barker et al. (2000)
	Tools and methods Development	To develop methods and tools for process planning, process controlling, and performance measurement of CSC network.	Azambuja and O'Brien (2009); Matthews et al. (2000); Eriksson (2010); Papadonikolaki et al. (2015); Amornsawadwatana (2011); Han and Golparvar-Fard (2017); Khalfan et al. (2001); O'Brien et al. (2004); Papadopoulos et al. (2016); Sarker et al. (2012); Serpell and Heredia (2004); Ahuja et al. (2017)
	CSC risks identification	To identify, assess risks, raise mitigation and contingency strategies, and respond efficiently to recognized threats as they arise.	Tah (2005); Tah and Carr (2001); Mohammaddust et al. (2015); Aloini et al. (2012)

Table 1.3 Descriptions of CSC decisions (continued)

Decision level	**Decision**	**Descriptions**	**Typical papers**
Strategic	Building partnerships	To apply SCM in construction to achieve long-term and supportive partnerships between actors in global perspective in order to improve construction performances, and create client value at lower cost.	Xue et al. (2007); Matthews et al. (2000); Briscoe et al. (2001); Xue et al. (2007); McDermotti and Khalfan (2012); Eriksson (2010); Beach et al. (2005); Briscoe and Dainty (2005); Briscoe et al. (2004); Cheng et al. (2010); Doran and Giannakis (2011); Emuze and Smallwood (2013); Eriksson (2015); Jian-hua and Wan (2010); Khalfan et al. (2007); Liu (2014); Lönngren et al. (2010); Meng (2010); Xiang and Qian (2012)
	Building construction information system	To develop IT systems to link all stakeholders and resources of the network, provide real-time data, and accelerate the innovations in the construction industry.	Chen et al. (2011); Azambuja and O'Brien (2009); Lin and Tserng (2001); Xue et al. (2007); Vaidyanathan (2009); Bryde et al. (2013); Khalfan et al. (2015); Lee et al. (2008); Soibelman and Caldas (2000); Song et al. (2007); Tserng and Lin (2002); Zhou (2008)
Tactical and operational	Production planning	To make the production plan and control for construction processes; and provide production information throughout the construction project to all stakeholders' requirements.	Dave et al. (2015); Tillmann et al. (2015); Dave et al. (2016); Barlow et al. (2003); Pinho et al. (2007); Sobotka and Czarnigowska (2005); Vrijhoef and Ridder (2007)

Table 1.3 Descriptions of CSC decisions (continued)

Decision level	**Decision**	**Descriptions**	**Typical papers**
Tactical and operational	Supplier selection	To apply efficient methods for supplier evaluation and selection.	Ng and Li (2006); Chen and Lin (2010); Soroor et al. (2012)
	Purchasing materials	To establish and employ the efficient models to optimize the material procurement and storage.	Polat et al. (2007); Liu and Tao (2015); Ahmadian et al. (2017); Akintoye et al. (2000); Castro-Lacouture et al. (2007); Cheng and Kumar (2015); Childerhouse et al. (2003); Errasti et al. (2007); Hall et al. (2000); Love et al. (2004); Palaneeswaran et al. (2001); Yeo and Ning (2006)
	Transportation system identification	To establish and control the transportation system (transport mode, size, and weight of shipments) for on-site and off-site construction execution.	Ying et al. (2014); Bankvall et al. (2010); Choudhari and Tindwani (2017); Fearne and Fowler (2006); Wegelius-Lehtonen (2001); Ahmadian et al. (2016)
	Site layout planning	To improve the on-site construction performance through optimizing the arrangement of temporary facilities in which transportation distances of on-site personnel and equipment are minimized.	Kumar and Cheng (2015); Soltani et al. (2004); RazaviAlavi and AbouRizk (2015); Voigtmann and Bargstädt (2010); Said and El-Rayes (2014); Abune'meh et al. (2016); Akanmu et al. (2016); Hammad et al. (2016); Hammad et al. (2017); Ning et al. (2016); RazaviAlavi and AbouRizk (2017); Said and El-Rayes (2013); Song et al. (2017)

Table 1.3 Descriptions of CSC decisions (continued)

Decision level	Decision	Descriptions	Typical papers
Tactical and operational	Controlling information flow	To control information flows in order to leverage the construction stakeholders' collaborations and avoid the instability in construction execution.	El-Ghazali et al. (2011); Dave et al. (2016); Aram et al. (2013); Irizarry, Karan and Jalaei (2013); Papadonikolaki et al. (2015); Ahiaga-Dagbui and Smith (2014); Tiwari et al. (2014); Tserng et al. (2005); Vrijhoef et al. (2001); Wang et al. (2007)
	Material handling	To convey, elevate, position, transport, package and store materials. It is straightly associated with site layout planning, as it shows how to arrange facilities in the zone of a construction site to attain efficiency and safety in the movement of resources.	Chan and Lu (2008); Alanjari et al. (2014); Said and El-Rayes (2014); Ala-Risku and Kärkkäinen (2006); Hinkka and Tätilä (2013); Said and El-Rayes (2010a); Said and El-Rayes (2010b); Thunberg and Persson (2014); Voigtmann and Bargstadt (2010)

At the stage of procurement, the GC focuses on the decisions of building partnerships, supplier selection, production planning, and purchasing materials. The strategic decision of building alliances with key partners requires a long-term integration, integrity, openness, commitment, shared vision, and trust. Based on the strategy of partnership building, the selection of suppliers is conducted to prepare for material procurement. After the production planning for construction is approved, the material procurement is processed to meet the requirement of construction operations. The efficiency of this stage needs the collaboration of the GC, the subcontractors, and the suppliers to ensure the reliability of materials supply process and sub-construction delivery, and mitigate the risks of supply delays. Therefore, a proposition is made as follows:

P2 - During the stage of procurement, the collaboration between the GC, subcontractors, and the key suppliers for a long-term period with the integrity, openness, commitment, shared vision, and trust creates the reliability of material supply process and sub-construction delivery, and mitigates the risks of supply delays.

At the stage of construction, the GC is responsible for making decisions related to on-site operations: IT-based decisions (building construction information system and controlling information flow on-site), and logistics-based decisions (identifying transportation system on-site, site layout planning, and material handling on-site). Since the GC and subcontractors work together on-site to finish the construction; thus, their corporations are very important in this stage to assure the schedule, cost, and quality of the construction. To make the construction stage efficient, it is suggested that the IT-based planning and logistics-based planning should be done carefully (calling for the contributions of related partners; planning with sufficient information) to respond to the uncertainty occurring during the on-site construction operations. Then, the owner checks and approves the finished construction delivered by the GC. Therefore, a proposition is made as follows:

P3 - To achieve an efficient performance in construction operations, the IT-based planning and logistics-based planning should be done with the collaboration of related partners and under the condition of having sufficient information to respond quickly to the uncertainty occurring during the on-site construction operations.

As mentioned above, for the present reality of the construction, the strategic decisions (building partnership; IT-based planning) and logistics-based planning are delivered in the phases of procurement and construction operations. This causes potential problems (supply delays, poor logistics performance, intermittence or lack of shared information) due to the lack of preparation of alternative solutions if the uncertain events occur. Hence, it is suggested that these decisions should be made in the stage of planning and design to leverage the quick responses to the uncertainties occurring on the construction site. Therefore, the other proposition is made as follows:

P4 - Together with the strategic decisions (CSC configuration, developing tools and methods for CSC planning and management, and identifying CSC risks), the decisions related to building partnership, IT-based planning, and logistics-based planning should be made at the planning and design stage to leverage the quick responses to the uncertainties occurring on the construction site.

1.5 Future directions in CSCM application

Based on the analysis of present focuses of decision-making in construction SCM mentioned above, and the highlights of the critical evolution in construction SCM, this section gives the discussions of future trends in construction SCM application in order to answer the research question "*What are the future trends of SCM applications in the construction industry to meet the new requirements of construction practices and technological progress.*"

1.5.1 Evolution and trends in CSCM application

Among the literature sample, there are ten (10) papers which discuss the evolution and trends of SCM application in construction (Vrijhoef and Koskela, 2000; Dainty et al., 2001; Xue et al., 2005; Albaloushi and Skitmore, 2008; Azambuja and O'Brien, 2009; Tennant and Fernie, 2014; Behera et al., 2015; Papadonikolaki et al., 2015; Simatupang and Sridharan, 2016; Lin et al., 2017). The timeline - **Figure 1.8** - shows the methods/techniques utilized for SCM strategies during the long period, which suggests possible methods/techniques used for decisions mentioned above at present and for the future trends in the construction industry in comparison to the trends in general. The process of SC maturity including six strategic focuses, in general, can present the evolution of SCM application: inventory control, production, and transport management, enterprise and resource management, process flow and waste, agility and resilience, value network, and value clusters (Stevens anad Johnson, 2015).

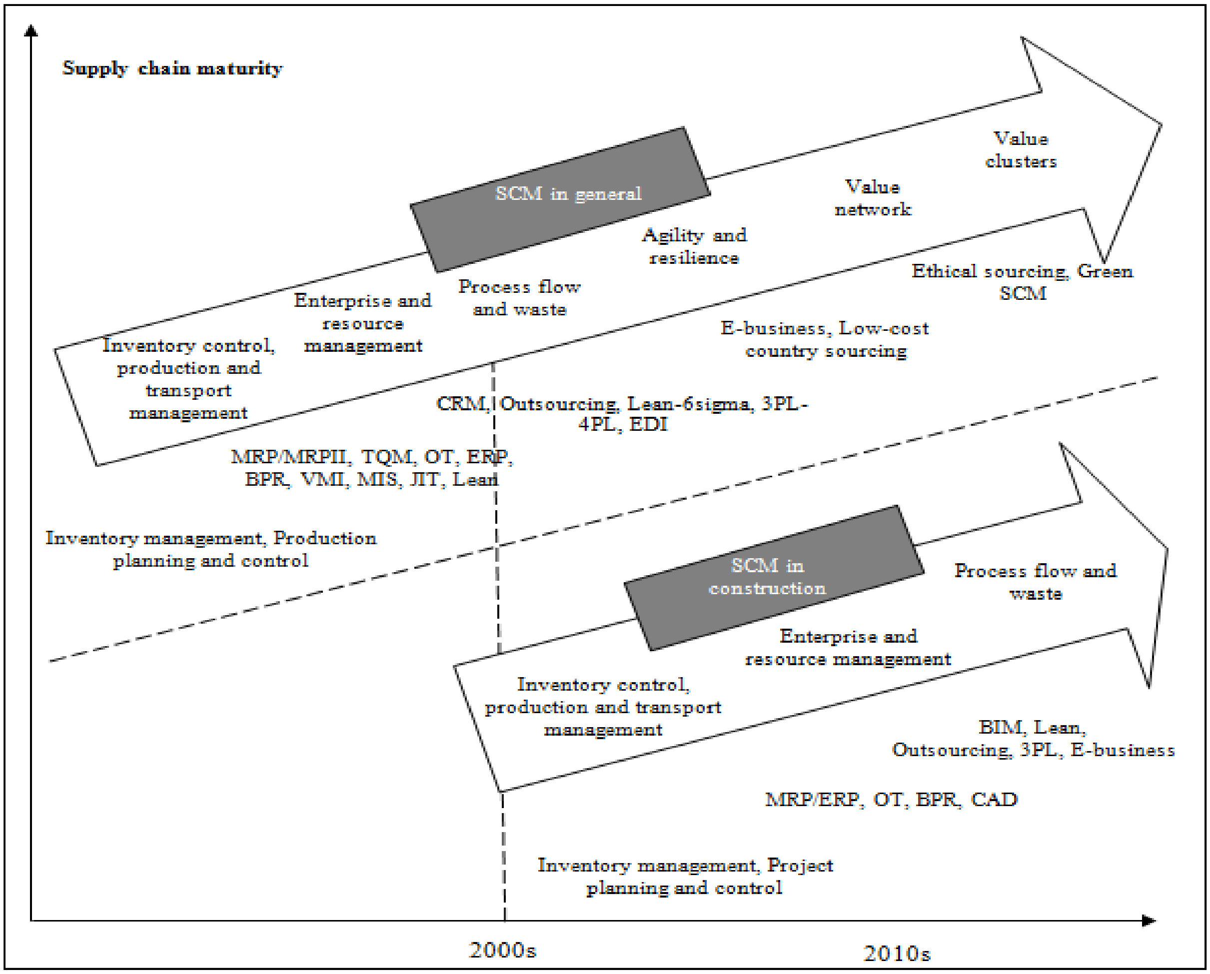


Figure 1.8 Evolution of SCM strategies and techniques in general and in construction

As shown in **Figure 1.8**, at the early stage of SCM application, the strategies focused on enhancing the inventory management and production planning and control. The next stage of the evolution in SCM was the management of enterprise and resources which deployed the methods and techniques to improve the competitiveness through the productivity improvement (MRP: Material requirement planning; ERP: Enterprise resource planning; TQM: Total quality management; OT: Optimization Techniques; BPR: Business process re-engineering; VMI: Vendor managed inventory; MIS: Management information systems; JIT: Just in time; Lean). These methods and techniques have been utilized to decrease the inventory through the continuous improvement of processes and flow, together with the involvement of suppliers in product and process design. The next stage of SCM evolution was marked by the introduction of advanced methods and techniques for controlling process flow and waste and dealing with the changes of customer requirements (CRM: Customer relationship management; Outsourcing; Lean-6 sigma; TPL-4PL: 3rd-4th party logistics provider; EDI: Electronic data interchange). Recent trends in SCM application have focused on creating agile and resilient supply chains, building the value network, and generating the value clusters. The methods mentioned above and techniques have been used for the new trends in SCM application, along with the modern methods and techniques (E-business; Low-cost country sourcing; Ethical sourcing; Green SCM). Agile and resilient supply chains have been created to respond quickly to the increasing levels of choice and differentiation in customer requirements (Govinda et al., 2015). Building the value network has become a strategic trend in SCM which bases on the concept that supply chain is a network of relationships, not a sequence of transactions. In this trend, a firm can improve its operational efficiency by using a TPL to process the customer orders. In such case, the relationship between the TPL and the customer is very important to the firm's business; thus, a network of relationships is created to achieve the great performances for the triad (Stadtler, 2015). The more advanced trend in SCM application is generating the value clusters. In accordance with this trend, a firm can outsource all non-core activities from clusters that are networks of suppliers related by type, product structure, or flow. The collaboration within and across each cluster depends on the goals which are aligned and managed by the firm's goals (Zeng et al., 2014; Qu et al., 2015). This kind of SC practice can take advantage of economy of scale and result in the resilient and effective supply chains. In the business environment of information distortion and global competitiveness, consumers and other stakeholders require the firms to have green and ethical supply chains (Srivastava, 2007). This forces the firms to get more transparent for supply sources, which leads to the increase in costs. Hence, the firms tend to look forward to low-cost country sourcing.

Meanwhile, the evolution of SCM application in the construction industry has been slower than that in general trend. The practices of SCM strategies, methods, and techniques were popularized in the early 2000s (Vrijhoef and Koskela, 2000). At this stage of SCM application, researchers in construction improvement tried to apply methods and techniques (inventory management, project planning, and control) to enhance the construction performances:

material control, on-site transportation management, and project planning (Soltani et al., 2004; Dainty et al., 2001). In recent years, the researchers in construction SCM application have focused on strategies for enterprise and resource management with the popular methods and techniques (MRP: Material requirement planning; ERP: Enterprise resource planning; OT: Optimization Techniques; BPR: Business process re-engineering; CAD: Computer Aided Design) (Xue et al., 2005; Vaidyanathan, 2009; Gan and Cheng, 2015). However, at present, SCM practices in the construction industry have mostly been at the level of internal integration. It means that the application of SCM methods and techniques aims at balancing the decisions (material purchasing, material handling, onsite transportation) across the functions of a construction firm within the constraints of the construction planning (Vaidyanathan, 2009). For the next stage of construction SCM evolution, as a near future trend for the popularized practices, the researchers propose to employ the methods and techniques (Lean; BIM: Building information modeling; Outsourcing; TPL; E-business) to control and improve the process flow and eliminate the construction wastes (Albaloushi and Skitmore, 2008; Papadonikolaki et al., 2015; Dave et al., 2016; Simatupang and Sridharan, 2016; Lin et al., 2017). For the efficiency in the process flow and waste elimination, the trend in construction SCM practices goes towards the more external integration which requires more involvement and cooperation of SC participants including supplier integration, sub-contractor integration, designer integration, and client/owner integration. This increases the productivity of construction planning and development and reduces the risk of non-compliance amongst the supply chain participants.

The development of SC integration in the construction industry has been limited and at a slower speed, in comparison to that in general. In recent years, the CSC capacity has still been at the level of internal SC integration which mainly focuses on material and resources management (Vaidyanathan, 2009; Gan and Cheng, 2015). This is related to the functional decisions mentioned above: production planning, supplier selection, purchasing materials, identifying transportation system, site layout planning, controlling information flow, and material handling. Due to the characteristics of the construction industry, the collaboration of SC participants (GC, sub-contractors, suppliers, designer, owner) has been limited; thus, the propositions mentioned above (P1, P2, P3, and P4) are important for the design of an efficient

CSC network with more external integration. Researchers have proposed framework to leverage the cooperation, information sharing, process flow, and reduce wastes in construction as a trend to achieve the external integration in SCM application (Xue et al., 2005; Azambuja and O'Brien, 2009; Said and El-Rayes, 2014; Tennant and Fernie, 2014; Lin et al., 2017). To reach the higher level of external integration in SCM application, the construction practitioners must focus on the strategic decisions: identifying CSC configuration; developing tools and methods for CSC planning and management; identifying CSC risks; building partnerships; and building construction information system.

1.5.2 Future directions

As mentioned above, external SC integration is the future trend in SCM application in the construction industry. Thus, **Figure 1.9** is formalized to present the focused decisions that are made by the integration of SC participants with the proposed methods and tools across three major construction phases.

Collaborative planning and design with advanced techniques: The planning and design stage is very critical, and have a major impact on CSC performance, which produces the strategies, for the following activities of construction management and execution. It normally requires the integration of GC, owner, and designer into the processes of construction design and development (as shown in **Figure 1.7**). Nevertheless, to achieve more efficiency in construction SCM, it is suggested that the involvement of the key suppliers and sub-contractors (as shown in **Figure 1.9**) in the stage of construction planning and design can increase the productivity and supply commitments, as well as decrease the risk of non-compliance. Besides, as mentioned in the previous proposition (P4), planning-based decisions should be conducted at this stage to prevent potential risks. Therefore, the decisions of SC planning (CSC configuration, developing tools and methods for CSC planning and management, building partnerships and supplier selection, identifying CSC risks) must be conducted efficiently at the stage of planning and design. Besides, decisions related to construction IT planning, and logistics planning (transportation, site layout, material handling) are also proposed to deploy at this stage as a future trend in the construction practice. In present practice, construction designers mostly concentrate on their architectural and structural design without considering logistics issues. Meanwhile, contractors use their experiences to conduct logistics execution on the construction site. This problem can be solved with the external integration in which the triad (GC, designer, and owner) can receive the consultancy from the key suppliers, and subcontractors about the materials, parts supply, and transportation services to obtain the effective design and appropriate planning for construction activities. The integration will lead to a better estimation of the total cost and time due to the reduction in construction rework and the avoidance of suffering from uncertainties of supply delay and poor quality of materials and transportation.

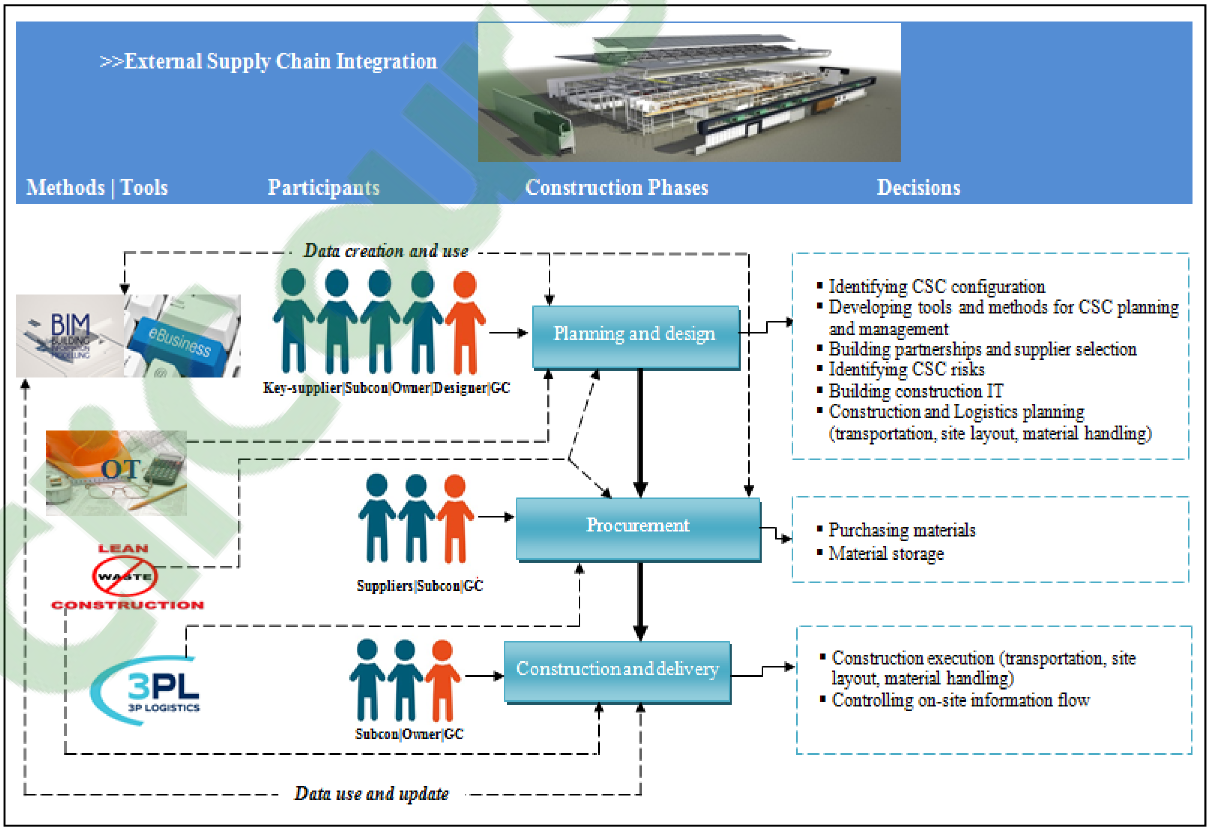


Figure 1.9 Decision-based framework for construction logistics and SCM

At this stage, Building Information Modeling (BIM) is strongly recommended as a data source for the SC participants to create, share, and use data together (Papadonikolaki et al., 2015; Said and El-Rayes, 2014; Kumar and Cheng, 2015). BIM is an approach that focuses on developing and employing the computer-generated model to leverage the planning, design, construction, and operation of the facility. BIM is believed to not only improve design coordination but also facilitate knowledge sharing when being combined with team co-location. The integrated BIM, which combines the 3D data with project schedule data and cost-related data, can provide SC participants with rich data for their decision making. The owner provides the requirements and changes which are the bases for the designer to develop the architect and engineering drawings. The designer also loads the approved data of the construction to BIM. During the construction project, the owner can check the project schedule, cost, and quality to assure the requirements are well satisfied. The GC uses the design data for the construction coordination and management. The GC works with the subcontractors and GC's suppliers to conduct the parts construction and logistics activities. The GC also updates the additional data (such as supplier data, subcontractor data) to BIM. During the construction phases, the GC is responsible for controlling project cost, schedule, quality, safety, and environmental issues, and updates these data to BIM.

Besides, construction and logistics planning (transportation, site layout, material handling) requires the optimal solutions to reduce the construction cost and time. Thus, optimization techniques (OTs) are suggested to obtain the goals in execution and logistics coordination with the lowest cost and mitigate the risks related to logistics problems. The OTs are appropriate techniques for construction and logistics planning. Agent-Based Modeling (ABM), Simulation, and Mathematical programming (linear programming, integer programming, dynamic programming, stochastic programming, multi-objective optimized modeling, game theory, meta-heuristics) are some of the methods that should be used in this context. ABM is defined as an emerging technology in which intelligent agents interact with others to reach the corporate objectives given by the model developer. ABM can be used to achieve the agreed solutions of logistics through the process of negotiation and interaction amongst the SC participants (Xue et al., 2005; Gan and Cheng, 2015). Simulation has an advantage of being able to explain the behaviors of construction logistics under different scenarios. Thus, simulation can be deployed to demonstrate how logistics costs are influenced by changes in demand and material supply, and under uncertainties occurring in the construction execution (Polat et al., 2007; Vidalakis et al., 2011). Mathematical programming has been continuously developed from the traditional techniques (linear programming, integer programming, etc.) to modern techniques (meta-heuristics: simulated annealing, Tabu search, greedy randomized adaptive search procedure, genetic algorithm, ant colony optimization, particle swarm optimization, etc.) for searching optimal solutions for quantitative problems (Zhang and Fan, 2010; Wei and Ying, 2013; Liu and Tao, 2015). These techniques are useful in construction and logistics planning through optimizing the construction logistics cost that includes ordering, carrying, shortage, and layout costs, optimal material supply and storage, creating dynamic site layout models or minimizing the transportation costs.

Under the pressure of variations in client/owner requirements, Lean can be applied to the design, procurement and construction execution to have the continuous improvements of process flow and waste reduction that leads to meet client/owner demands and enhance the efficiency for construction participants. Lean is a philosophy rather than purely a method; thus, Lean success depends on a lot of SC participants' commitments of a long-term perspective on continuous improvement (Dainty and Brooke, 2004; Eriksson, 2010; Dave et al., 2016). Lean construction planning and design require the external integration of all SC participants. It integrates client/owner, designer, contractors, and suppliers into a process of planning and design with the focus on creating values for the ultimate clients. Since the nature of construction is different from other manufacturing industries, the Lean application in a CSC project is necessarily different. There are many drastic changes from the start to an end of a construction project; thus, Lean planning and design motivate all SC participants to create specific goals, standards, and performance indicators for construction processes which optimize the values at every level for the client/owner. Lean construction planning and design also focus on predictability which prevents troubles in the construction standardization causing lost time, wastes and conflicts.

Construction procurement with third party logistics partnership: The external integration in construction planning and design supports a lot in improving the performance of procurement processes. Efficient material procurement and storage require the alliances of GC, suppliers, and sub-contractors (Matthews et al., 2000; Eriksson, 2010). The alliances based on the long-term relationship, which exists across multiple projects; therefore, this leads to creating a more long-lasting SC network. Owing to the nature of multiple-project, the strategic alliances in construction need to address the flexibility in expertise, capacity, and predictability to meet the changes from project to project. In large construction projects, to deal with the challenges of a CSC with temporary nature and complex, construction firms have thought of third-party logistics (TPL) providers to increase productivity at the construction site, reduce logistics costs and enhance the utilization of site assets. TPL is based on the idea that a construction firm hires logistics professionals to manage all the logistics activities (transportation, material procurement, and storage) (Vaidyanathan, 2009). Using TPL, an interface is formalized to connect the SC network to the construction site. The application of TPL is a new trend in terms of outsourcing in the construction industry, which engages the efficiency in construction logistics management.

Lean and BIM in construction operations and delivery: For the Construction and delivery phase, the contractors (GC and sub-contractors) deploy the construction execution onsite and deliver the finished construction to the client/owner. Lean construction can be applied to enhance the process flow and eliminate wastes and errors on the construction site (Dave et al. 2016). Lean construction can also make the working environment clean, safe, and efficient. The task of controlling onsite information flow can be taken with BIM that provides the integrated data to the contractors during the phase of construction and delivery. The contractors use the provided data for the construction execution and update the new data to BIM. This helps to create a continuous information flow that supports the onsite construction activities effectively.

A trend in BIM implementation is expanding 3D data into an nD information modeling since BIM is a source of rich data associated with the whole lifecycle of construction projects (Said and El-Rayes 2014; Kumar and Cheng 2015). The nD modeling distributes useful data to all construction participants to track the necessary information in a matching system, which results in the cohesive and efficient construction performances. Thus, BIM can play a vital role in e-business of construction firms. BIM leverages the construction e-commerce focusing on supporting downstream supply integration processes such as sales and delivery to client/owner, e-procurement focusing on the improvement of the processes for order fulfilment and supplier selection. Also, e-collaboration supports the processes involved in planning and design, predictability, and logistics management with the external integration of all SC participants.

As another trend in the CSCM application, the integration of Lean and BIM is proposed as an efficient approach for improving the performances across the construction phases, especially for the efficiency of construction logistics when being conducted at the early stage of planning and design (Sacks et al. 2010; Dave et al. 2016). Although some authors propose the integration of BIM and Lean approach in the construction industry, no study that focuses on optimizing construction logistics with the practical integration of SCM, BIM, and Lean is found. At present, the integration of the three concepts (SCM, BIM, and Lean) for the construction industry is just conceptually proposed. This limitation opens an opportunity for further researches in BIM-based construction logistics and supply chain management.

1.6 Conclusions

Over the last decades, researchers attempted to apply SCM concepts and methods for the construction management. However, the application has been limited and at the slower speed than that in general applications. At present, the SCM application is still focusing on material and resources management with the internal SC integration. Due to the lack of collaboration amongst the SC participants, strategic decisions related to building a partnership, IT-based planning, and logistics-based planning are not conducted in the phase of planning and design. This common practice reduces the effectiveness and the flexibility of the CSC ability in terms of responding to uncertainties occurring across the construction phases.

For future trends in SCM application in construction, this study proposes a framework that leverages three important points: the collaborative planning and design with advanced techniques; the lean procurement with BIM and 3PL; and the application of Lean and BIM in construction operations and delivery. The framework plays an important role in supporting an external SC integration of contractors, designer, owner/client, and suppliers to achieve the efficiency in decision-making across the construction phases. For the trends, decisions of SC planning, IT planning, and logistics planning are proposed to conduct the phase of construction planning and design. BIM is recommended as an efficient approach that leverages the e-business (e-collaboration, e-procurement, and e-commerce) of construction firms. The combination of Lean and BIM is proposed to enhance construction project management and CSC performance through the different phases due to the continuous improvement in the process flow and value creation. Together with BIM and Lean, other SCM methods and tools (optimization techniques and 3PL providers) are suggested to improve the processes of procurement and construction execution.

CHAPTER 2

INTEGRATED CONSTRUCTION SUPPLY CHAIN: AN OPTIMAL DECISION-MAKING MODEL WITH THIRD PARTY LOGISTICS PARTNERSHIP

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Abstract

Previous studies confirm the benefits of using Third-party logistics (TPL) for efficient construction management, especially for big projects. Nevertheless, there is a lack of decision-making model to evaluate the exact role of TPL provider as a driver for the supply chain integration and optimization. The purpose of this study is to develop a decision-making model for construction supply chain (CSC) optimization with possible TPL integration. The proposed model, which takes into account two types of purchased materials (Type-1 and Type-2), assists decision-makers to determine the strategies in construction supply chain management, including supplier selection, TPL integration, and inventory policy determination. Using the model, construction managers can take advantage of the TPL warehouse and order larger quantities if necessary, to obtain lower prices offered by suppliers. We find that, through the numerical case example in Canada, the proposed model performs better results in total supply chain cost in comparison with the CSC model without TPL. The results imply that the optimal decision making model for the integrated CSC with TPL partnership can be used to improve the construction logistics performance and deal with the practical requirements of the current issues in the construction industry.

Keywords: Supply chain management; logistics; decision making; optimization; integration.

2.1 Introduction

Construction supply chain (CSC) is considered as complex network with multiple interactions among actors during the construction processes (Winch 2001, Fellows and Liu 2012). The characteristics of the construction processes are project-based and temporary in arrangement; thus, temporary supply chains (SC) are usually formed in construction projects (Bakker 2010). The inefficiency in managing this complexity is one of the main reasons that cause low productivity level and cost increase in the construction industry (Vrijhoef and Koskela 2000, Love et al. 2004). However, supply chain management (SCM) principles are not well adapted to the construction industry (Fernie and Tennant 2013) and not yet achieved the full benefits by construction companies (Sundquist et al. 2018). One reason for this issue is the lack of collaboration among the actors in the SC network, which is a significant source of delays, errors, and duplications in construction projects (Xue et al. 2005). In terms of CSC planning and operations, there is a lack of SC driver who plays a role as the focal coordinator to integrate the associated actors across the construction network (Sundquist et al. 2018, Le et al. 2018).

For the performance improvement of CSCs, it is suggested to have better integration of business processes following the main principles of SCM (Ekeskär and Rudberg 2016, Bengtsson 2019). Efficient SC plans take into account the integration of the associated actors for better information sharing to improve collaboration and trust (Thunberg and Fredriksson 2018). Depending on other actors in the SC, the general contractor plays an essential role in implementing the SCM. However, in order to apply the principles of SCM in construction entirely, there exists a need for the logistics re-organization driven by the construction owner and the general contractor (Ekeskär and Rudberg 2016, Sundquist et al. 2018). As a part of the adoption of SCM in practice, general contractors and owners have turned to third-party logistics (TPL) providers, especially in the case of large construction projects (Ekeskär and Rudberg 2016). Indeed, other sectors have taken advantages of TPL providers' professionals to focus on their primary business, and achieve budget reduction, long-term strategic alliance, effective logistics reengineering, and advanced technologies approach (Li and Chen 2019). However, using TPL provider is a new phenomenon in the construction industry for all the associated actors such as owners, general contractors, suppliers, building merchants, and transportation providers (Ekeskär and Rudberg 2016). These actors encounter new interfaces and project settings when a TPL provider is considered as a coordinator of the SC network.

Based on the literature review mentioned in the next section, we find that studies related to the role of TPL provider in construction are very limited. Notably, no study focus on using decision-making model to analyze and identify the role that can play the TPL in the CSC network. Ekeskär and Rudberg (2016) explore that TPL solution can be considered as a useful tool for construction logistics since it establishes an interface between the construction site and the upstream SC. It is also believed that TPL providers can become a powerful tool for owners and general contractors to integrate the relevant actors of the CSC. Hence, this study aims to develop a decision-making model for CSC with TPL provider who plays a focal role as a logistics coordinator. The model focuses on the operational objectives in making an optimal plan for material procurement, transportation, and storage. Although scholars widely studied the theories of purchasing and supply operations in construction projects, the optimization for SC operations has not yet been fully explored (Liu et al. 2017a). Thus, a new optimization model is proposed in this study to integrate the supplier selection, material purchasing, transportation, and inventory within the CSC in order to obtain the optimal cost for the entire SC network. Under the consideration of uncertainties in material prices, delivery lead-times, and daily demands, the proposed model helps the decision-makers to determine an efficient plan for the logistics operations of the construction project. This plan gives the optimal material quantities they should purchase from different suppliers, and whether they should hire the TPL provider's warehouse for material storage.

Compared to previous studies in developing CSC optimization models, our work contributes to the literature with many features. Firstly, an optimization model with the consideration of multi constraints (uncertain prices, safety stock to deal with uncertainties in demand and supply lead-time, inventory status, and SC trade-off) is developed to minimize the total SC cost. Furthermore, the model treats the TPL provider as the SC coordinator, who integrates the involvement of other SC actors to make the focal decision. Secondly, the model takes into account the logistics planning for the procurement, delivery, and storage of different types of materials. In this study, materials are divided into two types: type-1 (materials can be transported to a central warehouse or directly sent to the construction site), and type-2 (materials can be directly sent to construction site only). This division supports the decision-makers to consider the material amounts, which they can purchase with huge volumes to obtain the low prices and low transportation costs offered by suppliers. However, purchased materials are stored in the central warehouse provided by the TPL. Thus, in order to generate the optimal plans for construction logistics, the proposed model facilitates decision-makers to balance the relevant costs of material purchasing, transportation, storage, and checking.

2.2 Literature review

2.2.1 Construction supply chain improvement with third-party logistics

Lack of SC advances is the critical issue of construction logistics management (Sundquist et al. 2018). Previous studies have identified common problems in construction from the perspective of SCM, such as lack of collaboration among actors causing many problems in communication and information sharing with others (Le et al. 2018, Golpîra 2020); short-term benefit orientation (Dainty et al. 2006, Gadde and Dubois 2010) leading to the inability of sharing updated plans and knowledge with all members of the SC (Love et al. 2004); lack of trust-building (Thunberg and Fredriksson 2018); late involvement of SC members (Dainty et al. 2001, Aloini et al. 2012). As a result, construction logistics practice and performance are considered to be lagged behind in comparison with other industries (Segerstedt and Olofsson 2010).

Building materials need for large storage capacity and require an efficient coordination system to ensure the quality as well as reduce the logistics costs. There are many problems associated with poor material management such as unqualified materials are delivered, the material purchasing is conducted too late, or wrong quantity orders are decided. These cause the disturbances for onsite assembly, delays in material delivery, or cost increase due to wastes (Sundquist et al. 2018). These problems can be improved by employing efficient plans and coordination systems of materials delivery, storage, and handling, as well as resource utilisation (Ying et al. 2014, Sobotka and Czarnigowska 2005, Jaśkowski et al. 2018). Productive construction logistics can facilitate the organization of materials delivery, storage, and handling as well as the allocation of spaces and resources to support the labour force and eliminate inefficiencies due to the congestion and the excess material movement (Thomas et al. 2005). As the construction industry has increasingly applied the approach of SCM, logistics management is considered as the core of such application (Hamzeh et al. 2007).

Logistics management is a part of SCM that plans, implements, and controls the efficient flows of material and related information as well as the inventory storage in order to meet customers' requirements (Ekeskär and Rudberg 2016). In the perspective of SCM, several previous studies suggested that logistics performance in the construction industry can be improved by relying on specialised actors for the coordination of material flows (Sundquist et al. 2018). For examples, the central role of material distributors as the main coordinators of the logistic activities (Vidalakis et al. 2011) or outsourcing for logistics service providers specialising in material coordination (Lindén and Josephson 2013). Ekeskär et al. (2014) conclude that such employment can reduce total logistics costs, and contractors seem to increasingly rely on logistics service providers in order to improve performances of related actors across the SC network. In a similar approach, Sundquist et al. (2018) advocate the vital role of the focal actor in construction logistics coordination. The focal actor is hired to be responsible for the planning of site layout regarding resources and spaces, coordinating the delivery and storage of the materials, and operating the materials handling. The focal actor team consists of a logistics manager, a logistics coordinator, a delivery planner, a person responsible for arrival control, and one or several gate guards. However, the involvement of the focal actor can vary from project to project. For instance, in a project, the team involves in materials handling operations, but for the other project, they can be hired for all logistics activities during the whole construction project. The focal actor is also called TPL provider, as mentioned by Ekeskär and Rudberg (2016). TPL can provide services from transportation, warehousing, inventory management to value-adding activities (such as secondary assembly, installation of products), or information-related activities (for instance, tracking or distribution planning), as well as SC design and reengineering (Hertz and Alfredsson 2003). Sobotka and Czarnigowska (2005) notice that through employing TPL provider for material handling, costs can be reduced. Lindén and Josephson (2013), who support this finding, also conclude that the use of TPL solution can result in the lower total cost and reduce the number of disturbances. Ekeskär and Rudberg (2016) recognise the positive effects of TPL partnership on creating an effective interface between the construction site and the SC.

Employing TPL solution can also increase the productivity of work at the construction site and reduce costs as well as increase the utilisation of site resources. TPL partnership is also known as logistics alliance, or logistics service provider (Skjoett-Larsen 2000). Therefore, TPL employment can promote the long-term relationship among the associated actors across the SC network. Long-term TPL partnership can create higher levels of commitment and integration among the actors, and eliminate or reduce many of the identified issues (Jazairy et al. 2017).

2.2.2 Optimal decision-making in construction supply chain management

For the efficiency in the process flow and waste elimination, the trend in construction supply chain management (CSCM) practice goes towards the more external integration, which requires more involvement and cooperation of SC participants including suppliers, contractors, and the owner (Meng et al. 2011, Lönngren et al. 2010). This increases the productivity of construction planning and development and reduces the risk of non-compliance among the SC participants (Bankvall and Bygballe 2010). In order to demonstrate the value of integrated SCM in the construction industry, previous studies have proposed several optimal decision-making models to solve the important SC tasks. Xue et al. (2005) propose an agent-based framework that integrates the relevant actors and employs the multi-attribute negotiation model to provide an optimized solution for SC coordination. Chen and Ma (2008) establish a two-stage dynamic incentive contract model, which integrates implicit reputation incentive mechanism with explicit revenue incentive mechanism to coordinate organisation relationships and prevent the deputy’s moral hazard in the construction industry. Said and El-Rayes (2011) develop an optimization model for construction logistics planning that simultaneously integrates and optimizes the critical planning decisions of material procurement and material storage in construction sites. The model minimizes construction logistics costs that cover material ordering, financing, stock-out, and layout costs regarding the impact of potential material shortages on-site because of late delivery on project delays and stock-out costs. Using the activity-based costing approach, Fang and Ng (2011) identify the cost elements incurred during the logistics process of precast components from the supplier’s yard to the construction site. Hashim et al. (2013) optimize the production-distribution construction network under fuzzy environment. Their model is developed to minimize costs and maximize the satisfaction levels for both plant planning and distribution network. Gan and Cheng (2015) leverage the agent-based cooperation to maximize backfill reuse and improve waste recovery efficiency for the CSC network consisting of construction sites, landfills, and commercial sources. The SC configuration is optimized through a negotiation process among the construction agents to achieve the reduction in the backfill shipment cost.

Recently, Liu et al. (2017a) establish a quantitative optimization model for the CSC, in which the concept of integrated operations among the construction actors is applied to optimize the costs and service level under uncertainties of price, supply delay, rush order and demand change. Choudhari and Tindwani (2017) develop an optimization model for material procurement and distribution in road construction projects. The model focuses on the cost minimisation at three points of the SC: supply sources, processing facilities, and demand consumption points. Jaśkowski et al. (2018) develop a mixed-integer linear programming model for optimising the material supply under the uncertainty of material prices. The model enables the determination of economic order quantities for consecutive periods of construction works as well as the selection of most economical supply channels for a particular material. Hsu et al. (2018) establish a mathematical model for the optimization of logistics processes in modular construction covering three tiers of operation: manufacturing, storage, and assembly. The model captures all possible demand variations in the construction site to consider their impacts on the factory manufacturing and inventory management. Lin et al. (2018) provide a method to optimize construction project management from the perspective of SC under the requirement of sustainable development. They develop an uncertain bi-level nonlinear model, in which the owner sets the proper intensities to minimize the total cost at first while the general contractor decides its alternative and the limits to subcontractors correspondingly. Rahimi and Ghezavati (2018) propose a multi-period multi-objective mixed-integer linear programming to design and plan a network of reverse logistics under uncertainty for recycling construction and demolition wastes. Feng et al. (2018) propose a novel bi-level multistage programming model for the multiple objectives optimization to examine the inherent conflicts and complex interactions among decision-makers in order to obtain the Stackelberg–Nash equilibrium solution under uncertainties. Recently, Deng et al. (2019) develop an integrated model using a geographical information system (GIS) and building information modeling (BIM) for the coordination of CSC. The proposed model is used for supplier selection, determination of the number of material deliveries, and allocation of consolidation centres. The summary of the recent studies, as well as the comparison of this study's approach and other studies, are presented in **Table 2.1**.

Table 2.1 Summary of recent studies in CSC optimization

Papers	Objectives	Uncertainties	Optimization model	SC driver	SC level
Xue et al. (2005)	Design of agent-based framework for CSC coordination	Not mentioned	Multi-attribute negotiation model	Decentralized CSC without focal actors	Strategic level: focusing on partnership building
Chen and Ma (2008)	Coordination of SC relationships and improvement of actors' reputation	Uncertainty of SC actor's competence	Dynamic reputation incentive model	Not mentioned	Strategic level: focusing on partnership building
Said and El-Rayes (2011)	Optimization of material procurement and storage on sites	Delays of activities	Construction logistics planning model	Not mentioned	Tactical level: focusing on material procurement and site layout planning
Fang and Ng (2011)	Analysis and calculation of construction logistics-related costs	Not mentioned	Activity-based costing model	Not mentioned	Tactical level: focusing on logistics activities (procurement, transportation, and storage)

Table 2.1 Summary of recent studies in CSC optimization (continued)

Papers	Objectives	Uncertainties	Optimization model	SC driver	SC level
Hashim et al (2013)	Planning production-distribution for CSC under fuzzy environment	Demand, production capacity, production cost, and transportation cost	Bi-level multi-objective programming model	Not mentioned	Tactical level: focusing on the optimization of operational cost and service level.
Gan and Cheng (2015)	Optimization of the backfill recovery among construction sites	Not mentioned	Centralized optimization model and distributed agent-based model	Not mentioned	Strategic level: focusing on SC configuration determination
Liu et al. (2017)	Optimization for the integrated CSC under uncertainties	Rush orders, delay times, material prices, demands	Multi-objective optimization model with fuzzy theory	Construction owner	Operation level: focusing on the optimization of operational costs and service level.
Choudhari and Tindwani (2017)	Planning the logistics of raw materials for road construction projects	Not mentioned	Logistics optimization model integrating three SC points: supply sources, processing facilities, and demand consumption points.	Not mentioned	Tactical level: focusing on the optimization of logistics cost
Jaskowski et al. (2018)	Planning material supply channels in construction	Material prices	Decision model for optimizing material supplies	Not mentioned	Operation level: focusing on the optimization of inventory management cost
Hsu et al. (2018)	Logistics planning for modular construction	Demand variations, weather conditions, delivery delay, labor productivity, crane status, assembly patterns	Two-stage stochastic programming model	Not mentioned	Operation level: focusing on the optimization of costs related to manufacturing, storage, and assembly

Table 2.1 Summary of recent studies in CSC optimization (continued)

Papers	Objectives	Uncertainties	Optimization model	SC driver	SC level
Lin et al. (2018)	Robust optimization for sustainable CSC	Cost, duration and carbon emissions	Bi-level programming model based on robust optimization	Owner and GC	Focusing on different SC levels: environmental, social and commercial goals
Rahimi and Ghezavati (2018)	Designing and planning reverse logistics network for recycling construction and demolition wastes	Demands, rate on investment	Multi-period multi-objective model	Not mentioned	Focusing on different SC levels: environmental impact, social effect, and network profit
Feng et al. (2018)	Optimization for integrated production-distribution-construction system in CSC	Costs, supply time, demand, material quantity	Bi-level multistage programming model	GC	Tactical level: focusing on the optimization of transportation duration, and costs related to inventory, transportation, and shortage
Deng et al. (2019)	Developing an integrated framework for CSC optimization using BIM and GIS	Not mentioned	Technology-based (BIM and GIS) optimization model	GC	Focusing on different SC levels: supplier selection, determination of delivery quantity and allocation of consolidation centers
This thesis	Developing the optimal plan for CSC operations with TPL partnership	Material prices, delivery lead-times, and daily demands	Mixed integer programming model for the optimization of CSC with the participation of TPL provider	TPL provider	Operation level: focusing on the optimization of logistics costs related to procurement, transportation, and storage for two material types.

2.3 Research gaps and objectives

As presented above, recent studies in the literature have attempted to develop various decision-making models to facilitate the optimization for CSC at different SC levels (strategic, tactical, operational, and mixed). Despite their significant contributions to the body of knowledge in construction management, the existing studies still have the following limitations:

- A large proportion of existing studies in construction logistics and SCM focus on the calculation or optimization of logistics costs related to material purchasing, transportation, and storage. However, most of the studies ignore the focal role of the SC driver, who is responsible for coordinating the entire SC network and integrating the involvement of relevant SC actors.
- Although some previous studies confirm the benefits of the employment of TPL solution for construction logistics, there is a lack of study developing the optimization model for construction logistics with the involvement of TPL provider as the SC driver.

- There is also a lack of study developing the optimal plan for the integrated CSC operations, which considers different types of materials transported directly to the construction site or conveyed to the intermediate warehouse due to the contractors' demands, material prices, and the transportation fees offered by suppliers.

In practice, suppliers can offer low prices and/or low transportation fees for the purchased materials but require high quantities to order. These materials can be purchased with high volumes and need for the warehouse to be stored; otherwise, they should be purchased with smaller quantity to be sent directly to the construction site, which has limited storage space. Besides, due to contractors demand and project constraints, some materials have to be delivered directly to the construction site to reduce the relevant risks. Therefore, it is essential to employ a focal actor who takes into account these issues for SC planning and coordination. To fill research gaps as well as meeting practical requirements of construction logistics, the main objectives of this paper are:

- Objective 1: Developing an optimal decision-making model for CSC operations with TPL partnership. The proposed model leverages the TPL provider as the focal decision-maker who coordinates the logistics activities: material purchasing, transportation, and storage. The model takes into account the two kinds of materials. Type-1 materials can be transported to a warehouse or directly sent to the construction site. Type-2 materials must be sent to the construction site only).

- Objective 2: Using the proposed model to assess the role of the TPL provider through the comparison between the total logistics costs calculated for the CSC with the TPL provider and without the TPL provider.

2.4 Problem statement

2.4.1 Construction supply chain process

Figure 2.1 (a) simplifies the CSC network with relevant actors. In a construction project, the general contractor is considered as a representative of the owner for the construction execution. According to the owner's directives, the general contractor contacts the selected suppliers for material procurement, and then the materials are transported to storage points. Then, raw materials are supplied to the contractors for their fabrication. The semi-fabricated units produced by the contractors are then shipped to the general contractor. In the end, the general contractor executes the construction project and delivers to the owner. The designer plays a consulting role in determining the material requirements. Also, the designer provides and checks the requirements and possible changes of materials with contractors, and then confirms this information with the owner (Liu et al. 2017a).

The construction industry has unique settings, which are fundamentally different from the other industrial sectors. The construction site is considered as a temporary plant initiated around the products, which are physically large and immobile (Bygballe and Ingemansson 2014). As mentioned in the above literature review, construction projects are temporary, multi-enterprise oriented (Behera et al. 2015), and dependent on various firms known as subcontractors causing the fragmentation in the CSC network (Miller et al. 2002), which requires construction companies to have different rules and regulations to manipulate (Eriksson 2010) . It is also noted that delays, errors, and duplications on projects are caused due to the lack of information sharing. Actors, such as general contractor or subcontractors, are concurrently managing several projects; thus, they have incentives to focus on enhancing the efficiency of their own business to realise immediate economic advantages rather than to improve the network performance (Vaidyanathan 2009). Hence, the CSC network is typically different from the other SC networks in many aspects: production process, SC structure (no retailer or wholesaler in CSC), and the information flow (Liu et al. 2017a). Due to such differences, the modeling of procurement and supply of materials in the CSC network needs to take into account the distinctive characteristics of the industry.

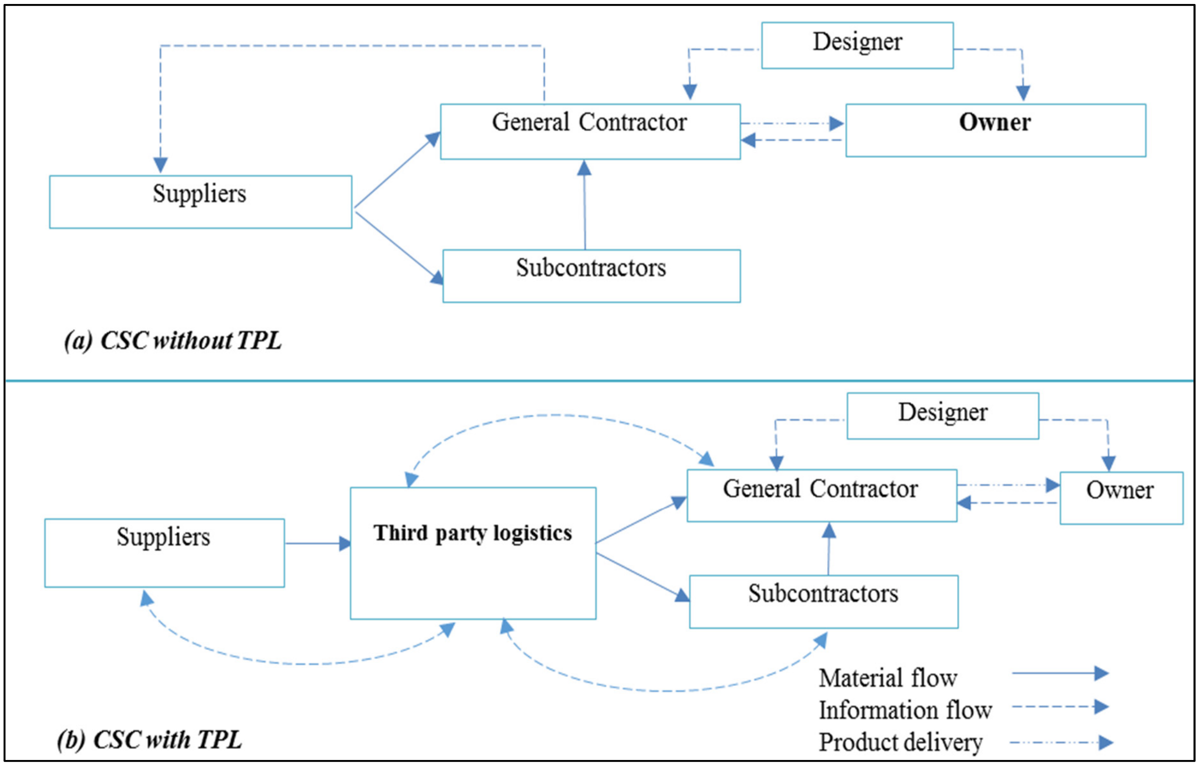


Figure 2.1 Comparison between two construction supply chain processes

2.4.2 Construction supply chain integration with TPL partnership

As mentioned in the literature review, previous studies support “SC integration” to become the key enabler that contributes to CSC performance (Briscoe and Dainty 2005, Bankvall and Bygballe 2010). Once conducted properly, SC integration can facilitate information sharing, and long-term trust among the SC actors (Meng et al. 2011, Lönngren et al. 2010), which in turn enhances efficient material flows throughout the whole SC (Liu et al. 2017a, Akintoye et al. 2000).

In large CSC projects, to deal with the challenges of temporary and complex nature of the industry as well as increase the SC integration, construction firms have thought of TPL providers to increase productivity at the construction site, reduce logistics costs and enhance the utilisation of site assets (Ekeskär and Rudberg 2016, Tommelein et al. 2009). As described above, the TPL partnership is based on the idea that a construction firm hires logistics professionals to manage all the logistics activities (transportation, material procurement, and storage). Using TPL, an interface is formalised to connect the SC network to the construction site (Le et al. 2018).

The integrated CSC network with TPL partnership is shown in **Figure 2.1** (b), which visualises the construction logistics process. Under the owner’s directives, the general contractor selects the suppliers and TPL provider who is responsible for material purchasing, storage, and transportation. In this CSC network, TPL provider plays a central role in coordinating all materials necessary for the construction work and equipment necessary for the materials handling on-site (Ekeskär and Rudberg 2016). The TPL provider creates the rules for material procurement, delivery, and storage, which are agreed by the general contractor and the owner. The rules are communicated to the contractors through official documents and reminded in periodic meetings held by the TPL provider. The TPL solution is mandatory for all contractors. Since all the materials are coordinated and handled by the TPL provider; thus, the CSC network with TPL partnership becomes the integrated SC network in which the TPL provider takes the role of a SC integrator (Fabbe-Costes et al. 2009).

Being different from a normal decentralised construction logistics network, the integrated CSC with TPL partnership leverages the cooperation between different SC actors (Ekeskär and Rudberg 2016), as well as the information and risk-sharing (Liu et al. 2017b). The integrated CSC is modelled as a focal network in which the construction owner, the general contractor, and the TPL provider are treated as focal decision-makers. In terms of construction logistics, the focal decision-makers need to identify the optimal costs to operate the project, including material ordering cost, checking cost, transportation cost, and storage cost (Fang and Ng 2011).

In this study, we take into account the operations of CSC network with TPL partnership, as shown in **Figure 2.2**. Under the owner's mandate, the general contractor checks the status of raw materials and then informs the TPL provider with the material demands. Based on this information, the TPL partner contacts the selected suppliers for material ordering. We use this TPL partnership for the first type of material (material type-1), which has two options: be sent to the TPL's warehouse or be directly sent to the construction site. The material type-1 can be sent to the TPL's warehouse with the sufficiently large truckload size (Q_{ms}), and then sent to the construction site based on the material demands. This kind of transportation can be applied for the materials, which are purchased from suppliers offering low prices but requiring high purchasing quantities. However, this material type can also be sent directly to the construction site with the lower delivery quantities, but with higher prices. In practice, there are also some materials, which should be only sent from the suppliers to the construction (material type-2). This type typically consists of materials, which can be delivered in working time for contractors in the construction site, such as concrete reinforcements, prefabricated concrete elements, or other special deliveries (Ekeskär and Rudberg 2016). This material type is ordered directly by the contractors in the construction site. In accordance with the two material types, we divide the suppliers into two types in which the supplier type 1 and supplier type 2 provide material type-1 and material type-2, respectively.

In order to optimize the logistics-related costs of the CSC network, this study aims to search for an optimal plan for material procurement and storage with the TPL partnership. For material type-1, we identify the optimal quantities (due to the delivery number a_{mst}) of these materials, which should be delivered to the TPL's warehouse, and the optimal quantities (X_{mst}) of these materials, which should be directly delivered to the construction site. For material type-2, we identify the optimal quantities (O_{mst}) of these materials, which are directly delivered to the construction site.

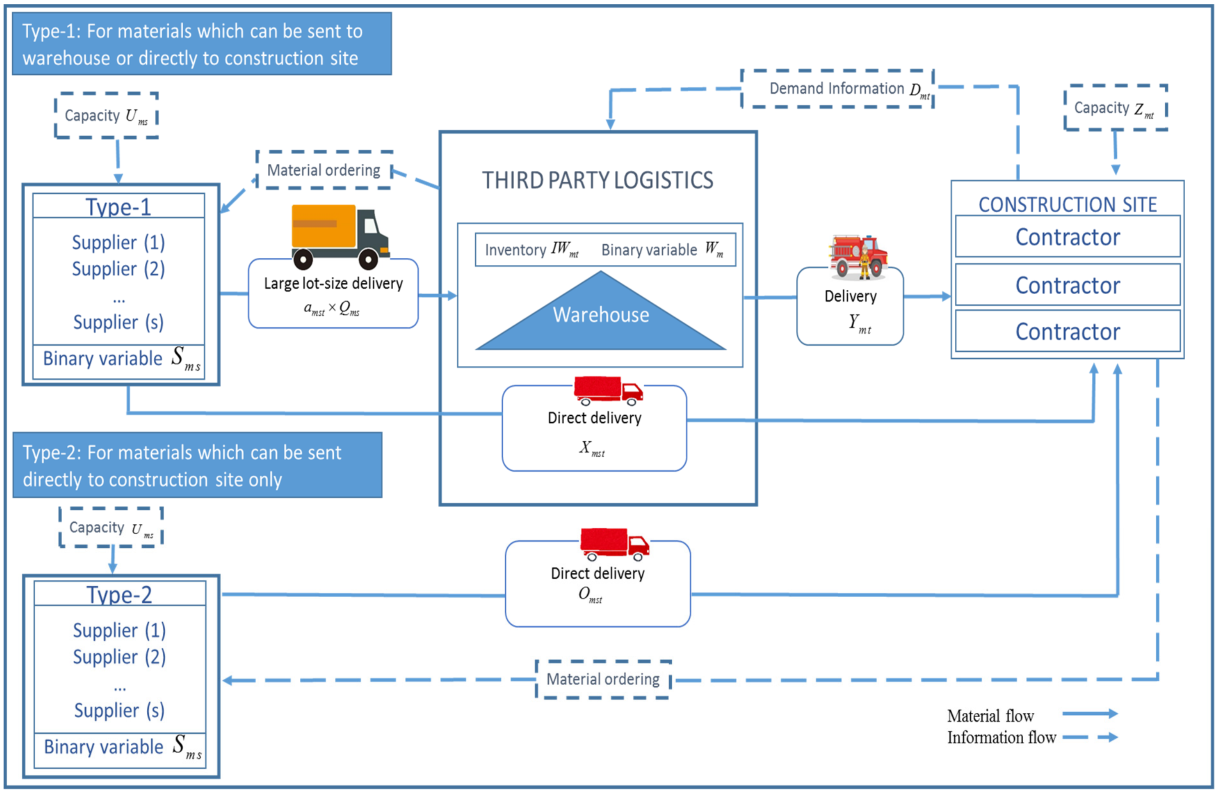


Figure 2.2 Operations of CSC with TPL partnership

2.5 Construction supply chain modeling

2.5.1 Assumptions

For modeling the operations of CSC network with TPL partnership (presented in **Figure 2.2**), the following assumptions are made:

a. The TPL provider and the contractors have a meeting at the beginning of each period to plan for the periodic deliveries in details. Thus, the planning period *(t)* is applied. It means the fixed-time policy is selected as the inventory policy.
b. The material type 1 can be delivered to the TPL's warehouse with a large lot size *(Q_{ms})* or sent directly to the construction site at any quantity *(X_{mst})* depending on the contractors' demand. Similarly, material type 2 is sent directly to the construction site at any quantity *(O_{mst})* depending on the contractors' demand. Thus, only the transportation cost applied for materials sent to the warehouse *(TS_{ms})* are calculated per lot size, while other transportation costs (the delivery from suppliers to construction site DC_{ms} and the delivery from the warehouse to the construction site l_m) are computed per material unit.
c. In order to eliminate the shortage cost caused by supply delay and demand uncertainty, a level of safety stock *(R_m)* at the TPL's warehouse is allowed.
d. The suppliers and the construction site have their own maximal capacity Ums and Z_{mt}, while the TPL's warehouse is assumed to have unlimited capacity since it is built to store the materials delivered in large lot size.
e. The model takes into account the uncertainties in material prices *(P_{mst})*, suppliers' delivery lead time *(L_{ms})*, and the daily demand *(d_m)*.
f. The suppliers *s*, who are once selected for materials *m*, are kept the same during the project.

2.5.2 Notation

Sets and indices:	
T	: Set of planning periods, indexed by t
M^1	: Set of materials (type 1) which can be transported to warehouse or directly sent to construction site, indexed by m
M^2	: Set of materials (type 2) which can be directly sent to construction site only, indexed by m
S^1	: Set of suppliers (type 1) who provide materials (type 1), indexed by s
S^2	: Set of suppliers (type 2) who provide materials (type 2), indexed by s

Supply parameters:

SCC	: Total construction supply chain cost
PC	: Total procurement and material ordering cost
TC	: Total transportation cost
Q_{ms}	: Fixed lot size of delivery truck offered by suppliers ($s \in S^1$) for materials ($m \in M^1$) for any period
FS_{mst}	: Fixed cost (administrative cost/procurement cost) for placing the order for materials ($m \in M^1$ and M^2) from suppliers ($s \in S^1$ and S^2) at period ($t \in T$)
TS_{ms}	: Transportation cost (per lot size) from suppliers ($s \in S^1$) to warehouse for materials ($m \in M^1$) for any period
DC_{ms}	: Direct transportation cost (per unit of material) from suppliers ($s \in S^1$ and S^2) to the construction site for materials ($m \in M^1$ and M^2) for any period
k_m	: Pre-processing cost (per unit of material) for loading and picking the delivered materials ($m \in M^1$ and M^2) for any period
$E(P_{mst})$	: Expected purchasing price from suppliers ($s \in S^1$ and S^2) for materials ($m \in M^1$ and M^2) at period ($t \in T$)
P'_{mst}	: Normal level of price offered by suppliers ($s \in S^1$ and S^2) for materials ($m \in M^1$ and M^2) at period ($t \in T$)
$P_{mst,\ min}$	: Minimal level of price offered by suppliers ($s \in S^1$ and S^2) for materials ($m \in M^1$ and M^2) at period ($t \in T$)
$P_{mst,\ max}$	: Maximal level of price offered by suppliers ($s \in S^1$ and S^2) for materials ($m \in M^1$ and M^2) at period ($t \in T$)
α_{ms}	: Probability of the price at minimal level $P_{mst,\ min}$
β_{ms}	: Probability of the price at maximal level $P_{mst,\ max}$
L_{ms}	: Expected delivery lead time for materials ($m \in M^1$) from suppliers ($s \in S^1$) for any period
$s_{L_{ms}}$	: The standard deviation of delivery lead time for materials ($m \in M^1$) from suppliers ($s \in S^1$)

e_{ms} : Expected service level for materials (m ∈ M^1) from suppliers (s ∈ S^1) for any period

U_{ms} : Supplier's capacity for materials (m ∈ M^1 and M^2) for whole project

TPL (warehouse) parameters:

HC : Total material storage cost

VC : Material checking cost at the warehouse

FW_{mt} : Fixed cost of warehousing for materials (m ∈ M^1) at period (t ∈ T)

h_m : Unit holding cost for materials (m ∈ M^1) at the warehouse for any period

v_m : Inspection cost for materials (m ∈ M^1) at the warehouse (checking point) for any period

l_m : Transportation cost (per unit of material) for materials (m ∈ M^1) from warehouse to the construction site for any period

R_m : Safety stock of materials (m ∈ M^1) at the warehouse for any period

IW_{m0} (or I_m) : Inventory level of materials (m ∈ M^1) at the beginning of the planning process in the warehouse

N : Sufficiently large number

Demand parameters:

D_{mt} : Demand of materials (m ∈ M^1 and M^2) at period (t ∈ T)

d_m : Daily demand for materials (m ∈ M^1) stored at the warehouse for any period

σ_{dm} : The standard deviation of daily demand for materials (m ∈ M^1)

σ_{Lm} : The standard deviation of the demand for materials (m ∈ M^1) during the lead time

Z_{mt} : Receipt capacity in the construction site for materials (m ∈ M^1 and M^2) at period (t ∈ T)

Decisions variables:

S_{ms} : Binary variable = 1 when a supplier (s ∈ S^1 and S^2) is selected for material (m ∈ M^1 and M^2)

W_m : Binary variable = 1 when the material (m ∈ M^1) is stored in the warehouse

a_{mst} : Delivery number of the truckload for materials (m ∈ M^1) from suppliers (s ∈ S^1) to the warehouse at period (t ∈ T)

X_{mst} : Quantity of materials (m ∈ M^1) from suppliers (s ∈ S^1) to the construction site at period (t ∈ T)

O_{mst} : Quantity of materials (m ∈ M^2) from suppliers (s ∈ S^2) to the construction site at period (t ∈ T)

Y_{mt} : Quantity of materials (m ∈ M^1) from the warehouse to the construction site at period (t ∈ T)

IW_{mt} : Inventory level of materials (m ∈ M^1) at the warehouse at period (t ∈ T)

2.5.3 Executive objective

The integrated CSC model with TPL partnership is designed to solve the common tasks in construction SCM: (1) supplier selection, (2) determination of order quantity, and (3) consideration of the efficiency in using TPL's warehouse. These tasks are optimized through minimizing the construction logistics costs. The logistics costs can be estimated by considering the componential costs: ordering cost, transportation cost, storage cost, and material checking cost. Ordering cost refers to cost of material procurement and placing the orders to suppliers. The transportation cost consists of the delivery cost from suppliers to TPL's warehouse, the direct transportation cost from suppliers to construction site, and the transportation cost from TPL's warehouse to construction site. Storage cost represents the holding cost for materials, which includes cost of storage setup and operations at the TPL's warehouse. The material checking cost at the TPL's warehouse consists of the relevant costs, such as testing the batch and weighting the delivered materials at the checkpoint (Ekeskär and Rudberg, 2016; Fang and Ng, 2011). The problem is formulated as a MIP (mixed integer programming) model since all the related costs are defined as linear in nature, while other parameters (S_{ms}, W_m, a_{mst}) are integer variables.

The procurement and material ordering cost: The procurement and material ordering cost (*PC*) consists of the fixed cost for placing the order (FS_{mst}), the cost of pre-processing for the delivered material (k_m per unit of material), and the value of the purchased materials. The purchased materials are transported to the warehouse with the quantity $a_{mst} \times Q_{ms}$ and directly transferred to the construction site with the quantities (X_{mst} for materials m ∈ M^1 and O_{mst} for materials m ∈ M^2). Thus, the total numbers of purchased materials are $a_{mst} \times Q_{ms} + X_{mst}$ for materials m ∈ M^1 and O_{mst} for materials m ∈ M^2. With the purchasing price $E(P_{mst})$, the procurement and material ordering cost is calculated by:

$$\begin{aligned} PC = & \sum_{m \in M^1 \cup M^2} \sum_{s \in S^1 \cup S^2} \sum_{t \in T} FS_{mst} \times S_{ms} + \sum_{m \in M^1} \sum_{s \in S^1} \sum_{t \in T} [k_m + E(P_{mst})] \times [a_{mst} \times Q_{ms} + X_{mst}] + \\ & \sum_{m \in M^2} \sum_{s \in S^2} \sum_{t \in T} [k_m + E(P_{mst})] \times O_{mst} \end{aligned} \tag{2.1}$$

The transportation cost from suppliers/warehouse to warehouse/construction site: The transportation cost (*TC*) consists of the delivery cost from suppliers to TPL's warehouse (TS_{ms} per lot size), the direct transportation cost from suppliers to construction site (DC_{ms} per unit of material), and the transportation cost (l_m per unit of material) from TPL's warehouse to construction site:

$$TC = \sum_{m \in M^1} \sum_{s \in S^1} \sum_{t \in T} TS_{ms} \times a_{mst} + \sum_{m \in M^1} \sum_{s \in S^1} \sum_{t \in T} DC_{ms} \times X_{mst} + \sum_{m \in M^2} \sum_{s \in S^2} \sum_{t \in T} DC_{ms} \times O_{mst} + \sum_{m \in M^1} \sum_{s \in S^1} \sum_{t \in T} l_m \times Y_{mt}$$

(2.2)

The material storage cost: The material holding cost at the TPL's warehouse consists of two components: the first component is the fixed cost of warehousing (FW_{mt}) which is independent to the material quantity; and the second component is the variable cost, which varies due to the change in material quantity. For the variation of inventory amount, the follow is considered for the inventory estimation. At the beginning of the planning period *t*, the initial inventory level at the warehouse is $IW_{m,t-1}$. Once the materials are received, the inventory level turns into

$IW_{m,t-1}+a_{mst}\times Q_{ms}$. Assuming that the inventory level drops at a constant rate, the inventory level at the end of planning period (t) is IW_{mt}. Thus, the average inventory level across the planning period (t) is $\frac{IW_{m,t-1}+a_{mst}\times Q_{ms}+IW_{mt}}{2}$. With the unit holding cost (h_m), the total material storage cost (HC) is computed by:

$$HC=\sum_{m\in M^1}\sum_{t\in T}FW_{mt}\times W_m+\sum_{m\in M^1}\sum_{s\in S^1}\sum_{t\in T}\left(\frac{IW_{m,t-1}+a_{mst}\times Q_{ms}+IW_{mt}}{2}\right)\times h_m \qquad (2.3)$$

The material checking cost at the warehouse: When delivered to the checkpoint at the TPL's warehouse, the received materials are verified by the TPL partner to ensure the material requirements before handling them to the construction site. The checking cost (VC) is assumed to be dependent to the material quantity and consist of the relevant costs (testing the material quality and weighting the delivered material at the checkpoint). This cost is calculated by:

$$VC=\sum_{m\in M^1}\sum_{s\in S^1}\sum_{t\in T}v_m\times a_{mst}\times Q_{ms} \qquad (2.\ 4)$$

2.5.4 Constraints

Uncertain price: In practice, the prices offered by suppliers are normally uncertain and stochastically distributed in a certain range due to the fluctuations of many factors such as financial exchange rates or crude oil prices. Thus, at every stage, the purchase prices are assumedly estimated on three levels: minimum level ($P_{mst,\ min}$), and maximum level ($P_{mst,\ max}$), and normal level (P'_{mst}), at three probabilities: α_{ms}, β_{ms}, and $1-\alpha_{ms}-\beta_{ms}$ respectively. As a result, the expected value of the prices can be computed as:

$$E(P_{mst})=\alpha_{ms}\times P_{mst,\min}+\beta_{ms}\times P_{mst,\max}+(1-\alpha_{ms}-\beta_{ms})\times P'_{mst},\forall m\in M^1\cup M^2 \qquad (2.5)$$

Safety stock: In order to avoid the shortage costs related to supply delay and demand uncertainty, this study allows a level of safety stock for the purchasing materials. The safety stock is only applied for the materials stored at the TPL's warehouse. The daily demand of these materials provided by the warehouse can be estimated on their total daily demand. It is assumed that the delivery lead-time from suppliers follows a normal distribution with the expected value (L_{ms}) and the standard deviation (s_{Lms}). Similarly, the daily demand (provided by the warehouse) distributes normally with the mean value (d_m) and the standard deviation (σ_{dm}). The standard deviation of the demand during the lead time is calculated by:

$$\sigma_{Lm} = \sqrt{L_{ms} \times \sigma_{dm}^{2} + d_{m}^{2} \times s_{Lms}^{2}}, \forall m \in M^{1} \tag{2.6}$$

During the lead-time, the expected service level for material ($m \in M^1$) is denoted by e_m, with $e_m \in [0, 1]$. A higher value of e_m indicates a reduction in shortage risk, but an increase in the level of safety stock. *NORMSINV* (e_m) is the function to compute the inverse of the standard normal cumulative distribution of e_m. The safety stock (R_m) for material ($m \in M^1$) is estimated by:

$$R_m = NORMSINV(e_m) \times \sigma_{Lm}, \forall m \in M^1 \tag{2.7}$$

Inventory status: For each period (t), the TPL's warehouse provides the construction site with the material quantity Y_{mt}. The inventory level of the previous period is $IW_{m,t-1}$. At the beginning of period t, the material amount is received by $a_{mst} \times Q_{ms}$. Then, the inventory level for material m at the warehouse can be kept in balance from one stage to the next:

$$IW_{mt} = IW_{m,t-1} + \left(\sum_{s \in S^1} a_{mst} \times Q_{ms} \right) - Y_{mt}, \forall t = T_1, T_2, ..., T_{n-1}, \forall m \in M^1 \tag{2.8}$$

The total amount of the received materials and the materials stored at the beginning of period t has to cover the period demand and the safety stock (R_m) to mitigate risks of shortage:

$$IW_{m,t-1} + \left(\sum_{s \in S^1} a_{mst} \times Q_{ms} \right) \geq Y_{mt} + R_m, \forall t = T_1, T_2, ..., T_{n-1}, \forall m \in M^1 \tag{2.9}$$

At the beginning of the planning process, the inventory levels at the warehouse are given to the certain value (I_m) to guarantee the supply security:

$$IW_{m0} = I_m, \forall m \in M^1 \tag{2.10}$$

At the end of the planning process, all material quantity needs to be consumed:

$$IW_{m,t-1}+\left(\sum_{s\in S^1} a_{mst}\times Q_{ms}\right)=D_{mt}=Y_{mt},t=T_n,\forall m\in M^1 \tag{2. 11}$$

SC trade-off: The suppliers usually have their own maximum capacity (*U_{ms}*) for the purchasing materials. Thus, the purchasing amounts need to satisfy the following constraints:

$$\sum_{t\in T} a_{mst}\times Q_{ms}+X_{mst}\le U_{ms}\times S_{ms},\forall m\in M^1,\forall s\in S^1 \tag{2.12}$$

$$\sum_{t\in T} O_{mst}\le U_{ms}\times S_{ms},\forall m\in M^2,\forall s\in S^2 \tag{2.13}$$

The total quantity of the flow of material from suppliers to the construction site *(X_{mst}* for materials m ∈ M^1*)* and the flow of material from the TPL's warehouse to the construction site *(Y_{mt})* must cover the demand of the material during the period (*D_{mt}*). The similarity is applied for the total quantity of the flow of material from suppliers to the construction site *(O_{mst}* for materials m ∈ M^2*):*

$$\left(\sum_{s\in S^1} X_{mst}\right)+Y_{mt}\ge D_{mt},\forall m\in M^1,\forall t\in T \tag{2.14}$$

$$\sum_{s\in S^2} O_{mst}\ge D_{mt},\forall m\in M^2,\forall t\in T \tag{2.15}$$

The total quantity of the flow of material from suppliers to the construction site *(X_{mst}* for materials m ∈ M^1*)* and the flow of material from the TPL's warehouse to the construction site *(Y_{mt})* cannot exceed the receipt capacity in the construction (*Z_{mt}*). The similarity is applied for the total quantity of the flow of material from suppliers to the construction site *(O_{mst}* for materials m ∈ M^2*):*

$$\left(\sum_{s\in S^1} X_{mst}\right)+Y_{mt}\le Z_{mt},\forall m\in M^1,\forall t\in T \tag{2.16}$$

$$\sum_{s\in S^2} O_{mst}\le Z_{mt},\forall m\in M^2,\forall t\in T \tag{2.17}$$

For the material type 1, the materials can be transported to the warehouse with the delivery number *a_{mst}* or delivered directly to the construction site with the quantity *X_{mst}.* Then, the materials stored at the warehouse are transported to the construction site with the quantity Y_{mt}. The binary variable W_m is used to identify the status of materials if they are stored in the warehouse. It is assumed that the value of $Wm = 1$ if the material $m \in M^1$ is stored in the warehouse. This means that during the period t, there will be the delivery of material $m \in M^1$ to the warehouse ($a_{mst} > 0$ and $Y_{mt} > 0$). Otherwise, $Wm = 0$, the material $m \in M^1$ is sent directly to the construction site with the quantity $X_{mst} > 0$. If N is considered as a sufficiently large number, the constraints of flow conservation for materials $m \in M^1$ delivered to the warehouse or directly to the construction site are presented by:

$$a_{mst} \le W_m \times N, \forall m \in M^1, \forall s \in S^1, \forall t \in T \tag{2.18}$$

$$X_{mst} \le (1 - W_m) \times N, \forall m \in M^1, \forall s \in S^1, \forall t \in T \tag{2.19}$$

$$Y_{mt} \le W_m \times N, \forall m \in M^1, \forall t \in T \tag{2.20}$$

In order to make sure that the suppliers s, who are once selected for materials m, are kept the same during the project, the following constraint needs to be satisfied:

$$\sum_{s \in S^1 \cup S^2} S_{ms} = 1, \forall m \in M^1 \cup M^2 \tag{2.21}$$

2.5.5 Optimal decision-making model

As mentioned above, the integrated CSC with TPL partnership is modelled as a focal network in which the TPL provider plays a role as focal decision maker and coordinates the entire logistics process with the involvement of associated SC actors (construction owner, contractors and suppliers). Thus, the optimal decision-making model for minimizing the supply chain cost (SCC) is presented as the below model which can be solved by some universal software, such as LINGO, Mathematica, MatLab, MathCAD, CPLEX or Excel. In this thesis, in order to find the optimal solution for the MIP model, we use the means of LINGO 17.0 Optimization Modeling Software. The LINGO Code is presented in **Appendix I**.

$$\boldsymbol{Min\ SCC = PC + TC + HC + VC}$$

$$\begin{aligned}
&= \sum_{m\in M^1\cup M^2}\sum_{s\in S^1\cup S^2}\sum_{t\in T} FS_{mst}\times S_{ms} + \sum_{m\in M^1}\sum_{s\in S^1}\sum_{t\in T}[k_m + E(P_{mst})]\times[a_{mst}\times Q_{ms} + X_{mst}] + \\
&\sum_{m\in M^2}\sum_{s\in S^2}\sum_{t\in T}[k_m + E(P_{mst})]\times O_{mst} \\
&+ \sum_{m\in M^1}\sum_{s\in S^1}\sum_{t\in T} TS_{ms}\times a_{mst} + \sum_{m\in M^1}\sum_{s\in S^1}\sum_{t\in T} DC_{ms}\times X_{mst} + \sum_{m\in M^2}\sum_{s\in S^2}\sum_{t\in T} DC_{ms}\times O_{mst} + \sum_{m\in M^1}\sum_{s\in S^1}\sum_{t\in T} l_m\times Y_{mt} \\
&+ \sum_{m\in M^1}\sum_{t\in T} FW_{mt}\times W_m + \sum_{m\in M^1}\sum_{s\in S^1}\sum_{t\in T}\left(\frac{IW_{m,t-1} + a_{mst}\times Q_{ms} + IW_{mt}}{2}\right)\times h_m + \sum_{m\in M^1}\sum_{s\in S^1}\sum_{t\in T} v_m\times a_{mst}\times Q_{ms}
\end{aligned}$$

s.t.

$$\left\{\begin{array}{l}
E(P_{mst}) = \alpha_{ms}\times P_{mst,\min} + \beta_{ms}\times P_{mst,\max} + (1-\alpha_{ms}-\beta_{ms})\times P'_{mst}, \forall m\in M^1\cup M^2 \\
\sigma_{Lm} = \sqrt{L_{ms}\times \sigma_{dm}{}^2 + d_m{}^2\times s_{Lms}{}^2}, \forall m\in M^1 \\
R_m = NORMSINV(e_m)\times \sigma_{Lm}, \forall m\in M^1 \\
IW_{mt} = IW_{m,t-1} + \left(\sum_{s\in S^1} a_{mst}\times Q_{ms}\right) - Y_{mt}, \forall t = T_1, T_2, ..., T_{n-1}, \forall m\in M^1 \\
IW_{m,t-1} + \left(\sum_{s\in S^1} a_{mst}\times Q_{ms}\right) \geq Y_{mt} + R_m, \forall t = T_1, T_2, ..., T_{n-1}, \forall m\in M^1 \\
IW_{m0} = I_m, \forall m\in M^1 \\
IW_{m,t-1} + \left(\sum_{s\in S^1} a_{mst}\times Q_{ms}\right) = D_{mt} = Y_{mt}, t = T_n, \forall m\in M^1 \\
\sum_{t\in T} a_{mst}\times Q_{ms} + X_{mst} \leq U_{ms}\times S_{ms}, \forall m\in M^1, \forall s\in S^1 \\
\sum_{t\in T} O_{mst} \leq U_{ms}\times S_{ms}, \forall m\in M^2, \forall s\in S^2 \\
\left(\sum_{s\in S^1} X_{mst}\right) + Y_{mt} \geq D_{mt}, \forall m\in M^1, \forall t\in T \\
\sum_{s\in S^2} O_{mst} \geq D_{mt}, \forall m\in M^2, \forall t\in T \\
\left(\sum_{s\in S^1} X_{mst}\right) + Y_{mt} \leq Z_{mt}, \forall m\in M^1, \forall t\in T \\
\sum_{s\in S^2} O_{mst} \leq Z_{mt}, \forall m\in M^2, \forall t\in T \\
a_{mst} \leq W_m\times N, \forall m\in M^1, \forall s\in S^1, \forall t\in T \\
X_{mst} \leq (1-W_m)\times N, \forall m\in M^1, \forall s\in S^1, \forall t\in T \\
Y_{mt} \leq W_m\times N, \forall m\in M^1, \forall t\in T \\
\sum_{s\in S^1\cup S^2} S_{ms} = 1, \forall m\in M^1\cup M^2
\end{array}\right.$$

2.6 Numerical case example

2.6.1 Data description

In order to apply the proposed model, a hydropower construction project is illustrated in this section. The project needs a wide range of material items for the sub-construction of gravel wall, rock-filled dam, tunnel spillway, electricity generating system, and diversion work, which require a large amount of labor and capital. Therefore, the logistics activities of material purchasing, transportation, storage, and delivery to the site are selected as a numerical case to validate the productivity of the proposed model in SC practice. The project employs the TPL solution as the mandatory requirement for all contractors. The TPL is hired to take into account all activities related to construction logistics, including the provision of a warehouse with unlimited capacity. Based on the offerings from the suppliers (about the material prices and the relevant costs), the general contractor has to organize the formal meetings with the TPL provider and the associated contractors to determine the optimal plan for the material purchasing, storage, and delivery. The data used for the decision-making is presented by the TPL specialist and discussed with the contractors for the data validation.

For the purpose of illustration, the case study is simplified with the procurement, storage, and delivery of four materials: cement (m_1), steel (m_2), dinas (m_3), and lumber (m_4), which follows the approach of Liu et al. (2017). These materials are demanded to produce reinforced concrete and mode. The material m_1 is directly sent to the construction site only (known as *material type 2* in this study). Three local suppliers, s_1, s_2, and s_3, are the potentials that can be selected for the material m_1. Meanwhile, the materials m_2, m_3, and m_4 can be transported to the warehouse or directly sent to the construction site (known as *material type 1* in this study). For the material m_2, three suppliers: s_4 (from the remote Asian country), s_5 (from the South American country), and s_6 (the local supplier in Canada) can be potentially selected due to their offerings. The material m_3 can be supplied by one of the three suppliers s_7, s_8, and s_9. Similarly, the material m_4 can be supplied by one of the three suppliers s_{10}, s_{11}, and s_{12}. Among these suppliers, s_7 and s_{10} are from the remote Asian countries, s_8 and s_{11} are from the South American countries, while s_9 and s_{12} are the local suppliers in Canada.

Table 22 Material prices

	Prices ($P_{mst,min}$; P'_{mst}; $P_{mst,max}$) offered by suppliers for each material in $											
Period	T_1			T_2			T_3			T_4		
	s_1	s_2	s_3	s_1	s_2	s_3	s_1	s_2	s_3	s_1	s_2	s_3
m_1	19.45; 20.23; 21.11	20.70; 21.50; 22.62	20.36; 21.42; 21.65	20.51; 21.70; 22.24	20.62; 21.88; 22.46	19.78; 21.62; 22.77	20.72; 21.57; 22.90	19.59; 20.73; 22.39	20.19; 21.86; 22.84	19.45; 20.68; 21.78	20.78; 20.90; 21.34	19.66; 21.88; 22.16
	s_4	s_5	s_6	s_4	s_5	s_6	s_4	s_5	s_6	s_4	s_5	s_6
m_2	158.07; 159.64; 161.20	189.73; 191.57; 193.40	207.36; 207.63; 207.90	154.74; 158.52; 162.30	188.35; 190.38; 192.40	203.83; 206.23; 208.63	153.15; 158.68; 164.20	188.11; 190.66; 193.20	205.14; 206.62; 208.10	159.29; 159.70; 160.10	190.73; 191.62; 192.50	206.09; 207.55; 209.01
	s_7	s_8	s_9	s_7	s_8	s_9	s_7	s_8	s_9	s_7	s_8	s_9
m_3	0.78; 1.05; 1.32	1.26; 1,29; 1.32	1.38; 1.40; 1.42	1.11; 1.15; 1.18	1.36; 1.38; 1.39	1.47; 1.49; 1.51	1.06; 1.11; 1.16	1.31; 1.34; 1.36	1.44; 1.45; 1.46	1.13; 1.16; 1.19	1.38; 1.40; 1.41	1.50; 1.51; 1.52
	s_{10}	s_{11}	s_{12}	s_{10}	s_{11}	s_{12}	s_{10}	s_{11}	s_{12}	s_{10}	s_{11}	s_{12}
m_4	102.72; 104.51; 106.30	124.20; 125.43; 126.65	134.90; 135.85; 136.80	103.57; 104.61; 105.65	124.78; 125.54; 126.30	133.53; 135.92; 138.30	101.25; 104.78; 108.30	124.21; 125.76; 127.30	133.82; 136.16; 138.50	105.52; 107.26; 109.01	128.25; 128.73; 129.20	138.65; 139.43; 140.20

For the material prices, the local suppliers s_6, s_9, and s_{12} offer higher prices, but lower transportation costs due to the shorter distances. Meanwhile, the international suppliers s_4, s_7, *and* s_{10} (from the remote Asian countries) can supply the materials with lower prices in comparison with the local suppliers s_6, s_9, and s_{12} at the discounts of 23% respectively for the same materials. The other international suppliers s_5, s_8, *and* s_{11} (from the South American countries) can also supply the materials with lower prices in comparison with the local suppliers s_6, s_9, and s_{12} at the discounts of 8% respectively for the same materials.

The decision is made to consider the quantity of each material to be delivered to the TPL's warehouse (a_{mst}) as well as the material quantity to be directly sent to the construction site (X_{mst} and O_{mst}) in order to achieve the optimal logistics plan for the SC operations. The material prices and periodic demands for each material are presented in **Table 2.2 and 2.3**.

Table 2.3 Demand for the materials

Material demand (D_{mt}) in units				
Period	T_1	T_2	T_3	T_4
m_1	532	631	663	513
m_2	3,134	3,249	3,310	3,113
m_3	3,410	4,042	4,249	3,287
m_4	95	96	97	97

Due to the contractors' demands, the material m_1 is required to be sent directly to the construction site with the transportation costs per unit (DC_{ms}) offered by the potential suppliers s_1, s_2, and s_3. For the materials m_2 (potential suppliers s_4, s_5, s_6), m_3 (potential suppliers s_7, s_8, s_9) and m_4 (potential suppliers s_{10}, s_{11}, s_{12}), these potential suppliers offer two options for the material purchasing: (1) the low transportation costs per lot size (TS_{ms}) but requiring large enough quantity (Q_{ms}) for each delivery, and (2) the delivery at any amount (X_{mst}) due to the demands with normal transportation costs (DC_{ms}). The values of transportation costs and other parameters for the four planning periods are presented in **Table 2.4 and Table 2.5**.

Table 2.4 Values of supplier-related parameters

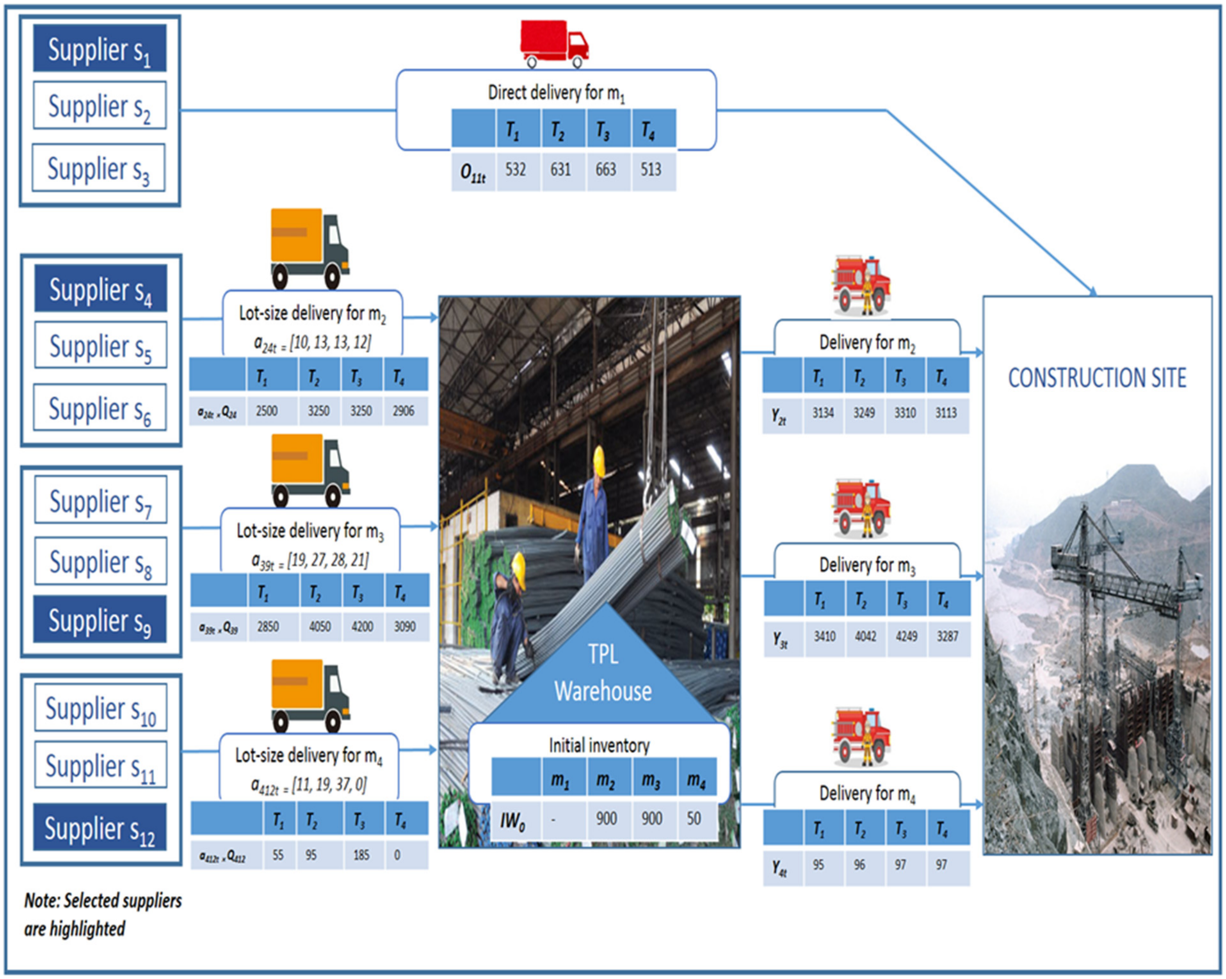
For all periods T_1, T_2, T_3, and T_4												
	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}	s_{12}
Transportation cost from supplier to warehouse (TS_{ms} per lot size) in $												
m_2	-	-	-	3000	1000	100	-	-	-	-	-	-
m_3	-	-	-	-	-	-	2500	700	70	-	-	-
m_4	-	-	-	-	-	-	-	-	-	2800	900	80
Direct transportation cost from supplier to construction site (DC_{ms} per unit) in $												
m_1	10	12	13	-	-	-	-	-	-	-	-	-
m_2	-	-	-	150	100	12	-	-	-	-	-	-
m_3	-	-	-	-	-	-	80	5	1.50	-	-	-
m_4	-	-	-	-	-	-	-	-	-	200	180	19
Ordering fixed cost (FS_{mst}) in $												
m_1	14	16	17	-	-	-	-	-	-	-	-	-
m_2	-	-	-	100	30	10	-	-	-	-	-	-
m_3	-	-	-	-	-	-	50	15	10	-	-	-
m_4	-	-	-	-	-	-	-	-	-	75	35	15
Fixed lot size (Q_{ms}) in units												
m_2	-	-	-	250	100	20	-	-	-	-	-	-
m_3	-	-	-	-	-	-	450	300	150	-	-	-
m_4	-	-	-	-	-	-	-	-	-	25	10	5
Probabilities of the offered prices (α_{ms}; β_{ms})												
m_1	0.24; 0.25	0.23; 0.23	0.25; 0.24	-	-	-	-	-	-	-	-	-
m_2	-	-	-	0.26; 0.32	0.24; 0.30	0.25; 0.31	-	-	-	-	-	-
m_3	-	-	-	-	-	-	0.19; 0.29	0.18; 0.28	0.17; 0.27	-	-	-
m_4	-	-	-	-	-	-	-	-	-	0.15; 0.16	0.14; 0.15	0.13; 0.17
Delivery lead times (days) and their standard deviations (L_{ms}; s_{Lms})												
m_2	-	-	-	2; 0.4	3; 0.5	4; 0.4	-	-	-	-	-	-
m_3	-	-	-	-	-	-	1; 0.4	2; 0.5	1; 0.4	-	-	-
m_4	-	-	-	-	-	-	-	-	-	3; 0.4	2; 0.5	2; 0.4
Supplier capacity (U_{ms}) in units												
m_1	2700	2000	2200	-	-	-	-	-	-	-	-	-
m_2	-	-	-	13450	13500	14000	-	-	-	-	-	-
m_3	-	-	-	-	-	-	15000	16000	15450	-	-	-
m_4	-	-	-	-	-	-	-	-	-	450	500	400

Table 2.5 Values of material-related parameters

For all periods (T_1, T_2, T_3, T_4)	m_1	m_2	m_3	m_4
$k_m\ (\$/\text{unit})$	0.01	0.06	0.002	0.03
e_m	-	0.80	0.80	0.80
$FW_{mt}\ (\$)$	-	50,000	5,000	40,000
$h_m\ (\$/\text{unit})$	-	2	0.20	0.70
$v_m\ (\$/\text{unit})$	-	0.70	0.10	0.40
$l_m\ (\$/\text{unit})$	-	10	0.50	3.50
d_m (units)	335	458	536	14
σ_{dm}	8.5	13.5	20.5	0.5
Z_{mt} (units)	800	3,500	5,000	200
I_{m0} (units)	-	900	900	50

2.6.2 Logistics plan with TPL integration

Figure 2.3 presents the operations of the CSC network for the case study with the result of supplier selection. The result for material purchasing, transportation, and storage during the four planning periods: T_1, T_2, T_3, and T_4 is also detailed in the figure. The result serves as the optimal plan for construction logistics that the TPL provider has to follow for the operations with the consensus and participation of relevant contractors and owner. The optimal plan shows that it is essential to take advantage of the TPL's warehouse with a large capacity to order the large quantities $(a_{mst} \times Q_{ms})$ for materials m_2, m_3, and m_4 to get the efficiency in construction logistics. As shown in the figure, due to the requirement of the contractors, the material m_1 (the *material type 2* in this study) is provided directly to the construction site by the local supplier s_1 with the quantity being exactly equal to the demand. Meanwhile, the materials *type 1* in this study, such as m_2, is supplied by the international suppliers s_4, while the local suppliers s_9 and s_{12} are selected for the materials m_3 and m_4. These materials are transported to the TPL warehouse to be stored and used for the demands.



Direct delivery for m_1

	T_1	T_2	T_3	T_4
O_{11t}	532	631	663	513

Lot-size delivery for m_2

	T_1	T_2	T_3	T_4
$a_{24t} \times Q_{24}$	2500	3250	3250	2906

Lot-size delivery for m_3

	T_1	T_2	T_3	T_4
$a_{39t} \times Q_{39}$	2850	4050	4200	3090

Lot-size delivery for m_4

	T_1	T_2	T_3	T_4
$a_{412t} \times Q_{412}$	55	95	185	0

Initial inventory

	m_1	m_2	m_3	m_4
IW_0	-	900	900	50

Delivery for m_2

	T_1	T_2	T_3	T_4
Y_{2t}	3134	3249	3310	3113

Delivery for m_3

	T_1	T_2	T_3	T_4
Y_{3t}	3410	4042	4249	3287

Delivery for m_4

	T_1	T_2	T_3	T_4
Y_{4t}	95	96	97	97

Figure 2.3 Optimal plan for material purchasing, transportation, and storage

The details in demand-supply for the optimal plan are presented in **Figure 2.4.** In some period, the TPL warehouse can be taken advantage to store more quantity of materials which are used for the following periods in order to achieve the low cost in construction logistics. For example, for material m_4, in period T_3, the order *quantity* is decided with 185 units, which can cover the demands for both periods T_3 and T_4. However, in order to ensure a proficient plan for construction logistics, as shown in the figure, for most of the planning periods, the total of the initial inventory and the order quantity should be close to the value of demand in the same period. At the end of the planning process, T_4, for all the materials, the total of the inventory and the order quantity must be equal to the value of the demand in order to avoid the related costs when the project finishes.

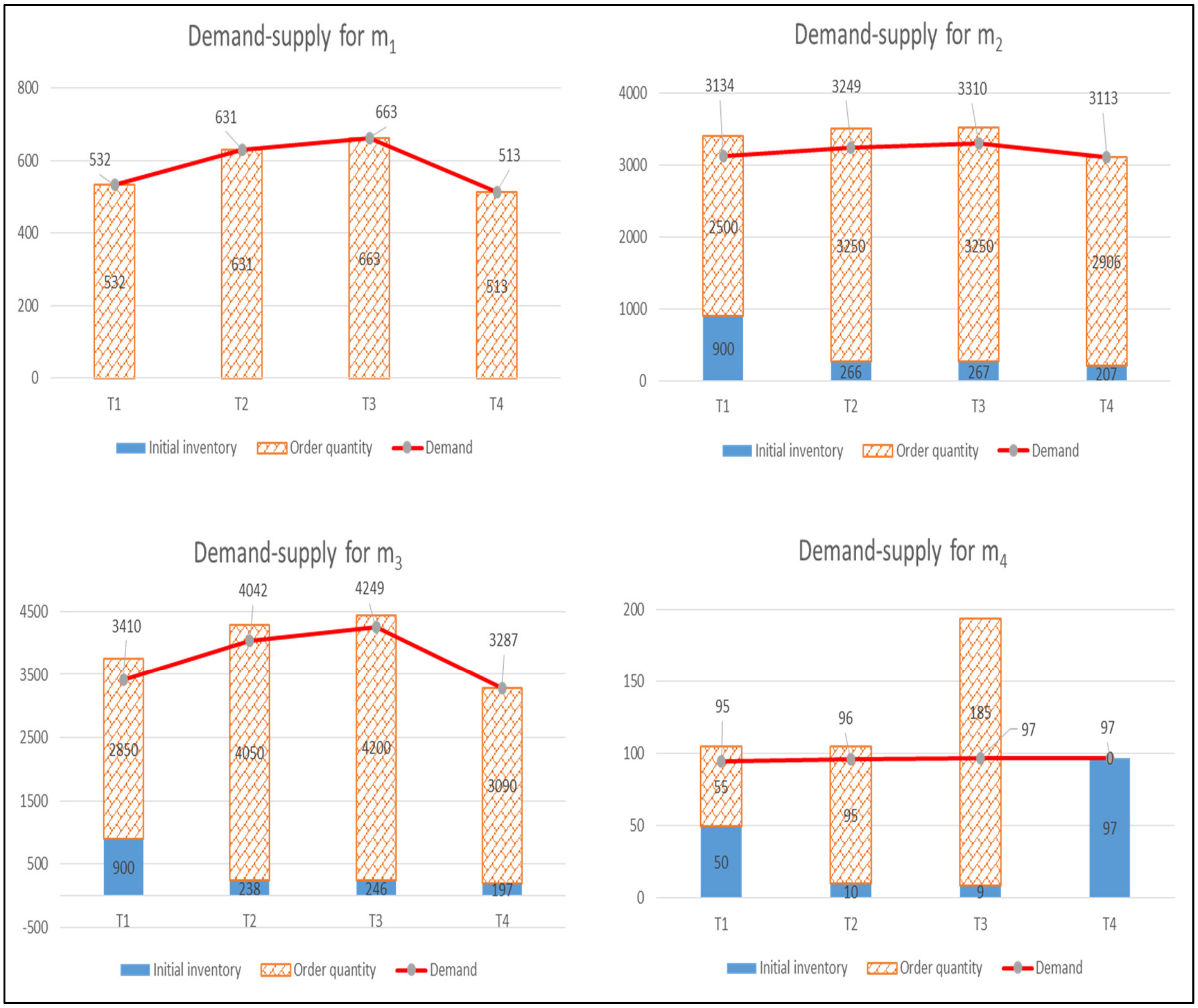


Figure 2.4 Details in demand-supply for the optimal plan

2.6.3 Model comparison

In order to consider the efficiency of using TPL partnership for CSC, we compare the results obtained from the three models: (a) the proposed CSC model applied for TPL partnership with different price discounts offered by different suppliers; (b) the proposed CSC model applied for TPL partnership with same prices offered by different suppliers, and (c) the CSC model without TPL partnership. We use the above case as an example of the application of the model (a). As mentioned above, the local suppliers s_1, s_2, s_3, s_6, s_9, and s_{12} offer the prices without discounts. Meanwhile, in comparison with the local supplier s_6, s_9 and s_{12} who supply the materials m_2, m_3 and m_4, the international suppliers from the remote Asian countries (s_4, s_7 *and* s_{10}) and the South American countries (s_5, s_8, *and* s_{11}) can offer the prices with discounts of 23% and 8% respectively for the same materials. For the model (b), we assume that the international suppliers offer the same prices as the local suppliers for the same materials. In this model, the differences between the suppliers are not reflected in prices, but in the transportation-related costs identified for both international and local suppliers. Meanwhile, the model (c) is based on the assumption that all purchased materials are directly transported to the construction, and there is no TPL's warehouse. Thus, for the model (c), only local suppliers are considered for the selection, and the same prices are offered for the same materials by these suppliers. For the comparison, we assume that there is no storage cost at the construction site. Thus, only the first two model have the storage cost at TPL's warehouse while there are no storage and checking costs applied for the third model.

The results (**Table 2.6**) show that the total cost savings for the whole project are 17% and 21% applying for the model (a) TPL with price discounts in comparison with the model (b) TPL without price discounts and the model (c) without TPL respectively. This is also significant to compare to previous studies, which have shown that the percentage of cost-saving in logistics optimization is around 10% (Deng et al. 2019; Le et al. 2019). These cost-savings are achieved because of the discounts in material prices offered by the international supplier. This benefit is only achieved if there is enough space (in this study, it is called TPL’s warehouse) to store the materials with high quantity purchased from international suppliers. In other models, the international suppliers are not selected because there is no discount for purchasing prices while the transportation costs associated to these suppliers are higher due to the farther distances.

Table 2.6 The results comparison of three models

Model	Supplier selection (material: supplier)	Procurement and order cost (PC)	Transportation cost (TC)	Storage cost (HC)	Checking cost (VC)	Total SC cost (SCC)	Total cost compared to model (a)
(a) TPL with price discounts	m_1: s_1 (local) m_2: s_4 (international) m_3: s_6 (local) m_4: s_6 (local)	2,062,213	186,735	113,320	9,887	2,372,156	-
(b) TPL without price discounts	m_1: s_1 (local) m_2: s_6 (local) m_3: s_6 (local) m_4: s_6 (local)	2,630,929	96,250	111,925	9,887	2,848,991	17%
(c) Without TPL	m_1: s_1 (local) m_2: s_6 (local) m_3: s_6 (local) m_4: s_6 (local)	2,826,467	184,638	-	-	3,011,106	21%

2.6.4 Impacts of uncertainties

Next, we consider the effects of the uncertainties on the SC costs (as shown in **Table 2.7**), which can provide managerial implications on the associated risk mitigation to enhance the SC performance. Firstly, the model is calculated without the safety stock *(R_m)* to check its impact on the objective function. As presented in the equations **(2.6)** and **(2.7)**, the safety stock is estimated on the consideration of uncertainties in the delivery lead-time (s_{Lms}) and the daily demand (σ_{dm}). Thus, the model running without R_m means the removal of these uncertainties. Without considering s_{Lms} and σ_{dm}, the holding cost (HC) decreases by 2.94% because of the less storage. The less purchasing quantity also makes the purchasing cost, transportation cost, and checking cost slightly decreases by 0.01%, 0.01%, and 0.05%, respectively. As a result, the total supply chain (SCC) without the safety stock is 0.15% less than the initially proposed model. This implies that, in this case, the uncertainties in delivery lead-time and daily demand have the moderate impact on the holding cost, but slightly impacts on other costs.

Secondly, we check the impact of the price uncertainty on the total SC cost. Since the material price, in this case, accounts for a large proportion of total SC cost, any change in the price can have an effect on the objective function. The equation **(2.5)** shows that the price uncertainty is defined through the probabilities ($\alpha_{ms}, \beta_{ms}, 1- \alpha_{ms} - \beta_{ms}$) of the three price levels ($P_{mst, min}$, $P_{mst, max}$, P'_{mst}). Hence, the model running without the price uncertainty means the zero settings for values of α_{ms} and β_{ms}. The result presented in the table shows that the price uncertainty also has a significant impact (4.08%) on total SC cost. The above analyzes show that among the mentioned uncertainties, the price uncertainty has the highest impact on SC costs. Besides, the uncertainties in daily demand and delivery lead-time are recognized to have the moderate impact on the storage cost.

Table 2.7 Effects of uncertainties on supply chain costs

Cost	TPL model	Without R_m (without s_{Lms} and σ_{dm})	Effect of R_m	Without price uncertainty (without α_{ms} and β_{ms})	Effect of price uncertainty
PC	2,062,213	2,061,978	0.01%	1,969,414	4.71%
TC	179,592	179,566	0.01%	179,592	0.00%
HC	113,320	109,982	2.94%	113,320	0.00%
VC	9,887	9,882	0.05%	9,887	0.00%
Total SCC	2,365,012	2,361,408	0.15%	2,272,212	4.08%

2.6.5 Sensitive analysis

The most advantageous feature of the proposed TPL model is to obtain the price discounts offered by suppliers to optimize the total SC cost. In big projects, the project managers can select international suppliers who offer lower prices than local suppliers. As described in the above case example, the TPL can be used for large purchasing from international suppliers to get the price discounts (23% from the remote Asian suppliers s_4, s_7 and s_{10} and 8% from the South American suppliers s_5, s_8, and s_{11}). In this case, the question is how the total SC cost is sensitive to the changes in materials prices through discounts offered by the international suppliers.

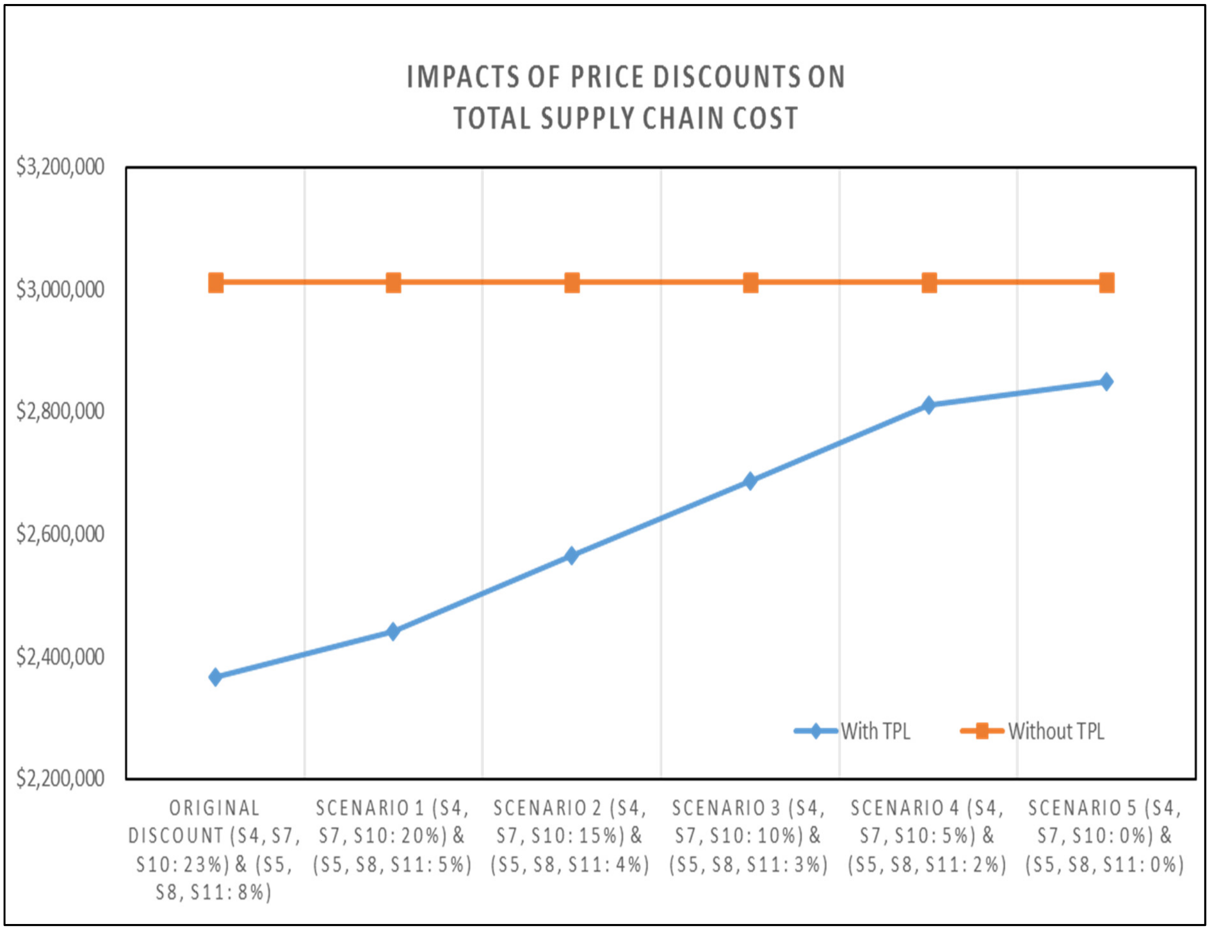


Figure 2.5 Sensitive analysis for impacts of price discounts on total cost

The results of sensitivity analysis are presented in **Figure 2.5**, which shows the total SC costs in the six scenarios for both models: with TPL and without TPL. In the model without TPL, the total SC cost does not change for all the scenarios with price discounts. Indeed, all the selected suppliers are local (without price discounts) since the TPL warehouse is not used.

Meanwhile, in the model with TPL, international suppliers with price discounts are selected. Therefore, the total SC costs are sensitive to the changes in price discounts offered by international suppliers. The result shows that the total SC costs in the model with TPL are lower than the total SC cost in the model without TPL for all scenarios. It is interesting to find out that even in scenario 5 in which there is no price discounts offered by the international suppliers, the model with TPL is still more efficient than the model without TPL. Thus, for this case, the TPL partnership is recommended for the construction project since it enhances the logistics and construction supply chain efficiency.

2.7 Discussions

This paper develops an optimization model to improve the logistics performance for CSC operations with TPL partnership (research objective 1). The proposed model considers the TPL provider as the CSC coordinator for logistics activities: material purchasing, transportation, and storage. The model aims to generate an optimal logistics plan for two kinds of materials. Type-1 materials can be transported to the warehouse or directly sent to the construction site. Type-2 materials can be directly sent to construction site only. The optimization model can assist the decision-makers to determine the operational strategies for common tasks in CSCM: supplier selection, determination of order quantity, and consideration of the efficiency in using TPL’s warehouse. The proposed model provides the optimal solution for construction logistics based on the consideration of the relevant costs, including procurement cost, transportation cost, holding cost at TPL warehouse, and material checking cost. For further analysis of the efficiency of the proposed model, we compare the total SC costs generated among three models: the proposed CSC model applied for TPL partnership with different price discounts offered by different suppliers; the proposed CSC model applied for TPL partnership with same prices offered by different suppliers; and the CSC model without TPL partnership (research objective 2). The model validation with the case example shows that the proposed model performs better results in total SC cost in comparison with the CSC model without the TPL partnership. This implies that the optimization model for the integrated CSC operations with TPL provider can be used to improve the construction logistics performance and deal with the practical requirements of the current issues in the construction industry. This finding supports the reasoning in the study of Ekeskär and Rudberg (2016), which confirms that TPL employment can provide CSC actors with lower costs and better resource utilisation.

The distinctive implication of this paper is the integration of TPL partnership for CSC operations. In the proposed model, there are important SC actors: the owner, the TPL provider, the contractors, and suppliers. In order to succeed in using the TPL service, the owner has to show the commitment to solving logistics issues by initiating the TPL solution. Then, the general contractor follows the owner's mandate to select the TPL provider. The TPL provider plays the focal role in construction logistics coordination with supplier selection, material procurement, transportation, storage, and handling to the site. In large construction projects, the owner and/or the general contractor can select international suppliers who offer lower prices than local suppliers for purchasing materials but require large purchasing quantity. Thus, the use of TPL provider's central warehouse for the storage of purchased materials is an option for optimising the logistics costs. The TPL service is used to improve the professional in construction logistics since no expertise in logistics may be found in the owner’s project management team.

The above analyzes show that the material prices account for a large proportion in total SC cost, especially in the large project; thus, the price uncertainties can result in the significant increase in the total SC cost. This result supports the finding of Liu et al. (2017a) in researching the construction logistics cost for a large project. Thus, it is recommended to collaborate with a TPL partner to search for price discounts as well as reducing the price uncertainties offered by the suppliers. The above analyzes also reflect the impacts of uncertainties in delivery lead-time and daily demand on the storage cost. Thus, the construction managers are required to have suitable strategies to deal with the uncertainties to reduce the total SC cost.

Finally, the risk of failure in using the TPL provider can exist when the relevant actors, especially the general contractor, do not accept the role of the TPL as the logistics coordinator. Ekeskär and Rudberg (2016) report that the general contractor overlooks the TPL provider by not following agreements and regulations, which should be applied for logistics coordination. The general contractor even sends a message to the subcontractors that "the agreements and regulations concerning the TPL solution are not that important." Therefore, to apply the proposed model, the following recommendations are given to obtain optimal logistics plans:

- The construction owner has to commit the use of TPL partnership for the logistics activities. The general contractor and the construction owner have to respect the role of TPL provider as the SC coordinator and follow the regulations which are agreed for the logistics operations.
- Under the owner's mandate, the general contractor and the TPL select the suppliers and integrate the suppliers to the logistics processes.
- Based on the data provided by the TPL and the suppliers (prices, transportation costs, warehousing costs, capacity), the general contractor and the TPL organise formal meetings with subcontractors to create the optimal plan (based on the proposed model) as well as the regulations for logistics operations.

2.8 Conclusions

In this paper, we provide a conceptual insight and how to model the complexity of an integrated CSC with TPL partnership. The TPL partnership can be used as a strategic tool for improving construction site logistics since it supports CSC operations with the integration of relevant actors. Recently, the use of TPL provider has been considered as the business opportunity for the construction industry where many problems in logistics management exist. This paper presents a mixed-integer programming model for the optimization of CSC operations with the TPL partnership, in which we promote the role of TPL provider as the logistics coordinator. The proposed model aims to create the optimal logistics plan for material purchasing, transportation, and storage. The model has distinctive contributions since it supports the determination of the optimal solution for construction logistics under the considerations of material types and uncertainties in supply, demand, and price. The model is especially useful for the construction managers to take advantage of the TPL warehouse to obtain lower prices and transportation costs offered by suppliers. Using the numerical case example, we recognize that the proposed performs better in total SC cost in comparison with the CSC model without TPL. Hence, it is implied that the integrated CSC model with TPL partnership can be used to improve the construction logistics performance and deal with the practical requirements of the current issues in the construction industry.

The usage of TPL solution is still a new phenomenon in the construction industry; thus, the proposed model can encounter some limitations. The proposed model should be validated by further implications to show its efficiency since it is only applied for a single case in this study. Besides, the proposed model only focuses on the single objective of SC cost, while other objectives such as time or quality are not yet mentioned. Thus, a multi-objective optimization model can be developed for further research. Finally, further research can also be conducted to investigate the role of TPL in SC integration to improve the service level, SC sustainability, or technology adoption in the construction industry.

CHAPTER 3

BIM-BASED FRAMEWORK FOR TEMPORARY FACILITY LAYOUT PLANNING IN CONSTRUCTION SITE: A HYBRID APPROACH

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Abstract

Purpose - This paper proposes an innovative BIM-based framework for multi-objective and dynamic temporary construction site layout design (SLD), which uses a hybrid approach of systematic layout planning (SLP) and mathematical modeling. Design/methodology/approach - The hybrid approach, which follows a step-by-step process for site layout planning, is designed to facilitate both qualitative and quantitative data collection and processing. BIM (Building information modeling) platform is utilized to facilitate the determination of the required quantitative data while the qualitative data are generated through knowledge-based rules. Findings – The multi-objective layout model represents two important aspects: layout cost and adjacency score. The result shows that the model meets construction managers' requirements not only in saving cost but also in assuring the preferences of temporary facility relationships. This implies that the integration of SLP and mathematical layout modeling is an appropriate approach to deliver practical multi-objective site layout design solutions. Research implications - The proposed framework is expected to serve as a solution, for practical application, which takes the advantage of technologies in data collection and processing. Besides, this paper demonstrates, by using numerical experimentation and applying Microsoft Excel Solver for site layout optimization, how to reduce the complexity in mathematical programming for construction managers. Originality/value - The original contribution of this paper is the attempt of developing a framework in which all data used for the site layout modeling are collected and processed using a systematic approach, instead of being predetermined as in many previous studies.

Keywords: Construction site layout, BIM, Optimization, Cost modeling, Systematic layout planning, Knowledge-based reasoning.

3.1 Introduction

Construction site space is a limited resource which requires a reliable site layout to create smooth material and equipment flows; thereby enhancing the safety and effectiveness of construction project execution (Sadeghpour and Andayesh, 2015). The layout of temporary facilities in construction site has attracted many researchers during the last decades. These studies follow various approaches of time dimensions: static construction site layout design (SLD) (Zhang and Wang, 2008; Easa and Hossain, 2008; Lien and Cheng, 2012) versus dynamic construction SLD (Ning *et al.,* 2010; Xu and Li, 2012; Yahya and Saka, 2014). Dynamic layout planning improves static layout planning since it takes into account the progress of project execution through different phases of the construction project (El-Rayes and Said, 2009).

Research studies in construction SLD can be classified into two main dimensions: resolution techniques and technology support. The first dimension consists of two main streams: mathematical and knowledge-based techniques. Mathematical modeling techniques require the development of single or multiple objective functions and the related constraints that can be solved by exact or approximated algorithms. In contrast, knowledge-based techniques use expertise and information to create rules which support planners in generating site layouts (Osman et al., 2003). For the second dimension, recent technological advancements facilitate data collection and processing for SLD such as: CAD (computer-aided design), BIM (Building Information Modeling), and location-tracking systems (GIS – geographical information system; RFID – radio frequency identification) (Osman et al., 2003; Kumar and Cheng, 2015; Akanmu et al., 2016; Kumar and Bansal, 2018). Researchers have recently attempted to generate smart systems for dynamic site layouts; for example, integrating BIM-based design software and scheduling software to automate site layout plans (Said and El-Rayes, 2014; Kumar and Cheng, 2015), combining BIM with RFID system to detect real-time available locations for site layout automation (Akanmu et al., 2016). The concrete benefit of these technologies applied for SLD is to visualise the temporary site area for allocating relevant facilities that store materials or perform specific tasks effectively and safely (Sulankivi et al., 2009). Especially, when being integrated with a cloud-enabled network, the advanced technologies can leverage the usage and sharing of information for SLD among related participants (Park et al., 2017). This encourages a remote project manager to collect sufficient data and call for contributions from different participants for layout planning.

3.1.1 Need for actors' integration in SLD

The biggest challenge in SLD is to take into account various aspects simultaneously such as: the identification of locations and site boundary (Akanmu et al., 2016); the determination of required facilities based on project activities (Xu and Li, 2012); the consideration of facility sizes and other related constraints (RazaviAlavi and AbouRizk, 2017); the estimation of relative positions of each facility (Kumar and Cheng, 2015); and the time aspects of facility establishment and removal (Sadeghpour and Andayesh, 2015). These aspects are concurrently considered in order to improve the productivity of a site layout plan in terms of cost reduction or travel distance decrease. The other major factor impacting SLD is the adjacent relationship among facilities which is determined by key elements such as workflow, information flow, safety concerns, and personal preferences (Ning et al., 2010; Xu and Li, 2012). Since multi-objectives with various constraints need to be addressed for an efficient SLD, in order to approach the safe, smooth and low-cost flows of material and information in the site, SLD requires the expertise from different associated actors (Zolfagharian and Irizarry, 2014; Schwabe et al., 2019). Extensive understanding of various interdisciplinary sources (project schedule, resource allocation, material logistics, building geometry, and so on) contributes to a productive plan for temporary facility allocation. For instance, the designers' expertise is needed for the estimation of location distances and other information related to the building area and site boundary. The experiences of site engineers and project managers (from the general contractor and subcontractors) are valuable for the assessments of workflow, information flow, safety concerns, and personal preferences that affect the facility relationships in the construction site. Empirical evidences show that the productivity of SLD is significantly impacted by these actors' integration and their expertise used for the layout planning process (Sjøbakk and Skjelstad, 2015).

3.1.2 Need for BIM-based data collection and processing system in SLD

Among emerging technologies applied for construction SLD, BIM has been increasingly applied by scholars and practitioners due to its advantages. BIM is defined as an intelligent 3D model-based technology that supports architecture, engineering, and construction specialists with tools and data to improve the efficiency of construction planning, designing, constructing, and controlling (Azhar, 2011; Rowlinson, 2017). BIM models are considered as plentiful sources of data that can be used as inputs for SLD. Material and spatial data from BIM can be integrated with activity data from the project schedule, and related costs from financial budget to create an extended-BIM platform called 5D-BIM (Ding et al., 2014). These integrated data can be utilized for the temporary facility layout planning in construction sites which can automatically capture changes in design and construction operations (Kumar and Cheng, 2015).

Though the adoption of BIM in the construction industry is growing, during the phase of construction site layout planning, a very limited number of digitalised tools are available to support these multifarious tasks. The construction experts normally have very limited time to conduct their tasks, especially for the planning activity (Schwabe et al., 2019). Despite there is a need for actors' integration, the information applied to SLD is reserved in many organizations as internal knowledge. Lack of trust is also a big problem for enhancing BIM-based collaboration among various multidisciplinary actors (Cao et al., 2015). Therefore, it is necessary to facilitate a platform which supports the information sharing among the construction actors. Besides, although BIM leverages optimal conditions for the generation of building models, the SLD for temporary facilities is not totally supported due to the existing limitations of computer-based tools. For example, some of the required data for SLD (such as the material quantity of columns, walls or beams) can be extracted from the modeling software; however, other data (such as frequency of these materials or schedule data) require a custom design (Hammad et al., 2016a; Schwabe et al., 2019). Schedule data are stored in separate file and can be integrated with the building data in a 4D-BIM software. Similarly, material frequency between facilities can be calculated from BIM-based data and integrated into the database for SLD. Thus, it is suggested to develop an integrated data collection and processing system to generate the required data for SLD based on the data from BIM and other sources.

3.1.3 Need for a systematic approach in SLD

As mentioned above, a productive site layout plan of temporary facilities needs the actors' participation to deal with the multi-objective problems and a BIM-based platform that facilitates the data collection and processing from multiple sources. However, it is found that previous studies mostly assumed the quantitative data (location distances, material transportation frequencies, and related costs) used for SLD are quantitatively predetermined (Li and Love 1998; Zhang and Wang, 2008; Easa and Hossain, 2008; Lien and Cheng, 2012; Hammad et al., 2016b; Yi et al., 2018). Some studies use knowledge-based rules for qualitative evaluation of closeness rating, safety rating, and users' preference to create data for the layout planning (Elbeltagi and Hegazy, 2001; Ning et al., 2010; Xu and Li, 2012; Yahya and Saka, 2014; Schwabe et al., 2019). A few studies are found to use BIM as a platform for computation of quantitative data for SLD: calculating material flow frequencies between facilities (Hammad et al., 2016a); computing available interior storage space during different stages of the project (Kumar and Cheng, 2015). However, these studies have not provided a systematic procedure to create input data for all parameters in site layout models using BIM platform and knowledge-based reasoning.

Systematic layout planning (SLP) is a procedural method which is widely utilized to generate effective layouts for the facility arrangement in manufacturing and service sections (Flessas et al., 2015; Lin et al., 2015). This method systematically facilitates the application of knowledge-based rules for qualitative evaluation of relationships between facilities (Ali-Naqvi et al., 2016). However, to the best of the authors' knowledge, SLP has not been used for temporary facility layout planning in construction sites. Moreover, in SLD, construction managers normally select a final layout solution based on multi objectives (Hammad et al., 2016b). Some objectives, such as closeness rating or safety rating, can be achieved through qualitative analysis of facility relationships. Other objectives, such as productivity in SLD (cost or distance), can be optimized through mathematical modeling. Therefore, the combination of the two methods (SLP and mathematical layout planning) is expected as a great solution to respect construction managers' requirements (cost, safety, closeness, etc.) during the project execution. Thus, the main objective of this study is to answer the main research question: "How to integrate qualitative and quantitative measures for dynamic SLD with the usage of emerging BIM technology and knowledge-based rules?" Specifically, this paper focuses on developing a hybrid site layout framework in which a new systematic approach is used for modeling multi-objective dynamic SLD; collecting quantitative data with BIM and qualitative data with the expertise from construction managers; and solving the problem with the Excel-based evolutionary algorithm.

3.2 Literature review and contributions

3.2.1 Practical issues of SLD

In practice, site space in urban construction projects is a restricted resource which must be wisely utilised to deal with issues of approachability, safety and congestion (Kumar and Cheng, 2015). This study focuses on developing a BIM-based framework for SLD in order to solve multi-objective problems occurring in congested construction sites: data requirement (updated and correct data provision for practical site layouts), productivity (layout cost), and layout safety. Practically, site layout planning is dynamic (various facilities required for different construction stages) and complex (multi-objective needed to achieve in constraints of limited space in an urban area). Presently, dynamic SLD models are created on the required information: number and types of associated facilities, related costs, workflow, and construction stages (to identify required facilities for each stage) (Lien and Cheng, 2012; Xu and Li, 2012; Akanmu et al., 2016). One of the realistic requirements of SLD is data correction and update. However, such data in previous studies are mostly predetermined by planners and added to layout programs in manual. The manual determination of layout data may be significantly inefficient and incorrect, mainly when there are unexpected changes in project schedules (Kumar and Cheng, 2015). These changes should be updated automatically for SLD instead of being entered manually into layout software by planners. Thus, automation for data update is needed for a practical plan to eliminate errors and inefficiency causing by manual work as well as ease the use of layout plans for different stages and various projects (Said and El-Rayes, 2014). This can be feasible through developing a BIM-based framework which uses BIM models as rich sources of information to automate the data update for mathematical models in dynamic SLD.

The other practical requirements of SLD are cost optimization and safety insurance for congested sites (Xu and Li, 2012). In this study, the multi-objective mathematical model is developed to optimize the layout cost and improve the adjacency between facilities (including safety and environmental issues). In order to provide required data for the first objective (layout cost), information from BIM model and construction schedule are extracted to compute the material trip frequencies, location distances and identify temporary facilities required for different stages of the project. The use of BIM ensures that changes in design and construction are automatically updated to feed the SLD models and reduces the laborious work for planners (Akanmu et al., 2016). BIM implementation for providing inputs to mathematical models has been reported in previous studies (Inyim et al., 2015; Irizarry and Karan, 2012). Nevertheless, previous studies have mostly integrated BIM model and construction schedule for visualisation of construction process instead of using data for estimation and planning purposes (Hammad et al., 2016a).

For the second objective (adjacency between facilities), knowledge-based reasoning is applied to collect the data for the mathematical model. For this aspect, expertise from managers is used to evaluate adjacency scores between facilities based on the combined conditions of three aspects: workflows, safety/environmental concerns, and manager preferences. The usage of managers' expertise can improve the safety and reliability of SLD (Elbeltagi and Hegazy, 2001; Schwabe et al., 2019). As mentioned above, SLP is a procedural approach which can facilitate the application of knowledge-based reasoning to generate a practically efficient layout. However, SLP has not been adjusted to apply for temporary facility layout planning in construction sites. Therefore, this study constructs a BIM-based framework for SLD integrating SLP and mathematical layout planning in order to answer the detailed research questions:

- How to use information from BIM to calculate/estimate the required quantitative data (material trip frequency, location distances, and related costs) for the optimization of site layout cost?

- How to apply knowledge-based reasoning to collect the required qualitative data (workflows, safety/environmental concerns, and manager preferences) for the optimization of adjacency between temporary facilities?

3.2.2 Related works

Figure 3.1 presents the classification of some recent works in construction SLD based on the two main dimensions: resolution techniques (mathematical and knowledge-based techniques) and technology supports. In the stream of applying mathematical techniques, Li and Love (2000) minimize the total travelling distance between facilities by setting a static site layout model. The model uses a genetic algorithm (GA) to allocate temporary facilities to candidate locations. Papadaki and Chassiakos (2016) propose a new GA model to improve the site layout productivity by using the case of Li and Love (2000) to validate the proposed model. Easa and

Hossain (2008) present an exact optimization technique to find a global optimal solution for a static site layout with the consideration of many constraints. Lien and Cheng (2012) also propose a model for a static site layout using a hybrid approximated algorithm for single-objective optimization in allocating facilities to predetermined locations. El-Rayes and Said (2009) develop a robust model for dynamic SLD using approximate dynamic programming to minimize the total site layout costs. For multi-objective optimization in construction site layout, Hammad et al. (2016b) utilise the mixed integer nonlinear programming to minimize transport costs and noise levels at different surrounding receivers of the construction site. Abotaleb et al. (2016) develop a site layout model that takes into account the regular and irregular shapes of facilities, and imitates their dynamic behaviours to propose a realistic approach for problems in SLD. RazaviAlavi and AbouRizk (2017) propose a framework that enables the planners to consider both site layout variables (such as: size, location, and orientation of temporary facilities) and construction plan variables (for example: resources and material delivery plan), then concurrently optimize them in an integrated model. Hammad et al. (2017) propose several mixed integer programming (MIP) models to represent the site layout problems which cover the presence of travel barriers. These models leverage the optimization for reasonable-sized site layout problems within a realistic time frame. Yi et al. (2018) propose a mathematical model to deal with a large variety of practices which can be included in the model either as constraints or as a multi-objective function. In order to deal with problems of dynamic SLD for large scale projects, Hawarneh et al. (2019) use the site blocks algorithm and binary integer linear programming to optimize the site layout cost considering availability, overlapping, setup, dismantling, prohibited regions, and relocation constraints. The proposed model uses a grid system for SLD based on the safety proximity level between facilities. It is summarised that a large proportion of previous studies in SLD focuses on developing mathematical algorithms for the optimization of site layout models. Mathematical programming approaches usually transfer all design constraints and objectives into quantitative functions for being solved by algorithms. Mathematical layout approaches do not typically take into account managers' qualitative evaluations for generating reliable layouts, such as multi-attribute evaluations of relationships between facilities.

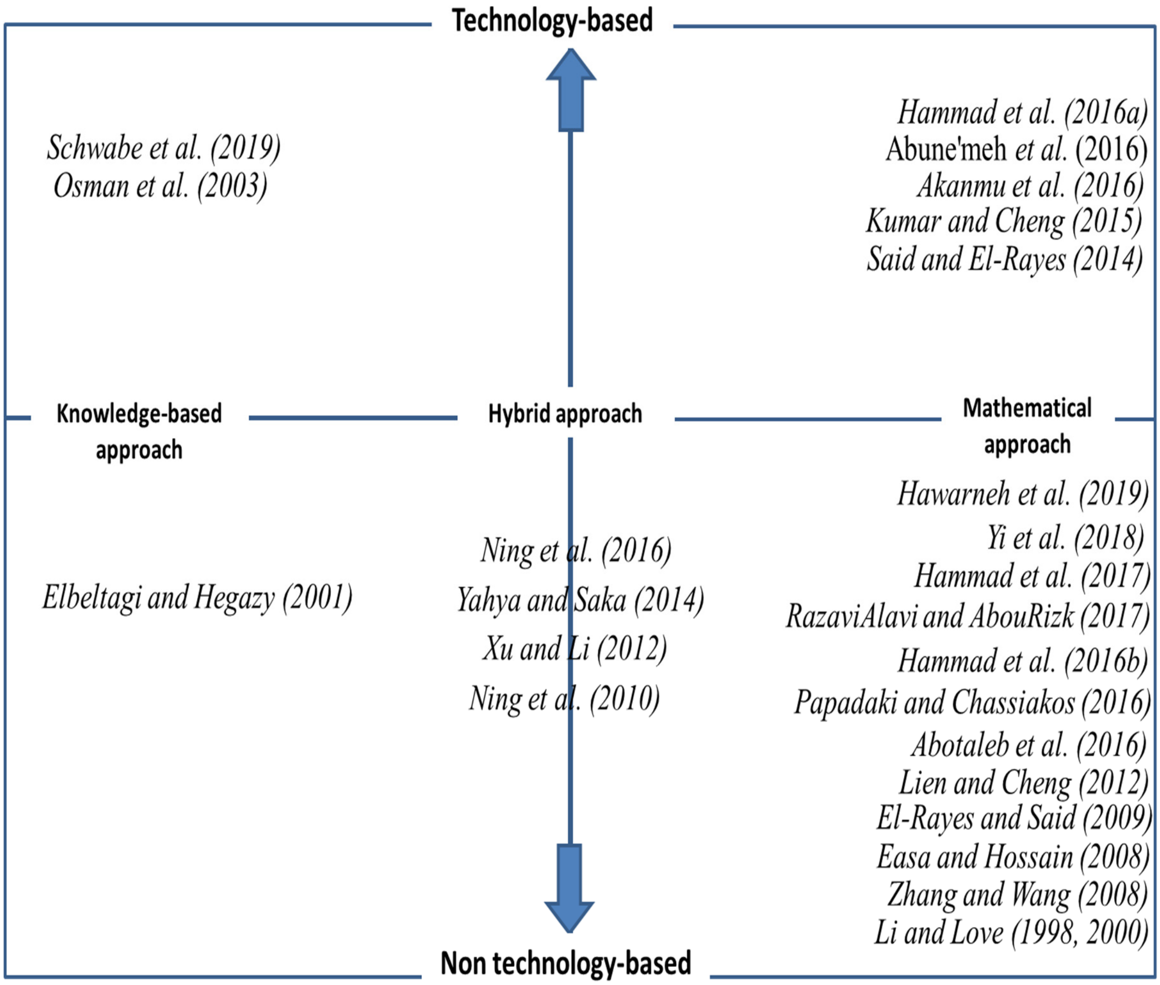


Figure 3.1 Sample of recent studies in site layout planning.

As mentioned above, the other aspects of SLD such as experts' assessments of facility relationships or the selection of the best solutions are normally ignored by the studies following mathematical programming approaches. Therefore, along with quantitative objectives (cost, distance, etc.), qualitative evaluations (closeness rating, safety rating, users' preference, etc.) given by managers should be integrated for an efficient site layout. Some researchers have tried to integrate knowledge-based techniques with mathematical techniques. Elbeltagi and Hegazy (2001) use an experience-based system to minimize the proximity weights among facilities. Ning et al. (2010) also create a fuzzy rule-based system to identify the facility closeness relationships which are determined by both quantitative factors (material flows, information flows, personnel flows, and equipment flows) and qualitative factors (safety/environment concerns, and users' preference). Using a similar approach, Xu and Li (2012) propose a multi-objective model for a dynamic site layout which minimizes the total transportation cost and maximizes the distances between high-risk facilities. Yahya and Saka (2014) use the project manager’s evaluations of proximity weights as input data for the multi-objective optimization of safety concerns and total transportation costs between facilities. Ning et al. (2016) construct a multi-attribute model for the evaluation and selection of site layout solutions based on expert’s knowledge reasoning. The model considers quantitative metrics such as cost and travel distance as objective functions, and qualitative issues such as the tie-in with external transportation or the safety as criteria for the layout selection.

Unlike the above mentioned studies, some researches take advantages of advanced technologies to create data collection platforms for the construction SLD. Osman et al. (2003) develop computer-aided design (CAD) platform to provide a visual observation for the layout planning which increases the layout productivity through minimising the “relative proximity weight”. These authors use “relative proximity weight” as an alternative parameter for transportation cost since the transportation cost is difficult to identify. Said and El-Rayes (2014) develop a framework which automates the extraction of project spatial and temporal data from the BIM platform and other integrated sources to minimize total logistics costs including site layout-related costs. Kumar and Cheng (2015) propose a framework for a dynamic SLD which uses BIM-based data to compute the required sizes and dimensions for facilities. The output data are then used by GA to find the optimal solution for the site layout. Akanmu et al. (2016) also combined BIM with RFID-RTLS system to detect available real-time locations for site layout automation. However, the RFID-RTLS application required heavy and expensive infrastructure to be installed in a construction site. Abune'meh et al. (2016) improve the SLD by developing a model that considers the hazard and vulnerability interactions among facilities. The study uses GIS to facilitate the visualisation and the analysis of spatial variability of risks within a construction site. Hammad et al. (2016a) integrate BIM and project schedule to generate quantitative data for the estimation of travel frequencies between facilities. The computation of the frequency parameter is performed by estimating the material quantity transported between different facilities to complete each scheduled activity. Song et al. (2017) propose a decision-making approach for SLD in large-scale projects to improve layout safety and cost. The fuzzy logic is employed to deal with uncertain factors in real-world situations. Besides, the knowledge-based system is developed to identify the temporary facilities and their areas. The proposed approach also uses GIS to facilitate the creation and analysis of spatial and non-spatial data. Kumar and Bansal (2018) apply GIS to allocate temporary facilities in the hilly construction site with the consideration of restricted areas, construction safety zones, and site topography. Schwabe et al. (2019) develop a rule-based model for checking the site layout planning tasks. The model retrieves data from BIM and uses the information within the rule engine. For geometry-associated rules, a solution approach called offset geometry is proposed to ensure the requirements of SLD such as the required safety distance between temporary facilities. The summary of the recent studies, as well as the comparison of this study's approach and other studies, are presented in **Table 3.1**.

Table 3.1 Summary of recent studies in construction site layout planning

Papers	**Time dimension**	**Objective function**	**Model**	**Data collection method**	**Solution approach**
Li and Love (2000)	Static	Single: DIS	Certain	Quantitative: predetermined	GA
Elbeltagi and Hegazy (2001)	Static	Single: PRO	Certain	Quantitative: predetermined; Qualitative: knowledge-based	GA
Osman *et al.* (2003)	Static	Single: PRO	Certain	Quantitative: CAD-based; Qualitative: knowledge-based	GA

Table 3.1 Summary of recent studies in construction site layout planning (continued)

Papers	**Time dimension**	**Objective function**	**Model**	**Data collection method**	**Solution approach**
Zhang and Wang (2008)	Static	Single: COS	Certain	Quantitative: predetermined	PSO
Easa and Hossain (2008)	Static	Single: DIS	Certain	Quantitative: predetermined	EO
El-Rayes and Said (2009)	Dynamic	Single: COS	Certain	Quantitative: predetermined	ADP
Ning *et al.* (2010)	Dynamic	Multi: COS and SAF	Certain	Quantitative: predetermined; Qualitative: knowledge-based	AC
Xu and Li (2012)	Dynamic	Multi: COS and SAF	Uncertain	Quantitative: predetermined; Qualitative: knowledge-based	PSO
Lien and Cheng (2012)	Static	Single: DIS	Certain	Quantitative: predetermined	PBA
Yahya and Saka (2014)	Dynamic	Multi: COS and SAF	Certain	Quantitative: predetermined; Qualitative: knowledge-based	BCA
Kumar and Cheng (2015)	Dynamic	Single: COS	Certain	Quantitative: BIM-based	GA
Hammad *et al.* (2016b)	Static	Multi: COS and NOP	Certain	Quantitative: predetermined	EO

Table 3.1 Summary of recent studies in construction site layout planning (continued)

Papers	**Time dimension**	**Objective function**	**Model**	**Data collection method**	**Solution approach**
Akanmu *et al.* (2016)	Dynamic	Single: COS	Certain	Quantitative: BIM-based	GA
Papadaki and Chassiakos (2016)	Static	Multi: COS and SAF	Certain	Quantitative: predetermined	GA
Abotaleb *et al.* (2016)	Dynamic	Multi: COS and PRO	Certain	Quantitative: predetermined	GA
Ning *et al.* (2016)	Static	Multiple attributes	Certain	Quantitative: predetermined; Qualitative: knowledge-based	FA
Abune'meh *et al.* (2016)	Static	Single: SAF	Certain	Quantitative: GIS-based	GA
Hammad *et al.* (2016a)	Static	Single: COS	Certain	Quantitative: BIM-based	EO
RazaviAlavi and AbouRizk (2017)	Static	Single: COS	Certain	Quantitative: predetermined	GA
Hammad *et al.* (2017)	Static	Single: DIS	Certain	Quantitative: predetermined	EO
Song *et al.* (2017)	Dynamic	Multi: COS and SAF	Uncertain	Quantitative: GIS-based; Qualitative: knowledge-based	GA

Table 3.1 Summary of recent studies in construction site layout planning (continued)

Papers	**Time dimension**	**Objective function**	**Model**	**Data collection method**	**Solution approach**
Yi *et al.* (2018)	Static	Multi: COS and SAF	Certain	Quantitative: predetermined	EO
Kumar and Bansal (2018)	Static	Single: SAF	Certain	Quantitative: GIS-based	NHT
Hawarneh *et al.* (2019)	Dynamic	Multi: COS and SAF	Certain	Quantitative: predetermined	EO
Schwabe *et al.* (2019)	Applied for both	Multiple rules	Certain	Quantitative: BIM-based; Qualitative: knowledge-based	RCA
This thesis	Dynamic	Multi: COS and ADJ	Certain	Quantitative: BIM-based; Qualitative: knowledge-based	EA

Notes:

Objective function *- DIS: Travelling distance, PRO: Proximity weight, COS: Cost, SAF: Safety, NOP: Noise pollution, ADJ: Adjacency score.*

Solution approach *- GA: Genetic algorithm, AC: Ant colony optimization, PSO: Particle swarm optimization, ADP: Approximated dynamic programming, PBA: Particle bee algorithm, BCA: Bee colony algorithm, FA: Fuzzy algorithm, EO: Exact optimization techniques, EA: Evolutionary algorithm, NHT: Non-heuristic technique, RCA: Rule-checking algorithms.*

3.2.3 Research gaps and objectives

As presented above, recent works of literature have attempted to apply various approaches (including mathematical-based, knowledge-based, and technology-based) to facilitate the optimization and the selection for temporary facility layouts. Despite their significant contributions to the knowledge body of SLD, the existing studies are found to have the following limitations:

- A large proportion of existing studies in SLD focus on developing mathematical algorithms for site layout models. However, these studies ignore how to collect and calculate the required quantitative data for the site layout models. Instead, they assume that quantitative data are predetermined by planners.

- A very limited number of studies is found to develop technology-based framework or model for SLD. However, these studies mostly apply the technologies to visualise the construction site and use the spatial data for SLD models. There still exists a lack of a systematic approach to leverage the technologies for the estimation of associated data (location distances, travel frequencies between facilities, etc.) and the integration of other data from multiple sources (costs from the financial budget, time-based data from project schedule, knowledge-based data from experts, etc.). These data from different sources are then used as the input for the optimization of multi-objective site layout models.

- Also, a very limited number of studies is found to take into account the usage of extensive knowledge from various interdisciplinary sources and the participation of various construction actors for SLD. Nevertheless, there is a lack of technology-based platform for data exchange and information sharing among the construction actors for the site layout planning and practice.

As mentioned in the previous sections, the expertise of relevant actors plays an important role in creating a productive and safe site layout. A well-known approach – SLP – has been used in many industries to develop step-by-step process for the layout planning which leverages the participation of relevant experts for the assessment of required parameters. SLP consists of three major stages which can be divided into further minor steps: (1) analysis, (2) research, and (3) selection (Tortorella and Fogliatto, 2008). For the first stage, the required data are collected and analyzed. It is usually that "From-to Chart" is used to present the transportation distances between facilities; whereas, "Relationship diagram" is deployed to show the managers' evaluation of relationships between facilities (Ali-Naqvi et al., 2016). Based on the established relationship diagram, the second stage is responsible for creating various layout alternatives which consider both criteria of logistics and non-logistics relationships between facilities. The final stage deals with choosing the best layout alternative based on selection criteria (Lin et al., 2015). The focus of SLP is the consideration of the relationships among all facilities in both terms of logistics and non-logistics. Logistics relationships can be measured by quantitative data such as workflow or trip frequencies among the facilities. Non-logistics relationships among the facilities require the assessments of managerial experts on many aspects such as safety, convenience, or preferences. Yet, SLP has limitations when the problem size increases. In manufacturing and service sections, SLP is broadly applied for small and medium scales (Flessas et al., 2015; Lin et al., 2015; Ali-Naqvi et al., 2016). In construction, in order to deal with the dynamic and complex characteristics of SLD, even for a large-scale project, SLP can be integrated with mathematical algorithms to solve multi-objective problems. Practically, SLD is short-term planning for construction executions on the site; thus, a large-scale project schedule can be separated into short-term phases based on the relations of construction activities. Therefore, in order to fill the research gaps as well as meet the practical requirements of site layout issues, this paper aims at the following objectives:

- Objective 1: Proposing a systematic approach which combines both SLP and mathematical layout modeling to solve the multi-objective problems in SLD. The approach consists of a step-by-step procedure which details how to achieve the site layout optimization and selection.

- Objective 2: Developing a BIM-based data collection and processing system which enables the data extraction and integration from various sources (quantitative data from BIM, project schedule and cost budget; qualitative data from the expertise of related actors). The system facilitates the creation of BIM-based database which can be updated and shared among the construction actors.

- Objective 3: Detailing the calculation and the integration of all necessary data (location distances, trip frequencies between facilities, layout costs, project schedule, and actors' assessments of facility relationships) used for the optimization of the site layout model.

3.2.4 Research contributions

As proven in the reviewed literature, previous studies in SLD have not paid attention to create a systematic approach that directs the integration of knowledge-based rules and mathematical modeling by using BIM as a data source. Thus, the objective of this paper is to develop a hybrid site layout framework to solve the multi-objective problem of layout costs and adjacency scores. The contribution of this study is on three aspects:

- Firstly, a novel data collection approach is proposed with the applications of (i) 5D BIM-based platform (3D modeling, related costs, and project schedule) to provide quantitative data for the site layout; (ii) Knowledge-based rules to facilitate the managers' evaluations to create qualitative data; and (iii) Cloud-enabled BIM network to communicate the contextual data between the construction participants.

- Secondly, a hybrid resolution approach, which combines SLP and mathematical layout planning is applied to facilitate both quantitative and qualitative data for creating the site layout following a structural step-by-step procedure.

- Thirdly, the multi-objective dynamic site layout problem is modelled as QAP (Quadratic Assignment Problem) and optimized by the evolutionary algorithm (EA) provided by Microsoft Excel Solver.

3.3 Methodology: a hybrid site layout framework

This section presents a methodology that covers three above-mentioned objectives: (1) proposing a hybrid site layout framework which presents a systematic site layout approach to solve the multi-objective problems for SLD; (2) developing a BIM-based data collection and processing system which enables the data extraction and integration from various sources as well as facilitates the data update and sharing among the relevant actors; (3) detailing the computation and integration of all necessary data for SLD. The proposed approach is to deal with the practical issues of SLD mentioned in the above literature: requirements for the correct and updated data for SLD; and multi-objectives are needed to achieve for SLD.

In specific, the systematic hybrid layout approach utilises the integration of systematic and mathematical layout methods, follows a step-by-step process. Required data are collected by a system that integrates the advanced technologies (BIM software and cloud-enabled platform) with the knowledge-based reasoning.

3.3.1 Hybrid site layout framework

This section illustrates how research objective 1 is achieved in details. **Figure 3. 2** presents the hybrid framework, for construction SLD, which includes four main components: systematic layout process, input data, output data, and mathematical programming.

Systematic site layout process: Systematic layout planning (SLP) is procedural layout method, which facilitates knowledge-based rules for data creation and analysis. In this study, the systematic site layout process consists of six steps:

- Overall analysis: At the first step, overall status of the construction site and relevant resources is presented as a base for further analysis in the next steps. Using the input database, the overall analysis is conducted to provide the basic requisite data: focused areas for the site layout, required facilities for each construction phase, and layout-related costs (transportation cost between facilities and facility setup cost).
- Material flow analysis: The material flows are analyzed to identify the material trip frequencies among facilities required for each construction phase. The "from-to chart" is used to present the material trip frequencies. The method for computing the trip frequencies between facilities is described in the below section of data collection and processing system.
- Facility relationship analysis: In this step, knowledge-based rules for the determination of closeness ratings between the facilities are used to evaluate the facility relationship. The closeness ratings are identified based on the combined rules of workflows, safety/environmental concerns, and manager preferences.
- Space analysis: For each construction phase, the space analysis is required to address the number of available locations in the layout area and distances among the locations. In this step, the input data provided by the data collection system are used to obtain the necessary outputs for the temporary layout planning in construction site.
- Layout optimization: The output data of the four above steps are used for the mathematical modeling of a multi-objective site layout problem. This step aims to search for optimized alternatives for the allocation of temporary facilities to the available locations in construction site. The optimization models for site layout planning can be found in previous studies such as: Li and Love (2000), Xu and Li (2012), Lien and Cheng (2012), Kumar and Cheng (2015), Papadaki and Chassiakos (2016), Hammad *et al.* (2017), Yi *et al.* (2018), or Hawarneh *et al.* (2019).

- Layout selection: A multi-objective optimization creates the Pareto frontier (a set of non-dominated layout alternatives). Thus, in this step, the project manager is required to select a final layout solution for the temporary facilities which is determined on the manager's preferences. In this study, the trade-off between two objectives: layout cost and adjacency score is considered for the final selection. The first objective represents the productivity of the site layout solution while the second objective takes into account safety and environmental concerns of site layout solutions.

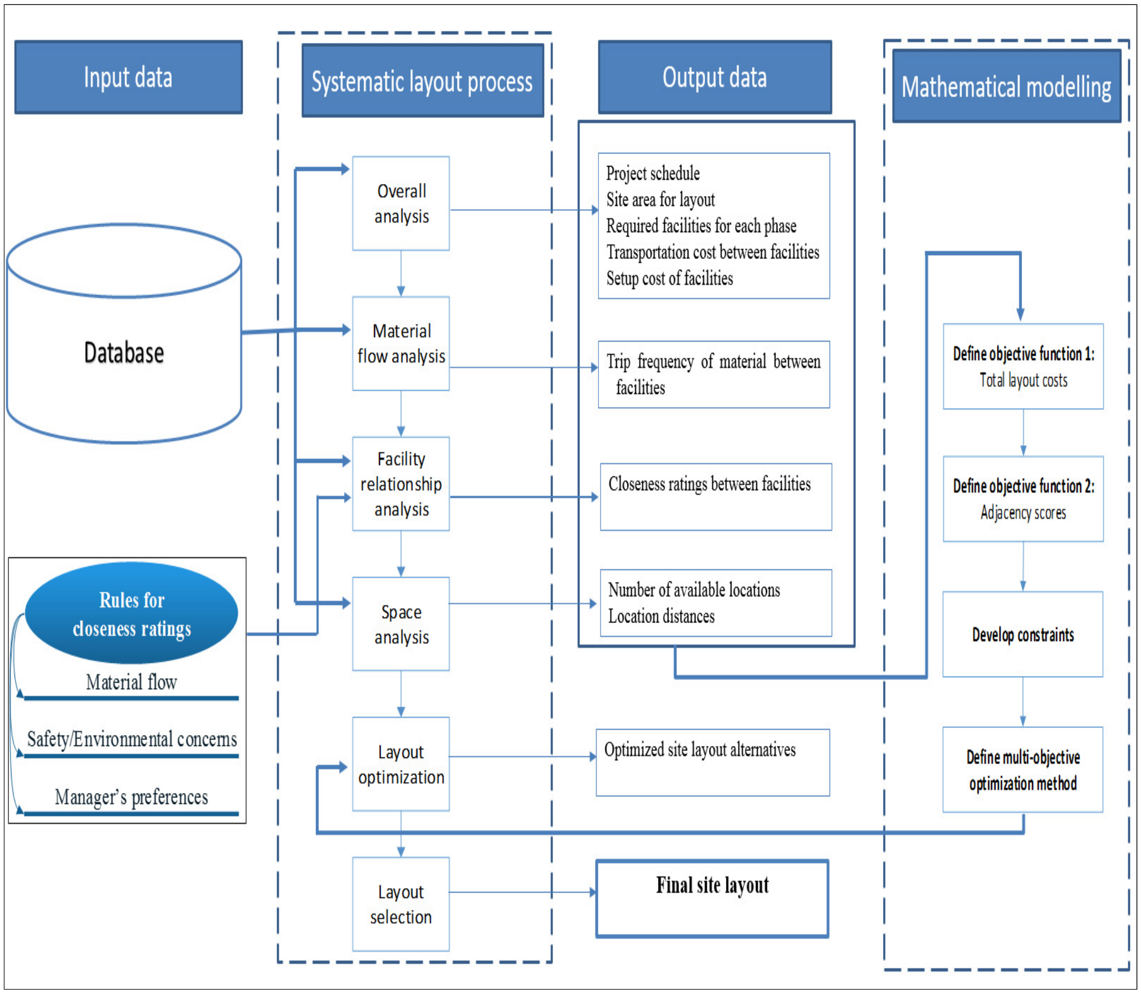


Figure 3.2 Hybrid framework for construction site layout planning.

Input data: The input data for systematic site layout process are provided by the database and the knowledge-based rules.

- Database: The database is created by the integrated data collection system using BIM software and cloud-enabled platform. Details of the database generation are clarified in the next section of the data collection and processing system.
- Knowledge-based rules for closeness ratings: Rules for closeness ratings between two facilities are generated on the combined conditions of three aspects: workflows, safety/environmental concerns, and manager preferences. The work flows represent the logistic relationships among facilities and embrace total material trip, equipment, personnel, and information flows. The non-logistic relationships among the facilities are presented by the safety/environmental issues that determine whether two facilities should be close to each other under the considerations of accidents, noise, undesirable temperature, and pollution. Managers' preferences reflect the desires of a project manager to allocate the two facilities close to each other due to the convenience of cooperation, the convenience of supervision, and/or ease of contact, even when there exists a low or no work flow between them. The closeness ratings are qualitatively identified through five levels: absolutely necessary (A), especially important (E), important (I), ordinarily close (O), and unimportant (U). In accordance with those five levels of closeness ratings, five-point scale for adjacency scores are identified: A (5), E (4), I (3), O (2), and U (1). **Table 3.2** presents the rules for the evaluation of closeness ratings between two facilities in construction site.

Output data: The output data of each step of the systematic site layout process are presented in **Figure 3.2.** Outputs of the first four steps are used as inputs for the mathematical modeling of the site layout problem. Whereas, outputs of the last two steps are used to determine the appropriate site layout solution.

Mathematical modeling: The mathematical modeling consists of the components: defining objective functions (total layout costs and adjacency scores), developing constraints, and defining the multi-objective optimization method (Yi *et al.*, 2018). The below section of problem formulation and optimization presents the detail of the site layout mathematical modeling which uses the ε-constraint method, and evolutionary algorithms executed by Microsoft Excel Solver.

Table 3.2 Rules for closeness rating evaluations between two facilities (Adapted from: Elbeltagi and Hegazy, 2001)

Condition	**Work flow**	**Safety/environmental issues**	**Manager's preference**	**Closeness rating**
A	Low (*L*)	Low (*L*)	Low (*L*)	Ordinary (*O*)
B	Low (*L*)	Low (*L*)	Medium (*M*)	Important (*I*)
C	Low (*L*)	Low (*L*)	High (*H*)	Especially important (*E*)
D	Low (*L*)	Medium (*M*)	Low (*L*)	Unimportant (*U*)
E	Low (*L*)	Medium (*M*)	Medium (*M*)	Ordinary (*O*)
F	Low (*L*)	Medium (*M*)	High (*H*)	Important (*I*)
G	Low (*L*)	High (*H*)	Low (*L*)	Unimportant (*U*)
H	Low (*L*)	High (*H*)	Medium (*M*)	Unimportant (*U*)
I	Low (*L*)	High (*H*)	High (*H*)	Ordinary (*O*)
J	Medium (*M*)	Low (*L*)	Low (*L*)	Important (*I*)
K	Medium (*M*)	Low (*L*)	Medium (*M*)	Especially important (*E*)
L	Medium (*M*)	Low (*L*)	High (*H*)	Absolutely important (*A*)
M	Medium (*M*)	Medium (*M*)	Low (*L*)	Ordinary (*O*)
N	Medium (*M*)	Medium (*M*)	Medium (*M*)	Important (*I*)
O	Medium (*M*)	Medium (*M*)	High (*H*)	Especially important (*E*)
P	Medium (*M*)	High (*H*)	Low (*L*)	Unimportant (*U*)
Q	Medium (*M*)	High (*H*)	Medium (*M*)	Ordinary (*O*)
R	Medium (*M*)	High (*H*)	High (*H*)	Important (*I*)
S	High (*H*)	Low (*L*)	Low (*L*)	Especially important (*E*)
T	High (*H*)	Low (*L*)	Medium (*M*)	Absolutely important (*A*)
U	High (*H*)	Low (*L*)	High (*H*)	Absolutely important (*A*)
V	High (*H*)	Medium (*M*)	Low (*L*)	Important (*I*)
W	High (*H*)	Medium (*M*)	Medium (*M*)	Especially important (*E*)
X	High (*H*)	Medium (*M*)	High (*H*)	Absolutely important (*A*)
Y	High (*H*)	High (*H*)	Low (*L*)	Ordinary (*O*)
Z	High (*H*)	High (*H*)	Medium(*M*)	Important (*I*)
AA	High (*H*)	High (*H*)	High (*H*)	Especially important (*E*)

3.3.2 Integrated data collection and processing system

This section presents the method to obtain the ***research objectives 2 and 3*** in details. For the ***research objective 2***, in order to create the BIM-enabled database for the above-mentioned systematic site layout process, an integrated data collection and processing system is proposed as shown in **Figure 3.3**. The system comprises five modules: (1) Data collection, (2) Data sharing, (3) Data processing, (4) Data storage, and (5) Systematically dynamic site layout. The details for the calculation and the integration of all required data for site layout planning are also presented to achieve the ***research objective 3***.

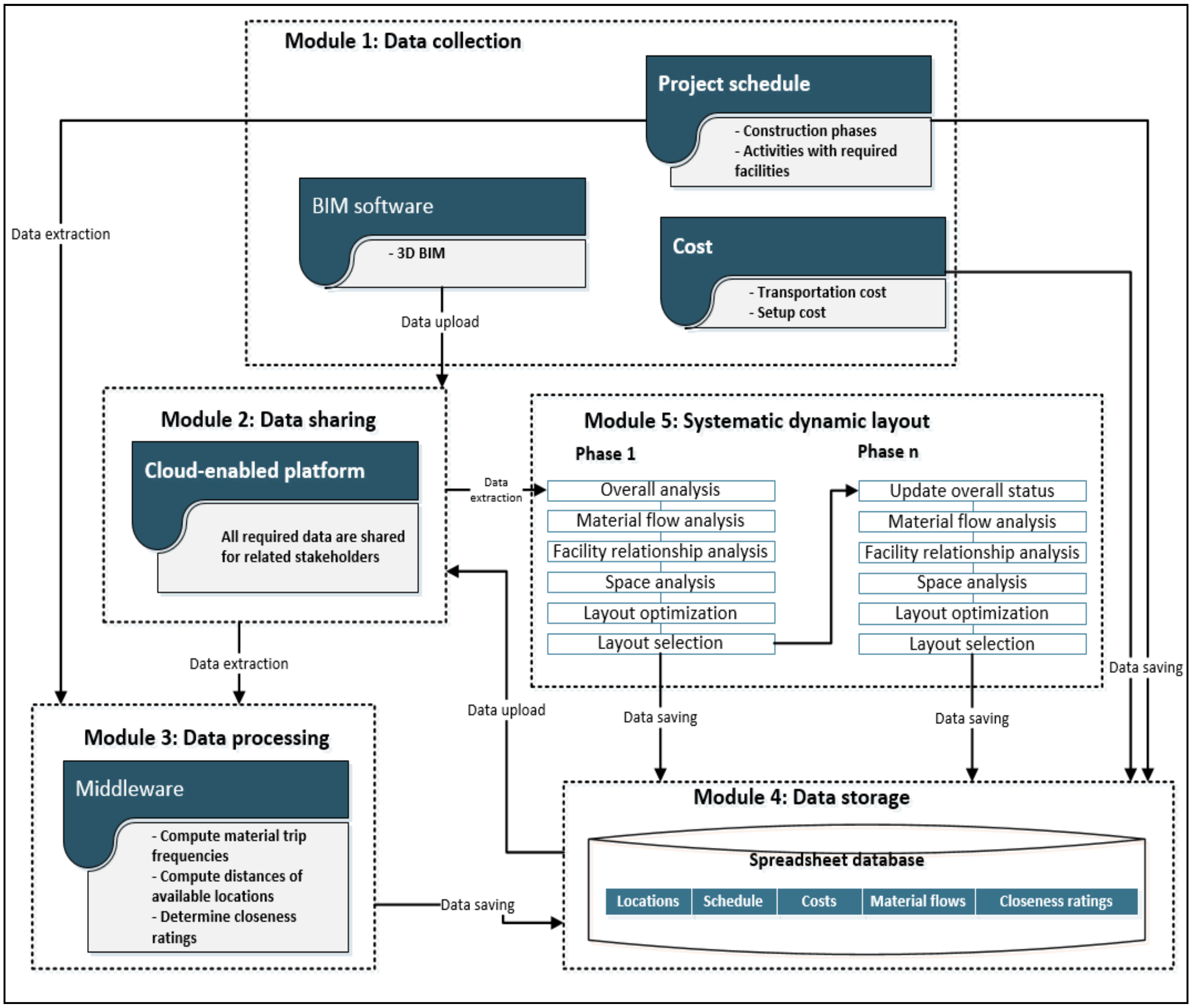


Figure 3.3 The integrated data collection and processing system.

Module 1 - Data collection encompasses three components: BIM software, cost, and project schedule.

- BIM software: Autodesk Revit is used as BIM software to provide building data for the temporary facility allocation in construction site. BIM provides the geometric data (site layout area: boundaries and location coordinates) as initial inputs to compute the distances between the available locations for the facility allocation in each construction phase (Kumar and Cheng, 2015; Akanmu *et al.,* 2016). BIM model also includes the main tasks of the building construction and related material quantities which are essential for the middleware to determine material flows between facilities (Hammad *et al.,* 2016a). The BIM-based data are shared onto the cloud-enabled network that can be accessed by related construction stakeholders.
- Project schedule: is prepared by Microsoft Project and saved into the database. The project schedule enables a manager to divide the construction project into phases and identify the activities with required facilities for each phase. Each construction phase aims at a clear milestone which is performed by a set of activities in construction site. These data are also required to compute material flows between facilities in each construction phase.
- Cost: The project manager tabulates the site layout-related costs (material transportation cost between facilities and facility setup cost) and inserted into the database. Typically, these costs are not included in the BIM models; thus, the project manager has to estimate these costs based on the historical data of previous projects. Then, the cost estimations are integrated into BIM models as input data for the site layout planning procedure.

Module 2 - Data sharing: The cloud-enabled platform is established to leverage the data sharing among the construction participants. It plays an essential role as a data center which provides input data for the systematic layout process and shares the optimal layout solutions to the relevant stakeholders. This cloud-based platform does share not only the BIM data, but also all other data required for the site layout process which are updated from the spreadsheet database. The emerging cloud-based BIM technology is considered as an efficient tool that enables higher levels of cooperation and collaboration, as well as facilitates an effective real-time communication platform for network participants (Wong *et al.,* 2014). Through a cloud-enabled network, a remote project manager can collect sufficient data for creating and updating site layout solutions at any time.

Module 3 - Data processing: Through a middleware using VBA (Visual Basic) programming, Excel-based macros are designed to extract and process the data. The middleware is responsible for computing: (1) material trip frequencies between facilities, (2) distances of available locations ($j \in N$), and (3) closeness ratings between facilities.

- Material trip frequencies between facilities: are computed through the following steps:
    - Step (i) - Identify quantity of materials: For this step, data from 3D BIM and project schedule are used to identify the quantity of materials required for each construction phase (Q_{ikt}). An Excel-based macro programmed by VBA is utilized to extract the construction activities from the project schedule and link them with corresponding components in BIM. Based on the bill of materials, the quantity of materials used for the component is identified. For instance, the column needs the two materials: concrete and rebar. A pair of relevant facilities is assigned to each activity based on the movement of the material required for this activity. Each activity is given a code to facilitate the extraction of the related components. For example, the activity "L1 – Column 001 – Rebar" is linked to the component "Column 001" in BIM model which uses the material "Rebar". Thus, for this activity, the quantity of rebar is needed to calculate for its transportation from facility i to facility k. Using Autodesk Revit API (Application Programming Interface), as the BIM data interface, VBA macro is developed to extract and tabulate the material quantities.
    - Step (ii) - Identify capacity of transportation modes: The material handling between temporary facilities is usually performed by the transportation modes: semitrailer, drop-side truck, and concrete mixer. For each activity identified in the step (i), it is required to define a transportation mode for material handling. The capacity of each transportation mode, which represents the volume of gross materials loaded by the

mode, is provided to estimate the transportation frequencies between the temporary facilities.

  - Step (iii) - Compute the material trip frequencies between facilities: The material travelling frequency between temporary facilities by each corresponding activity is computed using equation (1). In which, F_{ikt} represents the material trip frequency between facility (*i)* and facility (*k)* during construction phase (*t*), Q_{ikt} represents the material quantity transported between facility (*i*) and facility (*k*) during construction phase (*t*), and c_m represents the capacity of transportation mode (*m*). All frequencies between the same pairs of facilities are summed up and matrixed as input data for the mathematical model.

$$F_{ikt} = \frac{Q_{ikt}}{c_m} \quad (3.1)$$

- Distances of available locations: a VBA macro is developed to extract the coordinates of the available locations provided by BIM model to calculate the distances between the locations and insert them into a matrix to be input parameters of the optimization model.
- Closeness ratings between facilities: Based on the rules for closeness rating evaluations (see **Table 3.2**), a VBA macro is used to identify the closeness ratings between the facilities, and then utilises the relationship diagrams to display them as input data for the mathematical model.

Module 4 - Data storage: The related data of cost (transportation cost and setup cost) and project schedule (construction phases and activities with required facilities) are prepared and tabulated by the project manager and saved into the database in forms of the spreadsheet. Besides, the processed data (material trip frequencies, location distances, and closeness ratings) from the middleware and the layout solutions are also saved in the spreadsheet database. Each type of data is tabulated and saved in the database with an Excel-based macro which enables the computation for the data update. All the data are then uploaded into the cloud-enabled platform for the data sharing.

Module 5 - Systematically dynamic site layout: The step-by-step systematic site layout process is detailed in the previous section. This process uses the input data shared by the cloud-enabled platform which facilitates a project manager to proceed the site layout at any time and place. At the beginning of the first phase, the project manager is required to make an overall analysis of the construction site. The analysis calls for checking the project schedule and required resources to consider changes in the planned schedule and the actual progress schedule. After all, changes are captured, the site status is updated for the systematic layout process. Once the layout selection for the first phase is determined, the data are updated to continue the process of finding layout solutions for the next phase.

3.4 Problem formulation and optimization

This section presents how the mathematical modeling for the site layout problems is performed. It accounts for the detailed illustration of the step "Layout optimization" of the systematic site layout process presented in the previous section. This section correspondingly details how the optimization for the model is conducted in Excel-based spreadsheet. These detailed descriptions also contribute to the achievement of the ***research objective 3***.

3.4.1 Site layout assumptions

Site layout problem in construction can be modelled as a Quadratic Assignment Problem (QAP), which optimizes the allocation of a set of n facilities to an equal set of n locations. QAP site layout has the constraint in which each facility is allocated to only one location, and each location must contain only one facility. In case of the allocation of m facilities to n locations ($m < n$), $n-m$ dummy facilities are assigned with the total cost of zero (Drezner, 2005). QAP has been utilised for mathematical modeling of site layout problems by many studies (Li and Love, 1998; Xu and Li, 2012; Akanmu *et al.,* 2016). Tasks of a construction project can be divided into t phases due to their relevance in scheduling and facility requirements. The number of location (N) is static for the whole project while the number of facilities (M_t) changes across each construction phase (Xu and Li, 2012). For instance, in this study, the temporary facilities are allocated to 11 available locations in the construction site of a project which is divided into 3 phases. For phase I, the layout problem is the allocation of 9 facilities to 11 locations. For phase II, the layout problem is the allocation of 8 facilities to 11 locations. For phase III, the layout problem is the allocation of 8 facilities to 11 locations. The allocation of an unstable number of facilities to a certain number of locations in a construction site creates a problem called dynamic site layout. In this study, the two objectives are set for the dynamic site layout. The first objective (**F_1**) is to minimize the site layout cost which includes the material handling cost and facility setup cost. The material handling cost is the cost of transporting materials from a facility to another related facility. To calculate the material handling cost, it requires the following data: frequency of trips between facilities; distances between locations; and transportation cost between facilities. The facility set-up cost is the cost of arranging facilities in the construction site. The second objective (**F_2**) is to maximize the total adjacency score among facilities required for the site layout. Adjacency scores are identified on closeness ratings which are qualitatively evaluated by the construction managers. The ratings are based on the criteria which exist among facilities: material flows, safety/environmental concerns, and manager's preferences.

In this thesis, construction site layout planning is delimited as tactical planning which arranges a set of temporary facilities on the site in order to satisfy the constraints and optimize layout objectives (Xu and Li, 2012; Kumar and Cheng, 2015). This thesis aims to generate initial site layouts for different construction phases. Thus, site managers can base on these initial layouts for their further operations on the site. Although the proposed BIM-based data collection system can support managers to automate the data updating of changes which could lead to changes in site layout practice, the scope of this thesis does not include the re-planning for day-to-day activities. Similar to many previous studies (Li and Love, 2000; Xu and Li, 2012; Kumar and Cheng, 2015; Akanmu *et al.,* 2016), this study focuses on the assignment of appropriate site locations for temporary facilities such as warehouses, site offices, workshops, and batch plants. Therefore, other issues such as the arrangement of tower crane are also out of the study focus. The methodology mentioned above aims at solving the practical issues of site layout planning which involves multiple sources: the scheduling of activities, the location consideration, and the managers' expertise (experience, trial and error, insight, preference, common sense and intuition). In order to model the dynamic construction site layout planning problem, the following assumptions are considered:

- All the available locations for the assignment of temporary facilities are determined.
- For each construction phase, the number of facilities (M_t) is smaller than (or equal to) the number of available locations (N).
- Different facilities are assigned to locations with different set-up costs.
- All relevant costs and BIM-based data are available to be extracted and computed.
- The evaluation of facility relationships (safety, environmental issues and preferences) is subjective to managers' expertise and reliable for site layout planning.

3.4.2 Notations:

Sets and indices:	
T	: Set of construction phases, indexed by *t*
M_t	: Set of temporary facilities at phase *t*, indexed by *i* and *k*
N	: Set of locations, indexed by *j* and *l*
BIM-based parameters:	
F_{ikt}	: Trip frequency between facilities *i* and *k* during phase *t*
d_{jlt}	: Distance between locations *j* and *l* during phase *t*
Non-BIM parameters (Historical or estimated data)	
C_{ikt}	: Unit transportation cost between facilities *i* and *k* during phase *t*
S_i	: Setup cost of facility *i*
Knowledge-based parameter:	
θ_{ikt}	: Adjacency score between facilities *i* and *k* during phase *t*
Decision variables:	
X_{ijt}, X_{klt}	: Binary decision variables indicating facilities *i, k* allocated to locations *j, l* during phase *t* ($i \neq k$, $j \neq l$)

3.4.3 Site layout modeling

If two facilities *i* and *k* are respectively allocated to two locations *j* and *l*, then during phase *t*, materials are transported between the two facilities *i* and *k* with a frequency of F_{ikt} through a distance and unit transportation cost of d_{jlt} and C_{ikt} respectively, the material handling cost is identified by $F_{ikt}\ d_{jlt} C_{ikt} X_{ijt} X_{klt}$. Whenever a facility *i* is set up in any location *j* during the phase *t*, a setup cost is calculated by $S_i\ X_{ijt}$. Similarly, if θ_{ikt} represents the adjacency score between two facilities *i* and *k* during phase *t,* the total adjacency score is presented by θ_{ikt} $d_{jlt} X_{ijt} X_{klt}$. Thus, the multi-objective function is mathematically formulated as the following QAP:

$$\text{Minimize}\quad \text{F}_1 = \sum_{t=1}^{T}\sum_{i=1}^{M_t}\sum_{k=1}^{M_t}\sum_{j=1}^{N}\sum_{l=1}^{N} F_{ikt} d_{jlt} C_{ikt} X_{ijt} X_{klt} + \sum_{t=1}^{T}\sum_{i=1}^{M_t}\sum_{j=1}^{N} S_i X_{ijt} \quad (3.2)$$

$$\text{Maximize}\quad \text{F}_2 = \sum_{t=1}^{T}\sum_{i=1}^{M_t}\sum_{k=1}^{M_t}\sum_{j=1}^{N}\sum_{l=1}^{N} \theta_{ikt} d_{jlt} X_{ijt} X_{klt} \quad (3.3)$$

Subject to:

$$\sum_{i=1}^{N} X_{ijt} = 1,\ \forall j \in N; \forall t \in T \quad (3.4)$$

$$\sum_{l=1}^{M_t} X_{klt} = 1,\ \forall k \in M_t; \forall t \in T \quad (3.5)$$

$$\theta_{ikt} = \begin{cases} \theta_{ikt} & if\ facility\ i\ is\ adjacent\ to\ \ k\ at\ different\ levels \\ 0; & otherwise \end{cases} \quad (3.6)$$

Equation (3.2) represents the total layout cost including two components: material handling cost and set-up cost for each phase of the construction project. **Equation (3.3)** articulates the total adjacency score among all facilities in each phase of the project. **Equations (3.4) – (3.5)** ensure the constraints in which each facility is allocated to only one location, and each location contains only one facility. **Equation (3.6)** shows the evaluation of adjacency scores with different levels: absolutely necessary = 5, especially important = 4, important = 3, ordinarily close = 2, unimportant = 1.

In previous sections, the systematic layout process and the data collection system are detailed to prepare for the site layout optimization presented in this section. As stated in **Figure 3.1**, the data inputs for the site layout model consist of the quantitative data (BIM-enabled database) and the qualitative data (knowledge-based rules for closeness ratings). These data, which are extracted and stored in the spreadsheet database (presented in **Figure 3.2**), include: location distances, project schedule, related costs, material trip frequencies, and closeness ratings. These data are required to solve the mathematical layout problems presented by **equations (3.2) – (3.6)**. The first objective of the layout model (**equation 3.2**), which is to minimize the layout cost, needs the data of material trip frequencies (denoted by F_{ikt}), location distances (denoted by d_{jlt}), unit transportation cost (denoted by C_{ikt}), and facility setup cost (denoted by S_i). The second objective of the layout model (**equation 3.3**), which is to maximize the adjacency score between the facilities, requires the data of location distances (denoted by d_{jlt}), and closeness ratings (denoted by θ_{ikt}). The closeness ratings are determined by actors' evaluation of facility relationships based on the rules shown in **Table 3.1**, and receive the scores at different levels as presented in **equation (3.6)**. The project schedule data are used to identify the set of construction phases (indexed by t), and the required facilities for each phase (indexed by i and k).

3.4.4 Multi-objective optimization: the ε-constraint method

The ε-constraint method is used to reformulate a multi-objective optimization problem into a single-objective optimization problem. ε-constraint method bases on the idea that one of the objectives is kept and the other objectives are constrained by values identified by users. Thus, the optimization model of this study is reformulated as the below statement:

$$\begin{array}{lcl} \text{Minimize } F_1 \text{ (a)} & & \text{Minimize } F_1 \text{ (a)} \\ \text{Maximize } F_2 \text{ (b)} & \longrightarrow & \text{Subject to: } F_2 \geq \boldsymbol{\varepsilon}^* \text{ (b),} \\ \text{Subject to: (c), (d), (e), (f)} & & \text{(c), (d), (e), (f)} \end{array} \tag{3.7}$$

$\boldsymbol{\varepsilon}^*$ is the optimal value of F_2 when this objective is considered as the single-objective function. The constraint $F_2 \geq \boldsymbol{\varepsilon}^*$ is formed to ensure that the maximum value of F_2 is retained or improved during the optimization process for the objective function F_1 is running. This reflects the user's perspective in which the optimal value of F_2 is highly important and should be retained. In case, the user sets a high priority for the optimal value of the objective function F_1, the model can be reset (where $\boldsymbol{\varepsilon}^{**}$ is the optimal value of F_1 when this objective is considered as the single-objective function). In this study, $\boldsymbol{\varepsilon}$-constraint method is also applied to identify an approximate Pareto-frontier for the two objectives. Hammad *et al.* (2016b) used the same approach to generate the Pareto cuts for a multi-objective problem.

3.4.5 Solution approach

QAP site layout optimization with Microsoft Excel: QAP can be solved by some soft-wares which support the optimal calculation with mathematical algorithms. However, these soft-wares require much mathematical programming or coding. Besides, regarding optimization techniques, QAP can be solved by both exact algorithms and approximated algorithms. Exact algorithms can obtain the globally optimal solutions; yet, the drawback of exact algorithms is that the challenge increases exponentially in complexity with the increase in problem size. Thus, exact algorithms have been recently replaced with approximated algorithms such as meta-heuristics (Evolutionary algorithm, Tabu search, Simulated annealing, and so on) to achieve the efficiency and the computational practicability for larger layout problems (Sadeghpour and Andayesh, 2015; Yi *et al.,* 2018). In this study, evolutionary algorithm provided by Microsoft Excel Solver is used to solve the multi-objective site layout problem. If it calls $FC_{ikt} = F_{ikt}C_{ikt}$, Equations (3.2) and (3.3) can be represented more simply in Excel-based spreadsheet as the following formulas (Rasmussen, 2007):

$$\text{Minimize } F_1 = \frac{tr[(FC \bullet X)(X \bullet D)^T] + (S \bullet X)}{2} \quad (3.8)$$

$$\text{Maximize } F_2 = \frac{tr[(\theta \bullet X)(X \bullet D)^T]}{2} \quad (3.9)$$

In Equation (3.8), [FC• X] is the matrix created by multiplying matrixes FC and X, and [X• D]T is the transposed matrix created by multiplying matrixes X and D. Then, matrix [FC• X] is multiplied by the matrix [X• D]T. Finally, the produced matrix is traced (tr: the sum of the elements in the diagonal). The similar application is done for Equation (3.9). Since, in Microsoft Excel, there is no function to calculate the trace of a matrix, a dummy matrix T with suitable dimension is created in the spreadsheet. Then, the trace is computed by using SUMPRODUCT function for the matrix (which needs to be traced) and the matrix T. In order to correct the double counting of costs in Equations (3.2) and (3.3), the sums are divided by 2. The details of this application are presented in the next sections.

Evolutionary algorithm: Microsoft Excel strengthens the optimization tool by providing the modern technique – an evolutionary algorithm – for users with Solver Add-in. An evolutionary algorithm based on the natural principles of evolution to find an optimal solution to the problem. Evolutionary programming firstly produces offspring, and then individuals are chosen for the next generation. Each parent creates a single offspring by random mutations; therefore, the population size is doubled. These mutations are done by some probability distribution that can be changed across the evolutionary process (Gen *et al.,* 2017). The critical options for running an evolutionary algorithm with Microsoft Excel Solver are presented as the follows:

- Population size: Evolutionary solver starts with an initial population to produce the next generation. It maintains a population which is considered as candidate solutions. The value of population size can be selected between 10 and 200.
- Random seed: The 0 value of random seed presents that in each evolutionary run, a various set of pseudo-random numbers is utilized. Other selected values (not 0) indicate

that in each evolutionary run, the similar set of pseudo-random numbers is applied, and this set is determined by the selected value.

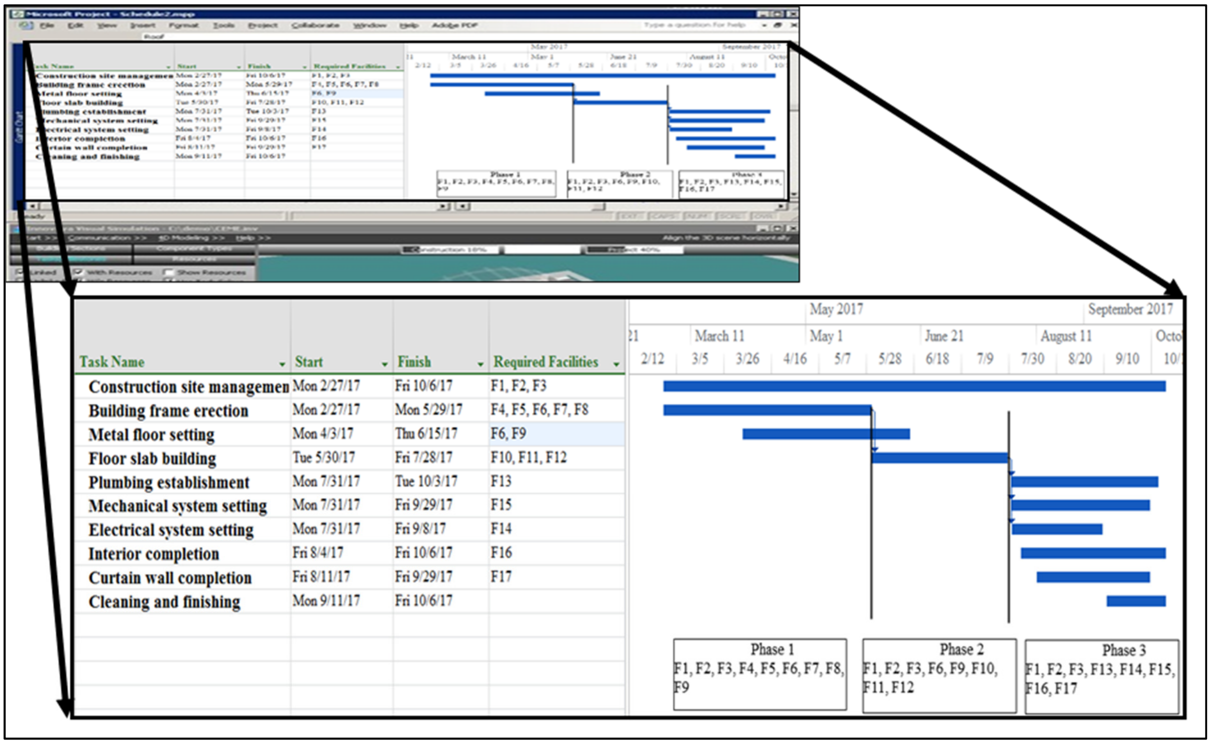
- Mutation rate: The value of mutation rate decides the percentage of the population is applied for mutation. A greater value of mutation rate is set, the more diverse the population is.
- Convergence: The convergence indicates the stopping condition: the percentage difference in the objective function values (calculated for the top 99% of the population) is not allowed to exceed the setting value.
- Maximum time without improvement: This option indicates the maximum quantity of time (in seconds) that the evolutionary solver uses for the search process.

3.5 Numerical example

In this section, the site layout planning for temporary facilities of the medium-size housing project is presented to illustrate the application of the proposed framework. The project uses BIM from initiation until construction. The BIM-based data are shared in the format of IFC (Industry Foundation Classes) files through a cloud-enabled network. The project manager and site engineer, who are responsible for the site layout planning, prepared a current solution for site layout planning based on their experience. However, the proposed framework is used to find an optimal solution which is validated by the comparison with the current solution.

3.5.1 Overall analysis

The nine-story building with concrete floor slabs is constructed with main tasks: framing, floor slabs construction, mechanical and electrical systems structuring, interior and exterior completion. An interface, which integrates the project schedule prepared by Microsoft Project and BIM model created by Autodesk Revit, is created to facilitate the data extraction. The project schedule consisting of three construction phases with required facilities is presented in **Figure 3.4**. The detail of required facilities for tasks is described in **Table 3.3**. As shown in the table, each phase of the project requires different facilities: phase 1 (F1, F2, F3, F4, F5, F6, F7, F8, F9), phase 2 (F1, F2, F3, F6, F9, F10, F11, F12), and phase 3 (F1, F2, F3, F13, F14, F15, F16, F17). The setup cost of each facility and the unit transportation cost are also extracted from the cloud-based BIM platform. In this example, the unit transportation costs between the each pair of facilities are assumed equally to $1.



Task Name	Start	Finish	Required Facilities
Construction site managemen	Mon 2/27/17	Fri 10/6/17	F1, F2, F3
Building frame erection	Mon 2/27/17	Mon 5/29/17	F4, F5, F6, F7, F8
Metal floor setting	Mon 4/3/17	Thu 6/15/17	F6, F9
Floor slab building	Tue 5/30/17	Fri 7/28/17	F10, F11, F12
Plumbing establishment	Mon 7/31/17	Tue 10/3/17	F13
Mechanical system setting	Mon 7/31/17	Fri 9/29/17	F15
Electrical system setting	Mon 7/31/17	Fri 9/8/17	F14
Interior completion	Fri 8/4/17	Fri 10/6/17	F16
Curtain wall completion	Fri 8/11/17	Fri 9/29/17	F17
Cleaning and finishing	Mon 9/11/17	Fri 10/6/17	

Figure 3.4 Project schedule with required facilities for tasks

Table 3.3 Facilities assigned to the site

Facility Name	Code	Type	Phase	Setup cost ($)
Site office	**F1**	Residence	1, 2, 3	100
Labor residence	**F2**	Residence	1, 2, 3	100
Tool and equipment storage	**F3**	Storage	1, 2, 3	150
Structural steel beams	**F4**	Storage	1	150
Structural steel columns	**F5**	Storage	1	150
Structural steel assembly workshop	**F6**	Processing	1, 2	200
Storage of scaffolding pile	**F7**	Storage	1	100
Storage of fire proofing materials	**F8**	Storage	1	100
Floor metal panels	**F9**	Storage	1, 2	110
Rebar storage	**F10**	Storage	2	130
Formwork storage	**F11**	Processing	2	150
Concrete batch workshop	**F12**	Processing	2	200
Plumbing storage	**F13**	Storage	3	120
Electrical system storage	**F14**	Storage	3	120
Mechanical system storage	**F15**	Storage	3	120
Interior material storage	**F16**	Storage	3	130
Curtain wall assembly	**F17**	Processing	3	150

3.5.2 Material flow analysis

The material flow analysis is conducted through the identification of material trip frequencies between facilities following the three steps mentioned in the methodology section. Using data from BIM and project schedule, the material quantity transported between the facilities are computed as the follows. Firstly, an Excel-based macro programmed by VBA is utilized to process the shared IFC data of construction activities which are linked to corresponding components in the BIM model. Based on the bill of materials, the quantity of materials used for the component is identified. A pair of relevant facilities is assigned to each activity based on the movement of the material required for this activity. Secondly, for each identified activity, transportation mode (semitrailer, drop-side truck, and concrete mixer) and capacity for the material handling between a pair of relevant facilities are defined. Finally, equation (**3.1**) is applied to calculate the material trip frequencies between the facilities by phase. The middleware uses VBA macro to tabulate them in the "from-to-chart" as shown in **Table 3.4**, which presents a 9×9 matrix of material transportation frequencies applied for 9 required facilities at phase 1, and 8×8 matrices for phase 2 and phase 3.

Table 3.4 Trip frequencies between facilities by phase

Phase 1									
From	To								
	F1	F2	F3	F4	F5	F6	F7	F8	F9
F1	0	9	18	10	10	18	9	7	7
F2	9	0	20	10	11	24	12	12	12
F3	18	20	0	10	11	25	11	12	12
F4	10	10	10	0	10	25	15	7	8
F5	10	11	11	10	0	25	13	7	8
F6	18	24	25	25	25	0	14	10	9
F7	9	12	11	15	13	14	0	9	7
F8	7	12	12	7	7	10	9	0	9
F9	7	12	12	8	8	9	7	9	0

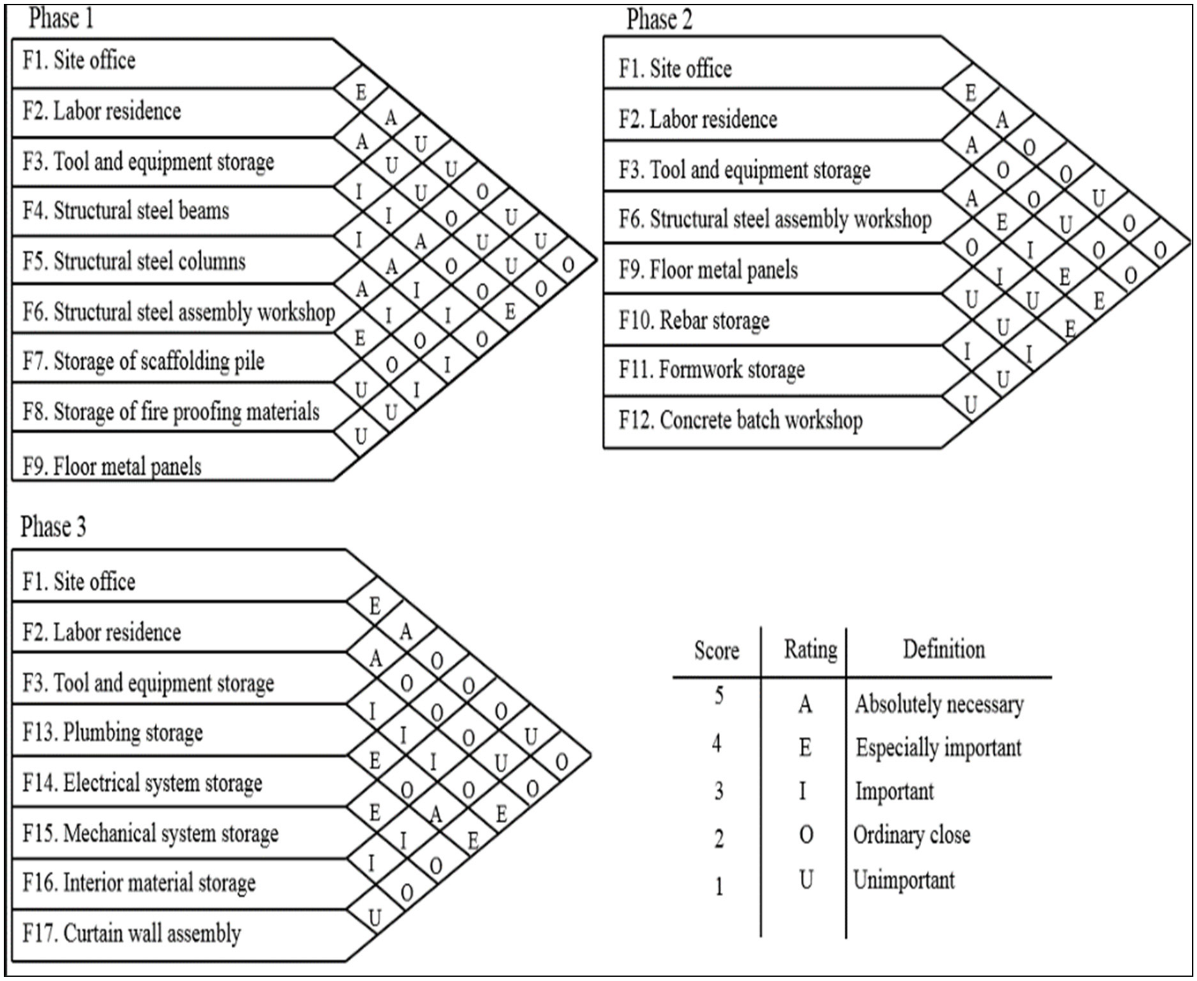
Phase 2								
From	To							
	F1	F2	F3	F6	F9	F10	F11	F12
F1	0	9	18	18	7	8	9	20
F2	9	0	20	24	12	13	15	17
F3	18	20	0	25	12	15	17	22
F6	18	24	25	0	9	12	8	9
F9	7	12	12	9	0	9	11	14
F10	8	13	15	12	9	0	10	15
F11	9	15	17	8	11	10	0	14
F12	20	17	22	9	14	15	14	0

Phase 3								
From	To							
	F1	F2	F3	F13	F14	F15	F16	F17
F1	0	9	18	8	10	10	7	7
F2	9	0	20	12	12	12	12	17
F3	18	20	0	15	14	17	18	20
F13	8	12	15	0	9	8	8	11
F14	10	12	14	9	0	8	22	10
F15	10	12	17	8	8	0	22	10
F16	7	12	18	8	22	22	0	15
F17	7	17	20	11	10	10	15	0

3.5.3 Facility relationship analysis

The relationships between facilities are determined through closeness ratings. Firstly, the project manager and site engineer take into account the evaluation of logistics and non-logistics relationships between pairs of required facilities, as well as their preferences of the closeness between facilities. The logistics relationship between facilities is evaluated on the workflows (including material trip, equipment, personnel, and information flows) between them. The non-logistics relationship between facilities is assessed on the safety and environmental issues (accidents, noise, undesirable temperature, and pollution) that closeness between two facilities can cause. The manager and site engineer also reflect their preferences of the closeness between facilities due to the criteria (convenience of cooperation, the convenience of supervision, and ease of contact). Then, based on the rules for the determination of closeness ratings (**Table 3.2**), a VBA macro is used to identify the closeness ratings between the facilities (**Figure 3.5**). The values of adjacency scores are then identified due to the defined ratings.

These values are used as input data for the optimization of the second objective function (**Equation 3.3**). The scores, once tabulated and saved in a spreadsheet database, are shared on the cloud for the further usage.

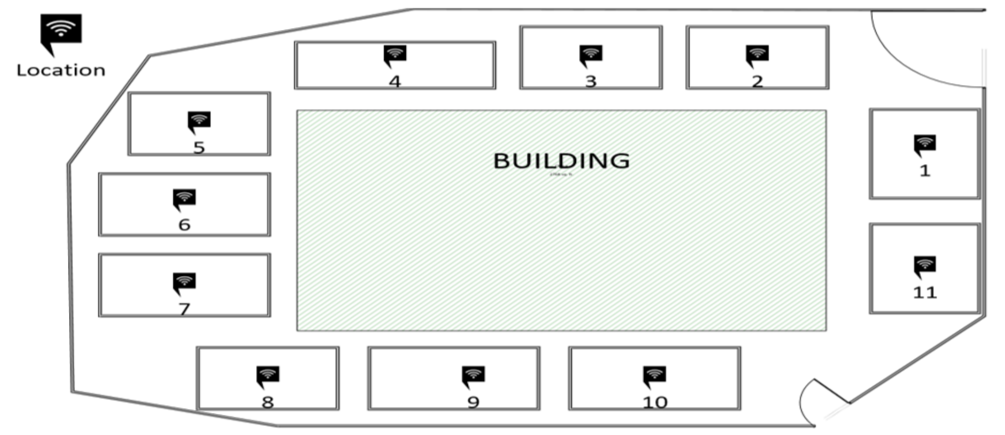


Score	Rating	Definition
5	A	Absolutely necessary
4	E	Especially important
3	I	Important
2	O	Ordinary close
1	U	Unimportant

Figure 3.5 Closeness relationship between facilities

3.5.4 Space analysis

The project site has the dimensions of 95 m × 65 m, in which the area used for the building under construction is 65 m × 40 m. The remaining area is used for the allocation of temporary facilities. This available area is divided into 11 possible locations to which the required facilities of each construction phase can be allocated. Data related to the site area (boundaries and coordinates (x_i, y_i) of locations) are extracted from the BIM model by the middleware to calculate the distances between available locations for the site layout optimization. Location distances are also tabulated in the form of a spreadsheet to be saved in spreadsheet database as shown in **Figure 3.6**.



From	DISTANCE To										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
1	0	18	25	35	40	43	47	56	35	32	20
2	18	0	11	17	23	27	32	40	50	45	36
3	25	11	0	8	15	17	22	32	52	55	45
4	35	17	8	0	7	9	14	24	44	49	53
5	40	23	15	7	0	2	7	17	37	42	52
6	43	27	17	9	2	0	5	15	35	40	50
7	47	32	22	14	7	5	0	10	30	35	40
8	56	40	32	24	17	15	10	0	20	25	35
9	35	50	52	42	37	35	30	20	0	5	15
10	32	45	55	49	42	40	35	25	5	0	10
11	20	36	45	53	52	50	40	35	15	10	0

Figure 3.6 Location distances

3.5.5 Layout optimization

Since all above-processed data are shared on the cloud-enabled network in the format of IFC files, the planners can utilize these data for the layout optimization at any time and place. **Appendix II** shows the spreadsheet illustrating the multi-objective site layout optimization which is performed by Excel Solver using Evolutionary method for the construction phase 1. As shown in the figure, facilities which are required for the construction phase consist of F1, F2, F3, F4, F5, F6, F7, F8, and F9. Therefore, the settings of relevant costs and adjacency scores associated with F10 and F11 are 0 to create a square matrix with m = 11. The trace matrix T (11 x 11) with the diagonal values of 1 is constructed to solve the QAP on the spreadsheet. The objective values of the total cost (cell G43) and total adjacency score (cell G44) are calculated by the formulas presented in the figure. The $\boldsymbol{\varepsilon}$-constraint method is applied for the multi-objective optimization with two strategies: best cost and best adjacency score. As shown in the figure, the optimal values of the two objectives (with the preference of the best cost for the phase 1) are found through twice of runs. For the run 1, an evolutionary method is utilized to find the minimal value of total cost (objective function 1); and then, this value is used as a constraint for the run 2 in order to search the maximal value of total adjacency score (objective function 2). Since the minimal value of total cost is assured during the runs, this setting of the optimal process is called best cost. The reversed runs are established to find the value of the best adjacency score. Following the similar process, the optimal values of the best cost and best adjacency score are found for the phase 2 and the phase 3. The binary decisive variables, which are presented in the matrix X, determine the site layout solutions for the three phases of the construction project.

The site layouts, which are generated for three phases, are presented in **Table 3.5**. The table presents the layout results of facility assignments in the construction site with the two strategies: best cost and best adjacency score. After phase 1, the project manager continues checking the schedule with required facilities for phase 2. Five facilities (F1, F2, F3, F6, and F9) are still used for phase 2; thus, these facilities are set as fixed to avoid costs related to facility moving. Then, only new required facilities (F10, F11, and F12) are taken into account for the layout generation of phase 2. Similarly, the new facilities required for phase 3 are F13, F14, F15, F16, and F17 which are considered for the site layout of phase 3.

Table 3.5 Site layouts for best cost and best adjacency score

Solution	**Phase**	**Assignment**									**Total cost ($)**	**Adjacency score**
		Facility to Location										
Best cost	**I**	F1 11	F2 8	F3 10	F6 4	F9 9	F4 7	F5 6	F7 2	F8 1	11,791	2,376
	II	F1 11	F2 8	F3 10	F6 4	F9 9	F10 3	F11 2	F12 6		11,310	2,090
	III	F1 11	F2 8	F3 10	F13 9	F14 1	F15 4	F16 3	F17 2		9,261	1,816
Best adjacency score	**I**	F1 5	F2 4	F3 3	F6 11	F9 2	F4 1	F5 7	F7 10	F8 9	14,668	2,939
	II	F1 5	F2 4	F3 3	F6 11	F9 2	F10 10	F11 9	F12 6		12,828	2,379
	III	F1 5	F2 4	F3 3	F13 11	F14 1	F15 10	F16 9	F17 2		11,868	2,446

3.5.6 Layout selection

The final step requires construction managers to select an appropriate alternative for the site layout. For a multi-objective optimization, a Pareto frontier is normally created in which a set of non-dominated layout alternatives is considered as candidates. **Figure 3.7** presents the Pareto front with cuts for the site layout of phase 1. The two extreme points (A and G) represent the solutions of best cost and best adjacency score which are mentioned above. The other points on the efficient frontier are then created using Equation (**3.7**). The similar Pareto front cuts can be made for the site layout of phase 2 and phase 3. As shown in the figure, seven points (A, B, C, D, E, F, G) can be considered as candidates for optimal layout solution. In this example case, the construction manager and engineer choose the point A as final selection since the best cost solution, with the consideration of facility adjacency as the second objective, is their preference for a layout selection.

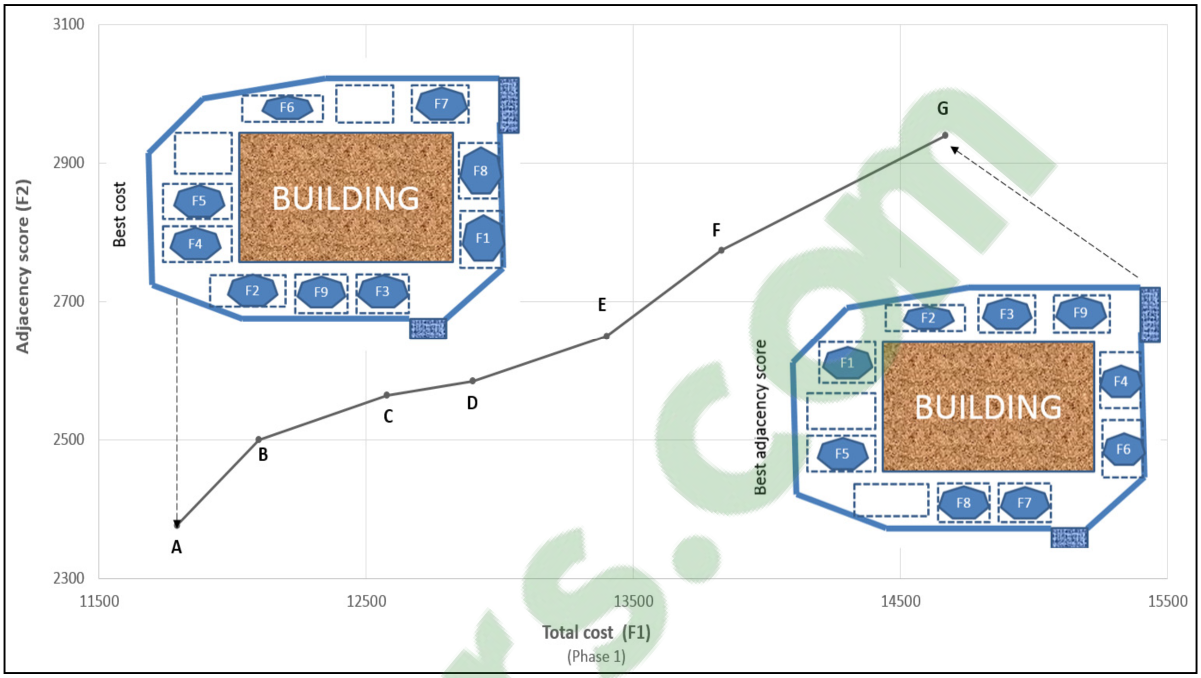


Figure 3.7 Pareto front with cuts for site layout at phase 1

3.6 Validation and discussion

3.6.1 Framework validation by the example

Three thesis objectives are illustrated through the above-mentioned example. For ***the objective 1***, the example presents the details of framework implementation in practice with a medium-size project. The framework embraces a systematic approach, which follows a six-step procedure to solve the multi-objective problem and select the optimized solution. For ***the objective 2***, the example shows how the BIM-based data collection and processing system works to enable the data extraction and integration from various sources and facilitates the data update and sharing among the construction actors. For ***the objective 3***, the example details how BIM-based quantitative and qualitative data are extracted and computed for site layout planning. The trip frequencies between facilities and location distances, which are two important parameters of a site layout planning model, are calculated on the available data in BIM. Besides, qualitative data, which are generated on the managers' expertise, are also used for the site layout planning model in order to consider other important aspects: safety, workflow between facilities, and managers' preference. As a part of the framework, multi-objective layout model is proposed to cover two features of a site layout planning: productivity of site layout (in terms of layout cost) and facility relationship (in terms of adjacency score). The facility relationship covers two dimensions: logistics relationships (work-flows) and non-logistic relationships (safety and environmental issues) between required facilities in each construction phase. In order to validate the proposed model, optimal values of the selected solution (best-cost solution) are used to compare to the current solution prepared by the site managers (**Table 3.6)**. As presented in the table, total costs of phase 1, phase 2, and phase 3, provided by the optimal solution, are saved by 12.24%, 1.40%, and 3.57% respectively in comparison with the current solution. Regarding facility adjacency, the optimal solution increases the scores by 13.40% and 2.25% for phase 2 and phase 3; however, it reduces the score by 10.71% for phase 1. For the whole construction project, the optimal solution proves its domination over the current solution in both terms of cost saving (6.23%) and facility adjacency increase (0.03%). This is significant to compare to previous studies which have shown that the percentage of cost saving in logistics optimization is above 3% (Choudhari and Tindwani, 2017). The current solution is mostly based on the manager and engineer's expertise of the closeness between facilities: convenience of cooperation, the convenience of supervision, and ease of contact. Whereas, the optimal solution considers not only the layout cost but also the facility adjacency; thus the result shows that it meets construction managers' requirements not only in saving cost but also in assuring facility relationships. This implies that the integration of systematic layout planning and mathematical layout modeling is an appropriate approach to deliver practical multi-objective site layouts.

Figure 3.8 visualizes the dynamic site layouts generated by the optimal and current solutions. Together with layout cost, safety is also an important criterion to assign a facility adjacent to the others. In order to ensure the safety for the construction staff, the site office and the labor residence should not be separated by the processing facilities (F6: Steel assembly workshop; F11: Formwork area; F12: Concrete batch workshop; or F17: Curtain wall assembly). Besides, as managers' preference, the site office should be allocated near to the construction gates to ease the operational control. Both current and optimal solutions satisfy these criteria of safety and managers' preference. The current solution, which is primarily preferred to convenience, creates a site layout where the site office is next to the labor residence. This means the construction staff and managers are convenient to move from their residential area to the site office. However, this solution does not take into account other layout aspects: cost optimization and workflow between facilities. Thus, both total cost and total adjacency score of this solution are dominated by the optimal solution.

Table 3.6 Comparison between optimal and current solutions

Phase	Solution	Locations											Total cost	Saving (%)	Total adjacency	Adjacency increase (%)
		1	2	3	4	5	6	7	8	9	10	11				
I	Optimal	F8	F7	-	F6	-	F5	F4	F2	F9	F3	F1	11,791	12.24%	2,376	-10.71%
	Current	F1	F3	F8	F9	-	-	F7	F6	F5	F4	F2	13,436		2,661	
II	Optimal	-	F11	F10	F6	-	F12	-	F2	F9	F3	F1	11,310	1.40%	2,090	13.40%
	Current	F1	F3	F10	F9	F12	-	-	F6	F11	-	F2	11,471		1,843	
III	Optimal	F14	F17	F16	F15	-	-	-	F2	F13	F3	F1	9,261	3.57%	1,816	2.25%
	Current	F1	F3	F14	F16	F13	F15	F17	-	-	-	F2	9,604		1,776	
Whole project	Optimal												32,362	6.23%	6,282	0.03%
	Current												34,511		6,280	

From another aspect, in case the managers choose the best-adjacency solution for site layout planning (as presented in **Table 3.5**), the two residence facilities (the site office and the labor residence) are allocated next to each other and far away from the processing facilities which may cause some dangers to the staff. For instance, in phase 1, the managers and construction labors do not have to pass by the steel assembly workshop to move from the site office to the labor residence. Similarly, the staff do not also have to go through the formwork area, the concrete batch workshop, and the curtain wall assembly to move from the site office to the labor residence in phase 2 and phase 3 respectively. The safety, the workflow, and the manager's preferences are three variables that decide the best-adjacency layout solution (as presented in **Table 3.2**). These are subjective to the managers' evaluations; thus, any changes in scores for facility relationships based on these three variables (as shown in **Figure 3.5**) can result in changes in layout solutions.

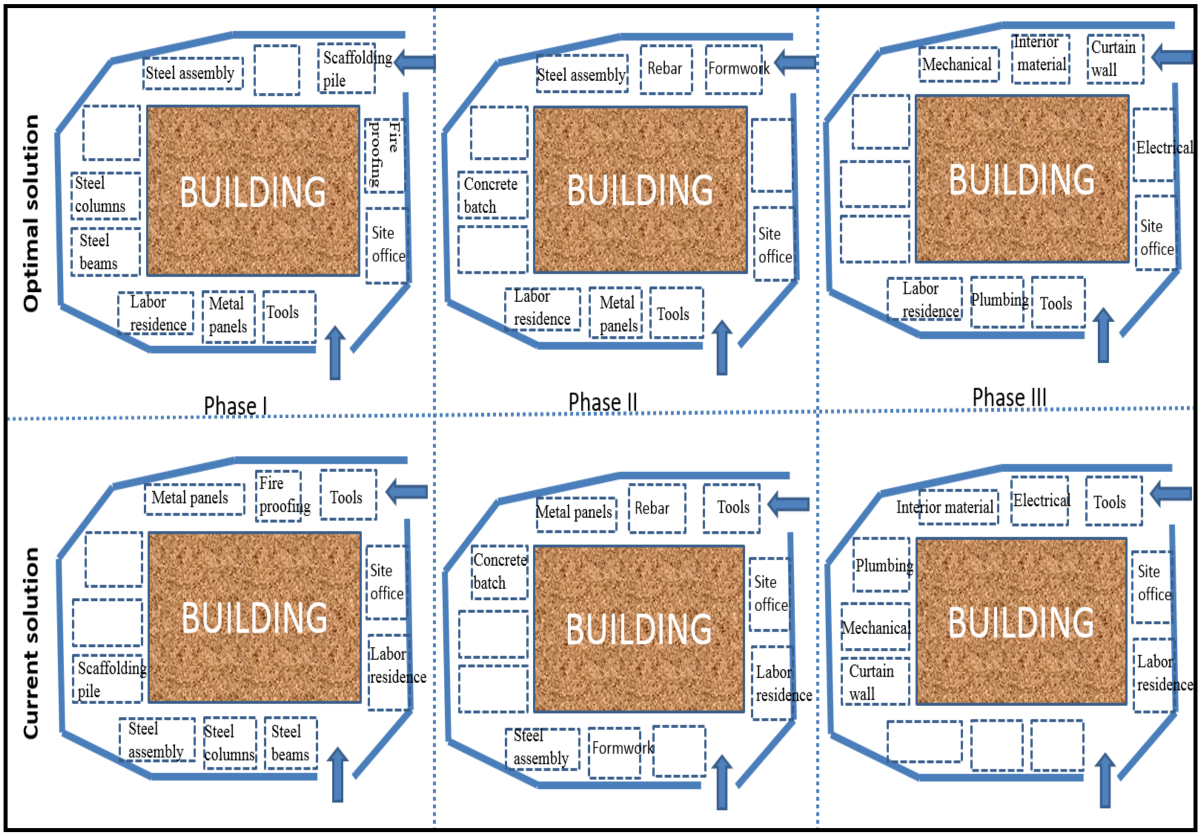


Figure 3.8 Site layouts of optimal and current solutions

In some case, a manager may not select either the best cost solution or the best adjacency solution, but a balanced solution. For instance, as presented in **Figure 3.7**, the best cost solution provides a rather low adjacency score; while the best adjacency score solution requires a high cost for the site layout. The selected solution can be the point that balances the two criteria of cost and adjacency. As presented in the figure, the two couple-points should be considered for the selection are (A, B) and (E, F). From A to B, a quite small increase in cost (2.62%) can result in a quite acceptable increase in adjacency score (5.22%). Similarly, from E to F, a quite slight increase in cost (3.20%) also leads to a quite suitable increase in adjacency score

(4.68%). However, this suggestion is only based on the evaluation of Pareto front cuts, without referencing the other selection criteria.

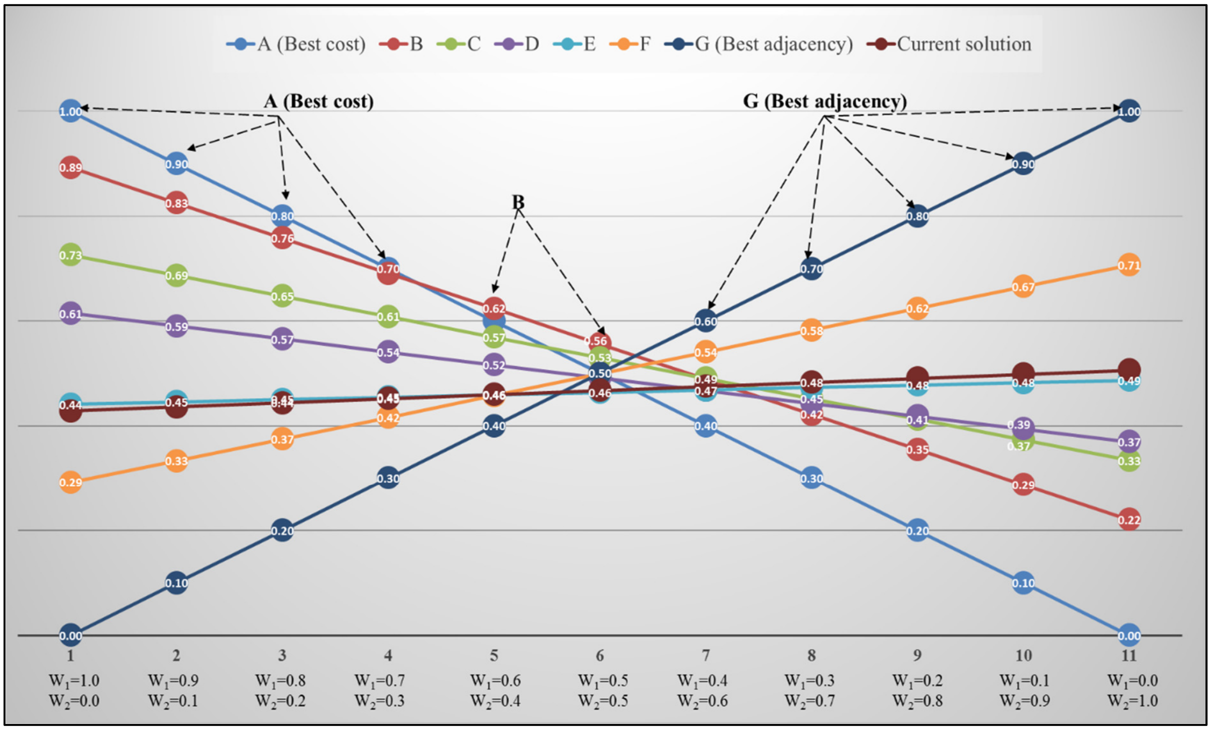


Figure 3.9 Changes in selecting solutions due to weights of cost and adjacency

In order to get an appropriate solution for site layout planning, it is required to make a set of evaluation criteria for the layout candidates. Depending on the relevant actors' priorities for the layout objectives, the weight of each objective can be suggested, which determine the final solution for the site layout. It is important to call for the participation of the associated actors (designer, site engineer, project manager, representative of subcontractor, and so on) to determine the weights for the layout objective based on their expertise and the consensus in group discussion. **Table 3.7** presents eleven scenarios of weights determined for the two objectives (W_1 as the weight for cost; and W_2 as the weight for adjacency score). Since the cost objective (f_i) needs to be minimized while the adjacency objective (h_i) needs to be maximized; therefore, the normalization for the values of these objectives needs to be computed. For each scenario, the weighted sum of normalized values for the non-dominated solutions (A "Best cost", B, C, D, E, F, G "Best adjacency", and the current solution) are calculated to decide the best solution. The normalized values of cost and adjacency score of each solution are computed respectively as follows:

$$f_i^{norm} = \frac{\max(f_i) - f_i}{\max(f_i) - \min(f_i)} \quad (3.10)$$

$$h_i^{norm} = 1 - \frac{\max(h_i) - h_i}{\max(h_i) - \min(h_i)} \quad (3.11)$$

Based on the weighted sum of normalized values of each solution, the best solution for each scenario is identified by the following formula:

$$\max f_i^* = W_1 \times f_i^{norm} + W_2 \times h_i^{norm} \quad (3.12)$$

As shown in **Figure 3.9**, when the weight of cost W_1 changes from 0.7 to 1.0 (that means the weight of adjacency score W_2 changes from 0.0 to 0.3), the solution A (Best cost) is selected for the site layout planning. When W_1 changes from 0.5 to 0.6 (that means W_2 changes from 0.4 to 0.5), the solution B is chosen as the replacement. Finally, once W_1 changes from 0.0 to 0.4 (that means W_2 changes from 0.6 to 1.0), the best choice is certainly G (Best adjacency). This scenario analysis shows that the selection of the best solution for site layout planning with the consideration of multi-objectives depends on the weights given for the objectives. Thus, the actors' expertise is very important to determine the appropriate layouts for temporary facilities within the construction site.

3.6.2 Model validation with previous studies

In order to validate the solution method proposed by the framework, the above mathematical model is applied for the site layout planning problem mentioned by Li and Love (2000). Then, a comparison of results is conducted to previous studies: Li and Love (2000), Lien and Cheng (2012), and Papadaki and Chassiakos (2016). All these previous studies adopted the same medium-sized project to test optimal site layouts by using different mathematical solution methods. The comparison is detailed in **Table 3.8**, while the best layouts resulted from previous studies and this study are simplified in **Figure 3.10** and **Figure 3.11** respectively. The information about location distances and trip frequencies is presented in the figures. To that extent, the suggested project aims at allocating 11 basic site facilities (such as site office, falsework workshop, labor residence, two storerooms, etc.) to an equal number of locations. The constraints consist of the following issues: side gate and main gate are assumed as fixed facilities, while site office, labor residence and concrete batch workshop have to be allocated to large-size locations.

Table 3.7 Selected solutions due to the weights of objectives

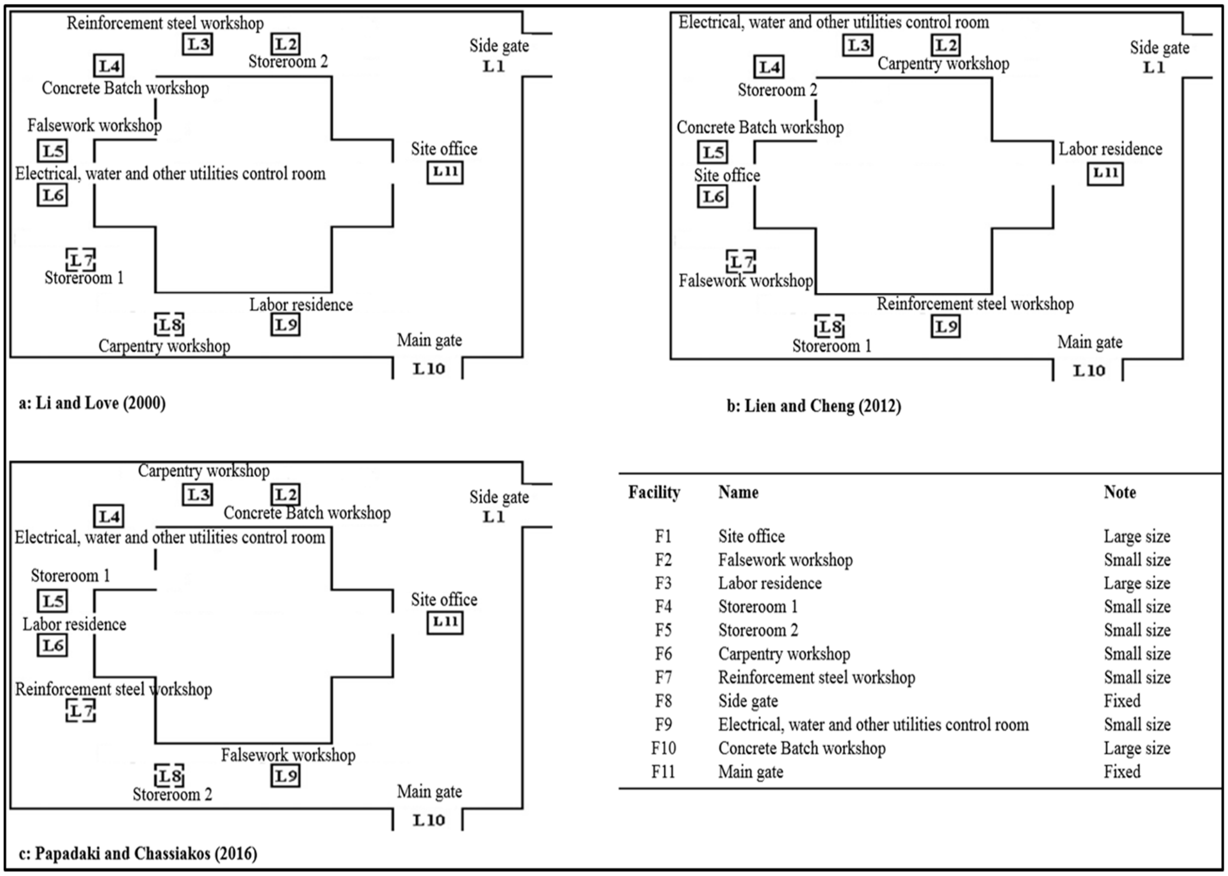
	Weights		**Weighted sum of normalised value (f_i*)**								
Scenario	*Cost (W_1)*	*Adjacency (W_2)*	*A (Best cost)*	*B*	*C*	*D*	*E*	*F*	*G (Best adjacency)*	*Current solution*	**Selected solution**
1	1.0	0.0	**1.00**	0.89	0.73	0.61	0.44	0.29	0.00	0.43	A (Best cost)
2	0.9	0.1	**0.90**	0.83	0.69	0.59	0.45	0.33	0.10	0.44	A (Best cost)
3	0.8	0.2	**0.80**	0.76	0.65	0.57	0.45	0.37	0.20	0.44	A (Best cost)
4	0.7	0.3	**0.70**	0.69	0.61	0.54	0.45	0.42	0.30	0.45	A (Best cost)
5	0.6	0.4	0.60	**0.62**	0.57	0.52	0.46	0.46	0.40	0.46	B
6	0.5	0.5	0.50	**0.56**	0.53	0.49	0.46	0.50	0.50	0.47	B
7	0.4	0.6	0.40	0.49	0.49	0.47	0.47	0.54	**0.60**	0.48	G (Best adjacency)
8	0.3	0.7	0.30	0.42	0.45	0.44	0.47	0.58	**0.70**	0.48	G (Best adjacency)
9	0.2	0.8	0.20	0.35	0.41	0.42	0.48	0.62	**0.80**	0.49	G (Best adjacency)
10	0.1	0.9	0.10	0.29	0.37	0.39	0.48	0.67	**0.90**	0.50	G (Best adjacency)
11	0.0	1.0	0.00	0.22	0.33	0.37	0.49	0.71	**1.00**	0.51	G (Best adjacency)

As shown in **Table 3.8**, all of three previous studies use predetermined data for their mathematical models to minimize the total travel distance in the construction site. This means that data are determined and entered into the optimization software manually by planners. It can lead to some problems of data in-correction and un-updated, especially when layout models are applied for a project with multi-phases or a larger scale. In contrast, this study proposes a BIM model as a data source to compute related data for parameters in the mathematical model as well as uses knowledge-based reasoning to take advantage of expertise for a safer site layout. Generally, the best-cost site layout suggested by the proposed framework is meaningfully efficient in comparison to previous studies (with a minimal total distance of 12,546). Regarding adjacency between facilities, since the previous selected studies did not consider this objective for their site layout planning, there is no comparison for adjacency scores. However, based on the characteristics of facilities and trip frequencies between them, this study creates a knowledge-based evaluation for the adjacency between facilities in the suggested project. The evaluation is based on three criteria: safe level when two facilities are allocated closely together, workflow between two facilities, and managers' preferences to facilities. As a result, the best adjacency site layout suggested by the proposed framework is achieved with the maximal value of the total score at 7,326.

Table 3.8 Comparison of results generated by the proposed model and previous studies

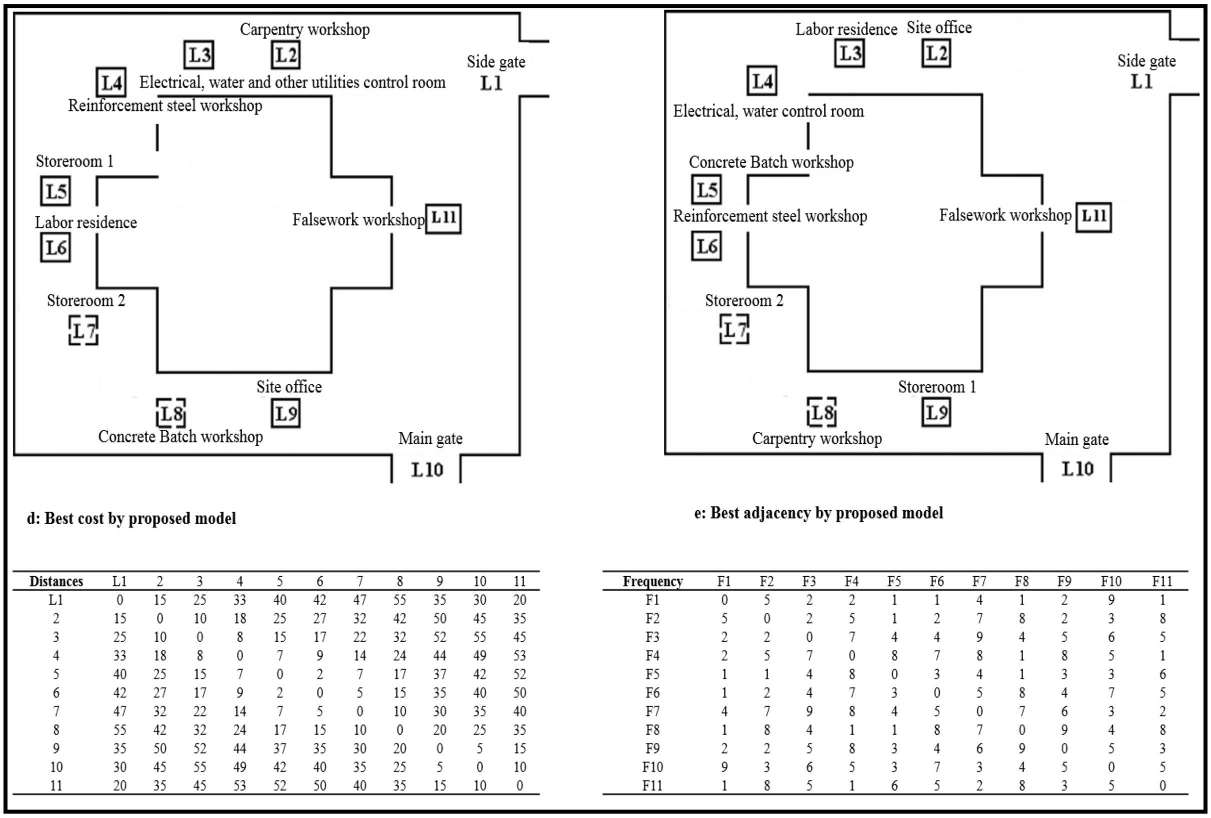
	Data Collection	**Research method**	**Total distance**	**Total adjacency**
Li and Love (2000)	Predetermined	Mathematical modelling (Genetic Algorithms - GA)	15,160	Not mentioned
Lien and Cheng (2012)	Predetermined	Mathematical modelling (Particle swarm optimization - PSO)	12,546	Not mentioned
Papadaki and Chassiakos (2016)	Predetermined	Mathematical modelling (Genetic Algorithms - GA)	12,606	Not mentioned
Best-cost solution by the proposed model	BIM-based data and Knowledge-based reasoning	Integration of Mathematical modelling (Evolutionary algorithm – EA) and Systematic layout planning	12,546	7,160
Best-adjacency solution by the proposed model	BIM-based data and Knowledge-based reasoning	Integration of Mathematical modelling (Evolutionary algorithm – EA) and Systematic layout planning	14,498	7,326

As visualized in **Figure 3.10** and **Figure 3.11**, site layouts suggested by Lien and Cheng (2012), Papadaki and Chassiakos (2016), and the best-cost solution (proposed by the framework of this study) are significantly economic in accordance with lowest total distances; however, these solutions have limitations in ensuring safety and practical issues for site layout planning. For instance, all layouts of Lien and Cheng (2012), Papadaki and Chassiakos (2016), and best-cost solution allow site staff to enter the site office via a long route and/or present dangers to the site staff to have to travel from the site office to the labor residence through the concrete batch workshop. In contrast, the solution of Li and Love (2000) is more practical when the site office and labor residence are close to each other, and both of them are near the main gate. However, this solution has a rather high total distance (15,160). Finally, the best-adjacency solution (proposed by the framework of this study), which considers safety in facility allocation, workflow between facilities, and managers' preferences, can be considered as a practical solution since it balances the two aspects of the economy (14,498) and adjacency (7,326). This solution allows the site office to be allocated adjacently to the labor residence and takes into account the logistical relationship (workflow) and non-logistical relationship (safety and managers' preference) between facilities in a construction site.



Facility	Name	Note
F1	Site office	Large size
F2	Falsework workshop	Small size
F3	Labor residence	Large size
F4	Storeroom 1	Small size
F5	Storeroom 2	Small size
F6	Carpentry workshop	Small size
F7	Reinforcement steel workshop	Small size
F8	Side gate	Fixed
F9	Electrical, water and other utilities control room	Small size
F10	Concrete Batch workshop	Large size
F11	Main gate	Fixed

Figure 3.10 Site layouts generated by previous studies



d: Best cost by proposed model

e: Best adjacency by proposed model

Distances	L1	2	3	4	5	6	7	8	9	10	11
L1	0	15	25	33	40	42	47	55	35	30	20
2	15	0	10	18	25	27	32	42	50	45	35
3	25	10	0	8	15	17	22	32	52	55	45
4	33	18	8	0	7	9	14	24	44	49	53
5	40	25	15	7	0	2	7	17	37	42	52
6	42	27	17	9	2	0	5	15	35	40	50
7	47	32	22	14	7	5	0	10	30	35	40
8	55	42	32	24	17	15	10	0	20	25	35
9	35	50	52	44	37	35	30	20	0	5	15
10	30	45	55	49	42	40	35	25	5	0	10
11	20	35	45	53	52	50	40	35	15	10	0

Frequency	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11
F1	0	5	2	2	1	1	4	1	2	9	1
F2	5	0	2	5	1	2	7	8	2	3	8
F3	2	2	0	7	4	4	9	4	5	6	5
F4	2	5	7	0	8	7	8	1	8	5	1
F5	1	1	4	8	0	3	4	1	3	3	6
F6	1	2	4	7	3	0	5	8	4	7	5
F7	4	7	9	8	4	5	0	7	6	3	2
F8	1	8	4	1	1	8	7	0	9	4	8
F9	2	2	5	8	3	4	6	9	0	5	3
F10	9	3	6	5	3	7	3	4	5	0	5
F11	1	8	5	1	6	5	2	8	3	5	0

Figure 3.11 Site layouts generated by the proposed model

3.6.3 Discussions and implications

This paper develops a hybrid site layout framework which combines the two well-known approaches – mathematical and systematic layout planning – to generate the step-by-step procedure for SLD (research objective 1). The framework systematically integrates qualitative and quantitative data for dynamic SLD using cloud-enabled BIM platform and the knowledge-based rules (research objective 2). The proposed framework takes advantage of the emerging BIM technology to support quantitative data collection and sharing. Besides, the qualitative data are generated on the managers' expertise through knowledge-based rules. All the data used for parameters in the site layout model are collected and processed in a systematic procedure, instead of being predetermined as in many previous studies (research objective 3). According to Miles and Huberman (1994) and Papadonikolaki et al. (2017), using multiple sources for data collection and applying a variety of data analysis approaches contribute to research credibility. Thus, this paper integrates different data collection sources and mixed data analysis approaches to contribute to the productive and safe SLD.

The validations show that the proposed framework performs better results in both terms of cost reduction and adjacency improvement. This implies that the hybrid approach which integrates the mathematical and the systematic site layout methods can be used to create productive site layout plans. Using this hybrid approach needs the expertise from the relevant actors for the assessment of facility relationships or the selection of the best solutions. Therefore, it is suggested that the knowledge-based techniques should be integrated with mathematical techniques to deal with site layout problems. These results support the findings of previous studies, such as Elbeltagi and Hegazy (2001), Ning et al. (2010), Xu and Li (2012), Yahya and Saka (2014), and Ning et al. (2016) who respect both mathematical algorithms and actors' expertise for SLD.

It is also important to ensure the data correction and updating for SLD. Thus, it is suggested that advanced technologies, especially BIM platform, should be used to facilitate the data provision and automation for the systematic site layout process. This paper suggests a BIM-based data collection and processing system to calculate and integrate all the required data for the site layout models. These statements support the findings of previous studies, such as: Said and El-Rayes (2014) automate the extraction of project spatial and temporal data from the BIM and other sources to minimize site layout-related costs; Kumar and Cheng (2015) use BIM-based data to compute the required sizes and dimensions for facilities; Hammad et al. (2016a) integrate BIM and project schedule to generate quantitative data for the estimation of travel frequencies between facilities; or Schwabe et al. (2019) retrieve data from BIM to develop a rule-based model for checking the site layout planning tasks.

The distinctive and important implication of this paper is the integration of systematic site layout process, BIM technology, and actors' expertise for a smooth and productive site layout plan. This triad supports the site planners to analyze the resources, collect and estimate the data, develop the site layout models, share and update the data, as well as select the optimal solution. Without a systematic approach for SLD, site planners may not know how to begin a planning process, ignore some important analysis of the resources, and get troubles in data preparation for the layout modeling and solution selection. As a consequence, they tend to select a layout solution only based on their past experiences. BIM technology supports the SLD not only in data provision and calculation but also in data sharing and updating. BIM-based platform can benefit construction companies with data correction and automation to deal with changes in project schedule or resources availability. A set of objectives needs to be achieved for SLD; thus, the relevant actors' expertise is required to determine the weights of these objectives. When logistical relationships between the facilities such as material flows can be quantitatively estimated on the data from BIM, their non-logistical relationships such as environmental issues or safety require the actors' evaluations based on the knowledge-based rules. Therefore, the reliability of the relevant actors' expertise has to be ensured to make site layout plans satisfying the practical needs of current SLD.

Based on the research implications, the following recommendations are given to the site planners in order to deliver a productive and safe site layout plan:

- The site planners are advised to follow the systematic layout process as proposed in this study for their SLD. The six-step process can support the planners for the resource analysis, the data collection and processing, the objective setting and optimization, and finally, the layout selection.
- It is recommended to facilitate the relevant actors' participation and use their expertise for the layout planning process. The actors' evaluation of facility relationships and their determination of weights for layout objectives significantly contribute to the efficiency of a site layout plan.
- It is essential to enable a BIM-based platform which supports the information sharing and data updating among the associated actors. An integrated data collection and processing system, as developed in this paper, should be established to generate the required data for SLD based on the data from BIM and other sources.

3.6.4 Research limitations and further research

The limitation of this study is that the proposed framework is only applied for one example of a medium-size project. For further research, the proposed framework can be used for small, medium, or even large scale projects to explore its potential for practical application. BIM can provide rich data for different project scales, especially for a large-scale project where many activities are necessary to be updated for SLD. Meanwhile, knowledge-based reasoning is considered to be suitable for small and medium scale projects since it requires the contributions of managers' expertise. For large scale projects, the relationships among a large number of facilities become more complex, and this requires more involvement of managers in evaluating the workflow, safety and preference among the facilities. In order to apply the expertise for SLD, it is suggested that the large-scale project schedule should be divided into possible short-term stages to reduce the complexity.

The other issue is the difficulty in satisfying the two objectives (layout cost and adjacency) simultaneously. For instance, as shown in **Figure 3.7**, no layout solution obtains both minimal layout cost and maximal adjacency score. Thus, the proposed solution method provides a set of candidates for managers to make decisions for SLD, including the two solutions of the best cost and the best adjacency. Depending on the preference for SLD, a site manager can choose a solution minimizing the layout cost, or a layout with the best safety, or a candidate that balances the two objectives.

Being integrated with IoT (Internet of Things), such as RFID (Radio Frequency Identification) or BLE (Bluetooth Low Energy), the proposed framework can be used for further researches to deal with real-time changes of day-to-day layout practice. RFID or BLE can support the automated tracking of on-site resources and available spaces; thus, site managers can continuously monitor and consider available spaces and required facilities for site layouts. Real-time data collected from these tracking technologies can be automatically integrated into BIM models to generate real-time layouts.

3.7 Conclusions

A site layout framework using a hybrid approach of systematic and mathematical layout planning is proposed in this study. The two types of qualitative and quantitative data are collected and analyzed with the support of an integrated system consisting of BIM platform, Knowledge-based rules, VBA programming middleware, and Microsoft Excel Solver. The detailed procedure of collecting, processing, and sharing data for a practical site layout is also presented. The results show that the proposed framework meets construction managers' requirements not only in saving cost but also in assuring facility relationships. This implies that the integration of systematic layout planning and mathematical layout modeling is an appropriate approach to deliver practical multi-objective site layouts. Besides, in this paper, a metaheuristic solution method (evolutionary algorithm provided by Microsoft Excel Solver) is used to solve the dynamic site layout optimization problem and to reduce the complexity of the development of the mathematical model. The proposed framework can be used for large-scale cases using the same solution approach, or other meta-heuristic methods such as tabu search or simulated annealing.

As a digital advance in other industries, BIM has become the factor that changes construction design and execution by leveraging the collaboration among participants during phases of a project. Nevertheless, there exist many challenges for BIM implementation. Thus, the extended 5D-BIM (3D BIM with schedule and costs) and cloud-enabled platform, which are proposed in this study, are not widely applied in practice of the industry. However, to deal with changes in a dynamic construction site, the prototype system is proposed for construction managers to deliver reliable and practical site layouts. The system is especially suitable for a remote manager who would like to update regularly the construction site status for automating a site layout practice.

CONCLUSION

Improving the performances of logistics activities is an essential reason for applying the concept of SCM in the construction industry. Based on the systematic literature review, we find the critical decisions, which are integrated into construction logistics and SCM. These decisions are identified for three main phases of a CSC project: planning and design, procurement, and construction execution (presented in **chapter 1**). In the scope of this thesis, we focus on logistics improvement for the construction projects; thus, decisions related to construction logistics are taken into account to model and optimize the CSC operations. In order to achieve efficiency in construction logistics, the four decisions are commonly conducted: transportation, material purchasing and storage, site layout, and material handling. In this thesis, issues related to material transportation and material purchasing and storage are considered to model and optimize the integrated CSC network with TPL partnership, which minimizes the total SC costs, including transportation cost, material purchasing cost, and material storage cost (presented in **chapter 2**). Meanwhile, site layout planning and material handling are concurrently considered to generate an efficient layout of temporary facilities in the construction site, which aims to minimize the material handling cost and maximize the adjacency score between the facilities (presented in **chapter 3**).

Contributions

This thesis aims to fill the research gaps identified in the field of construction logistics and SCM. Firstly, we find that recent researches have not proposed any framework to classify CSC decisions made in each construction stage or suggest when they should be integrated along with the construction phases. Besides, there exists a lack of study proposing future directions of decision making in construction SCM with detailed specification of methods and tools that meet new requirements of construction management practices and technological progress. Thus, the first contributions of this thesis are to identify the present focuses of decision-making in construction SCM and the relationships existing between the SC actors during the major construction phases (***Thesis objective 1.1***) and propose the future trends of SCM applications in the construction industry to meet the new requirements of construction practices and technological progress (***Thesis objective 1.2***).

Based on these contributions and the identified research gaps, the next thesis contributions focus on developing an optimization model to improve the logistics performance for CSC operations with the TPL partnership (***Thesis objective 2.1***). The proposed model considers the TPL provider as the CSC coordinator for logistics activities: material purchasing, transportation, and storage. The model aims to generate an optimal logistics plan for two kinds of materials: type 1 (materials can be transported to a warehouse or directly sent to the construction site), and type 2 (materials can be directly sent to construction site only). The optimal solution provided by the model can assist the decision-makers in determining the operational strategies for common tasks in construction SCM: supplier selection, determination of order quantity, and consideration of the efficiency in using TPL. The proposed model also facilitates the construction managers to take advantage of the TPL warehouse to order a larger quantity to obtain lower prices offered by suppliers. For further analysis of the efficiency of the proposed model, this study also makes the comparison of total SC costs generated among three models: the proposed CSC model applied for TPL partnership with different price discounts offered by different suppliers; the proposed CSC model applied for TPL partnership with same prices offered by different suppliers; and the CSC model without TPL partnership (***Thesis objective 2.2***).

It is also found that previous studies in site layout planning have not paid attention to create a systematic approach that directs the integration of knowledge-based rules and mathematical modeling by using BIM as a data source. Thus, the last contributions of this thesis focus on developing a hybrid site layout framework that combines the two well-known approaches – mathematical and systematic layout planning – to generate the step-by-step procedure for site layout planning (***Thesis objective 3.1***). The framework systematically integrates qualitative and quantitative data for dynamic site layout planning using a cloud-enabled BIM platform and the knowledge-based rules (***Thesis objective 3.2***). The proposed framework takes advantage of emerging BIM technology to support quantitative data collection and sharing. Besides, the qualitative data are generated on the managers' expertise through knowledge-based rules. All the data used for parameters in the site layout model are collected and processed in a systematic procedure, instead of being predetermined as in many previous studies (***Thesis objective 3.3***). According to Miles and Huberman (1994) and Papadonikolaki *et al.* (2017), using multiple sources for data collection and applying a variety of data analysis approaches contribute to research credibility. Thus, this thesis integrates different data collection sources and mixed data analysis approaches to contribute to a productive and safe site layout planning.

Main findings

In **chapter 1**, based on the identified present focuses of decision making in construction logistics and SCM, we found that the development of SC integration in the construction industry has been limited, and we observe a slower speed in comparison with other industrial sectors. Thus, it is suggested to improve the SC integration across the construction project phases to achieve more efficiency in CSC planning and operations. Specifically, during the planning and design stage, the integration between the General Contraction, the Owner, and the Designer contributes to the efficiency of CSC network planning and design through the decisions focused on identifying CSC configuration; developing tools and methods for CSC planning and management; and identifying CSC risks. During the stage of procurement, the collaboration between the GC, subcontractors, and the key suppliers for a long-term period with integrity, openness, commitment, shared vision, and trust creates the reliability of the material supply process and sub-construction delivery and mitigates the risks of supply delays. To achieve efficient performance in construction operations, logistics-based planning should be done with the collaboration of related partners and under the condition of having sufficient information to respond quickly to the uncertainty occurring during the on-site construction operations.

Consequently, we recommend the SC integration as a key factor for the efficiency in the construction logistics. Besides the integration of relevant SC actors, it is also essential to leverage the focal role of the SC driver acting as the coordinator for the construction logistics activities. In this thesis, the TPL partnership is proposed to achieve the SC integration in the construction logistics network. The integration of relevant actors is also important for construction operations. The BIM-based platform is suggested to facilitate the collaboration of construction actors in the logistics execution.

In **chapter 2**, the model validation with the case example shows that the proposed model performs better results in total SC cost in comparison with the CSC without the TPL provider. This implies that the optimization model for the integrated CSC operations with TPL providers can be used to improve the construction logistics performance and deal with the practical requirements of the current issues in the construction industry. This finding supports the reasoning in the study of Ekeskär and Rudberg (2016), which confirms that TPL employment can provide CSC actors with lower costs and better resource utilization. Moreover, the proposed model also assists the CSC actors to analyze the components of logistics cost and balance them to produce an optimal plan. Therefore, it can help to reduce the total logistics cost which is sometimes estimated as high as 250% of the materials procurement price in some case of poor logistics performance (Vrijhoef and Koskela, 2000), or typically more than 10% of the purchase price in usual case (Wegelius-Lehtonen, 2001). In terms of SC coordination, the TPL provider is employed to integrate all the relevant SC actors to ensure the effectiveness of the construction logistics processes. These benefits proposed by the model can address and solve the logistics issues mentioned by Thunberg and Persson (2014) that only less than 40% of deliveries are delivered in the right amount, right time and location, damage-free and right documentation.

In **chapter 3**, the validations show that the proposed framework performs better results in both terms of cost reduction and adjacency improvement. This implies that the hybrid approach, which integrates the mathematical and systematic site layout methods, can be used to create productive site layout plans. Using this hybrid approach needs expertise from the relevant actors for the assessment of facility relationships or the selection of the best solutions. Therefore, it is suggested that knowledge-based techniques should be integrated with mathematical techniques to deal with site layout problems. These results support the findings of previous studies, such as Elbeltagi and Hegazy (2001), Ning *et al.* (2010), Xu and Li (2012), Yahya and Saka (2014), and Ning *et al.* (2016) who respected both mathematical algorithms and actors' expertise for site layout planning. It is also important to ensure the data correction and updating for site layout planning. Thus, it is suggested that advanced technologies, especially BIM platforms, should be used to facilitate the data provision and automation for the systematic site layout process. This thesis suggests a BIM-based data collection and processing system to calculate and integrate all the required data for the site layout models. These statements support the findings of previous studies, such as Said and El-Rayes (2014) who automated the extraction of project spatial and temporal data from the BIM and other sources to minimize site layout-related costs; Kumar and Cheng (2015) who used BIM-based data to compute the required sizes and dimensions for facilities; Hammad et al. (2016a) who integrated BIM and project schedule to generate quantitative data for the estimation of travel frequencies between facilities; or Schwabe et al. (2019) who retrieved data from BIM to develop a rule-based model for checking the site layout planning tasks.

Managerial implications

The important implication of the proposed CSC optimization model (presented in **chapter 2**) is the integration of the TPL partnership for CSC operations. In the proposed model, there are important SC actors: the owner, the TPL provider, the contractors, and suppliers. In order to succeed in using the TPL service, the owner has to show the commitment to solving logistics issues by initiating the TPL solution. Then, the general contractor follows the owner's mandate to select the TPL provider. The TPL provider plays the focal role in construction logistics coordination with supplier selection, material procurement, transportation, storage, and handling to the site. In large construction projects, the owner and/or the general contractor can select remote suppliers who offer the low prices and transportation fees for purchasing materials but require large purchasing quantity. Thus, the use of the TPL provider's intermediate warehouse for the storage of purchased materials is an option for optimizing the logistics costs. The TPL service is used to improve the professional in construction logistics since no expertise in logistics may be found in the owner's project management team. The above analyses show that the material prices account for a large proportion of total SC cost, especially in the large project; thus, the price uncertainties can result in a significant increase in the total SC cost. This result supports the finding of Liu et al. (2017) in researching the construction logistics cost for a large project. Thus, it is recommended to collaborate with a TPL partner in order to search for the price discounts as well as reduce the price uncertainties offered by the suppliers. The above analyzes also reflect the impacts of uncertainties in delivery lead-time and daily demand on the storage cost. Thus, the construction managers are required to have suitable strategies to deal with the uncertainties in order to reduce the SC cost. Finally, the risk of failure in using the TPL provider can exist when the relevant actors, especially the general contractor, do not accept the role of the TPL as the logistics coordinator. Ekeskär and Rudberg (2016) report that the general contractor overlooks the TPL provider by not following agreements and regulations, which should be applied for logistics coordination. The general contractor even sends a message to the subcontractors that "the agreements and regulations concerning the TPL solution are not that important." Therefore, in order to apply the proposed model, the commitment of the owner and contractors for the use of the TPL partnership for the logistics activities is fundamental.

The distinctive implication of the proposed site layout framework (presented in **chapter 3**) is the integration of systematic site layout process, BIM technology, and actors' expertise for a smooth and productive site layout plan. This triad supports the site planners to analyze the resources, collect and estimate the data, develop the site layout models, share and update the data, as well as select the optimal solution. Without a systematic approach for site layout planning, site planners may not know how to begin a planning process, ignore some important analysis of the resources, and get troubles in data preparation for the layout modeling and solution selection. As a consequence, they tend to select a layout solution only based on their past experiences. BIM technology supports the site layout planning not only in data provision and calculation but also in data sharing and updating. The BIM-based platform can benefit construction companies with data correction and automation to deal with changes in project schedule or resource availability. A set of objectives needs to be achieved for site layout planning; thus, the relevant actors' expertise is required to determine the weights of these objectives. When logistical relationships between the facilities such as material flows can be quantitatively estimated on the data from BIM, their non-logistical relationships such as environmental issues or safety require the actors' evaluations based on the knowledge-based rules. Therefore, the reliability of the relevant actors' expertise has to be ensured to make site layout plans satisfying the practical needs of current site layout planning.

Limitations and further researches

As shown in the decision-based framework for construction logistics and SCM (**Figure 1.9** of **chapter 1**), the decisions are identified for the three phases of a CSC project: planning and design, procurement, and construction and delivery. The decisions for the stage of planning and design are made at the strategic level, while the decisions focused on the phases of procurement and construction and delivery are towards the tactical and operational levels. In the scope of this thesis, we mostly focus on the decisions for the last two phases to leverage the SC application for construction logistics improvement. Thus, further researches are suggested to focus on the strategic decisions for the first stage of planning and design. Further researches can concentrate on developing tools and methods for CSC planning and management, frameworks for CSC configuration and risk mitigation, or innovative approach for construction IT systems.

The employment of the TPL solution is still a new phenomenon in the construction industry; thus, the proposed model (presented in **chapter 2**) can encounter some limitations. The proposed model should be validated by further implications to show its efficiency since it is only applied for a single case in this study. Besides, the proposed model only focuses on the single objective of SC cost, while other objectives are not yet mentioned. Thus, a multi-objective optimization model can be developed for further researches. Further researches can also be conducted to investigate the role of TPL in SC integration to improve the performances in service level, SC sustainability, or technology adoption in the construction industry.

The other limitation is that the proposed framework (presented in **chapter 3**) is only applied for one example of a medium-size project. For further research, the proposed framework can be used for small, medium, or even large scale projects to explore its potential for practical application. BIM can provide rich data for different project scales, especially for a large-scale project where many activities are necessary to be updated for site layout planning. Meanwhile, knowledge-based reasoning is considered to be suitable for small and medium-scale projects since it requires the contributions of managers' expertise. For large scale projects, the relationships among a large number of facilities become more complex, and this requires more involvement of managers in evaluating the workflow, safety, and preference among the facilities. In order to apply the expertise for site layout planning, it is suggested that the large-scale project schedule should be divided into possible short-term phases to reduce the complexity. Being integrated with IoT (Internet of Things), such as RFID (Radio Frequency Identification) or BLE (Bluetooth Low Energy), the proposed framework can be used for further researches to deal with real-time changes of day-to-day layout practice. RFID or BLE can support the automated tracking of on-site resources and available spaces; thus, site managers can continuously monitor and consider available spaces and required facilities for site layouts. Real-time data collected from these tracking technologies can be automatically integrated into BIM models to generate real-time layouts.

APPENDIX I

LINGO CODE

MODEL:

```
! This optimizes construction supply chain (CSC) with TPL partnership, taking into account two kinds of materials: type 1 (materials can be transported to warehouse or directly sent to construction site), and type 2 that can only be sent to the construction site. This model minimizes the cost of inventory procuring, handling and transportation of materials.
```

SETS:

```
!*************************************     Sets are inserted here *****************************************************************************************;

! Here are the sets;
!**here are defined the primitive sets**;
!***period(t) is the planning period sets ,with t as an index ,in this example we consider 1 month as the planning period, each period is t  *** ;
period/1,2,3,4/;
!*** supplier(s): supplier set, combining the supplier for both materials, S = S1∪ S2, S = S1∩ S2 = {∅} ***;
supplier/1,2,3,4,5,6,7,8,9,10,11,12/;
!*** material(m) is the material set combining both the two type of materials M1,and M2 M = M1∪ M2 , M1 ∩ M2 = {∅} ***;
! in this study we consider 4 materials cement, steel, dinas, lumber;
material/1,2,3,4/;
!***** here are defined the derived sets for the combined set of the materials and the suppliers *****;
```

!material period (material, period) derived sets material_period (m,t);

material_period (material, period);

!materialsupplier (material, supplier): derived sets material_period (m,s); material supplier (material, supplier); material supplier period (material, supplier, period);

!materialt1 type 1, this type can be sent either to the construction site or to TPL warehouse, also index is m

fw(m): is the fixed cost for warehousing material 1 at TPL warehouse

h(m): unit holding cost for material 1 at TPL warehouse

v(m): inspection cost for material 1

I(M): transportation cost for material 1 from TPL to construction site

ss(m): safety stock for material 1 at the TPL warehouse

in(m): initial inventory for material 1 at the TPL warehouse

w(m): decision variable = 1 if material m is stored at the warehouse

k(m): pre-loading cost for material M1

ddmend(m): daily demand for material M1;

material t1(material) /2,3,4/: fw, h, v, i, ss, in, w, k, ddemand;

!supplier 1 that provides material 1 index s in this example supplier 1 can supply material 1;

Supplier t1(supplier)/4,5,6,7,8,9,10,11,12/;

! material supplier t1 (m,s): derived set for material 1 and supplier 1

q(m,s): fixed lot size applied by supplier 1 for material 1

ts(m,s): transportation cost from supplier to the TPL warehouse

slect1(M,S): decision variable if supplier 1 is selected for material1

FSt1(M,S): fixed supplier 1 cost for material 1

ut1(M,S): capacity of supplier 1 for material 1

dct1(m,s): direct transportation cost related supplier 1 for material 1

umt1(m,s): capacity of material 1 at supplier 1;

materialsuppliertt1(materialt1,suppliert1):q, TS,slect1,FSt1,ut1,dct1,umt1;

! materialt1_period (materialt1, period): derived set for material 1 and supplier 1

iw(m,t): inventory for material 1 at the supplier

y(m,t): transported quantity of material m at period t

```
d(m,t): demand for material 1 at period t
z(m,t): capacity for material 1 at the construction site ;
materialt1_period (materialt1,period): iw,Y,d,z;
materialsupplierperiodt1(materialt1,suppliert1,period):x,A,ept1;
! materialsupplierperiodt1(m,s,t): derived set for material 1 and supplier 1 and period t
x(m,s,t): direct transported quantity for material 1
a(m,s,t): number of deliveries from supplier to the warehouse
EPt1(m,s,t): the expected cost for material 1 and supplier 1;
!materialt2(m): materialt2 type 2  ,this type can only be sent in truckload quantity ,with the
direct shipment quantity set by the supplier, also index is m in this study only cement (m=1)
should be directly shipped to the construction site;
!l(m): pre-loading cost for material M2 ;  materialt2(material)|#NOT# @IN( materialt1, &1):l;
!supplier 2 for material type 2; suppliert2(supplier)|#NOT# @IN(suppliert1, &1);
!derived set for material 2 and period
g(m,t): demand for material 2
j(m,t): construction site capacity for material 1;
materialt2_period(materialt2,period): g,j;
! slect2 :decision variable for selection for supplier s2 for material  m2
FSt2: fixed cost for supplier s2
ut2: capacity set by supplier s2 for material m2
DCT2: direct transportation cost for material m2 from supplier to the construction site;
materialsuppliert2(materialt2,suppliert2):slect2,FSt2,ut2,dct2;
!derived set for material 2 and period
!o(m,s,t): direct quantity sent from the supplier to the construction site ;!ept2(m,s,t) :purchasing
price for material m2, supplier m2, at period t;
materialsupplierperiodt2 (materialt2,suppliert2,period): o,ept2;
ENDSETS

!****************DATA is inserted here **************************************;
DATA:
```

```
! Here are the parameters;
! Import the data from Excel;
q,k,l,h,v,fw,i,IN,ts,dct1,dct2,ut1,ut2,ept1,ept2,ss,Z,d,g,fst1,fst2=
 @OLE('DATA WITH THE THIRD PARTY
LOGISTICS.xlsx',"q","k","l","h","v","fw","i","IN","ts","dcone","dctwo","uone","utwo","epo
ne","eptwo","SS","Z","d","G","fstone","fstwo");
! Exporting Solutions to datasheet;
@ole('DATA WITH THE THIRD PARTY
LOGISTICS.xlsx','w','a','x','y','iw',"o","slecone","slectwo")= w,a,x,y,iw,o,slect1,slect2;
 ENDDATA
! n is the length of the planning period set;
n=4;
! OBJECTIVE function;
!the objective is to minimize the Construction supply chain;
!***************   the objective function is to minimize the total construction supply
chain with third party logistic partnership   ******** ';
[OBJ] min = cost;
cost = pc + tc + hc + vc ;
! PC is the total procurement cost and ordering cost;
PC =
@SUM(MATERIALt1(M):@SUM(SUPPLIERt1(S):FSt1(M,s)*slect1(M,s)))+@SUM(MAT
ERIALt2(M):@SUM(SUPPLIERt2(S):FSt2(M,s)*slect2(M,s)))
+@SUM(materialt1(M):@SUM(suppliert1(S):@SUM(PERIOD(T):K(M)*A(M,s,T)*Q(M,s)
)))
+@SUM(materialt1(M):@SUM(suppliert1(S):@SUM(PERIOD(T):K(M)*X(M,s,T))))
+@SUM(materialt1(M):@SUM(suppliert1(S):@SUM(PERIOD(T):EPt1(M,s,T)*A(M,S,T)*
Q(M,s))))
+@SUM(materialt1(M):@SUM(suppliert1(S):@SUM(PERIOD(T):EPt1(M,S,T)*X(M,S,T))
))
```

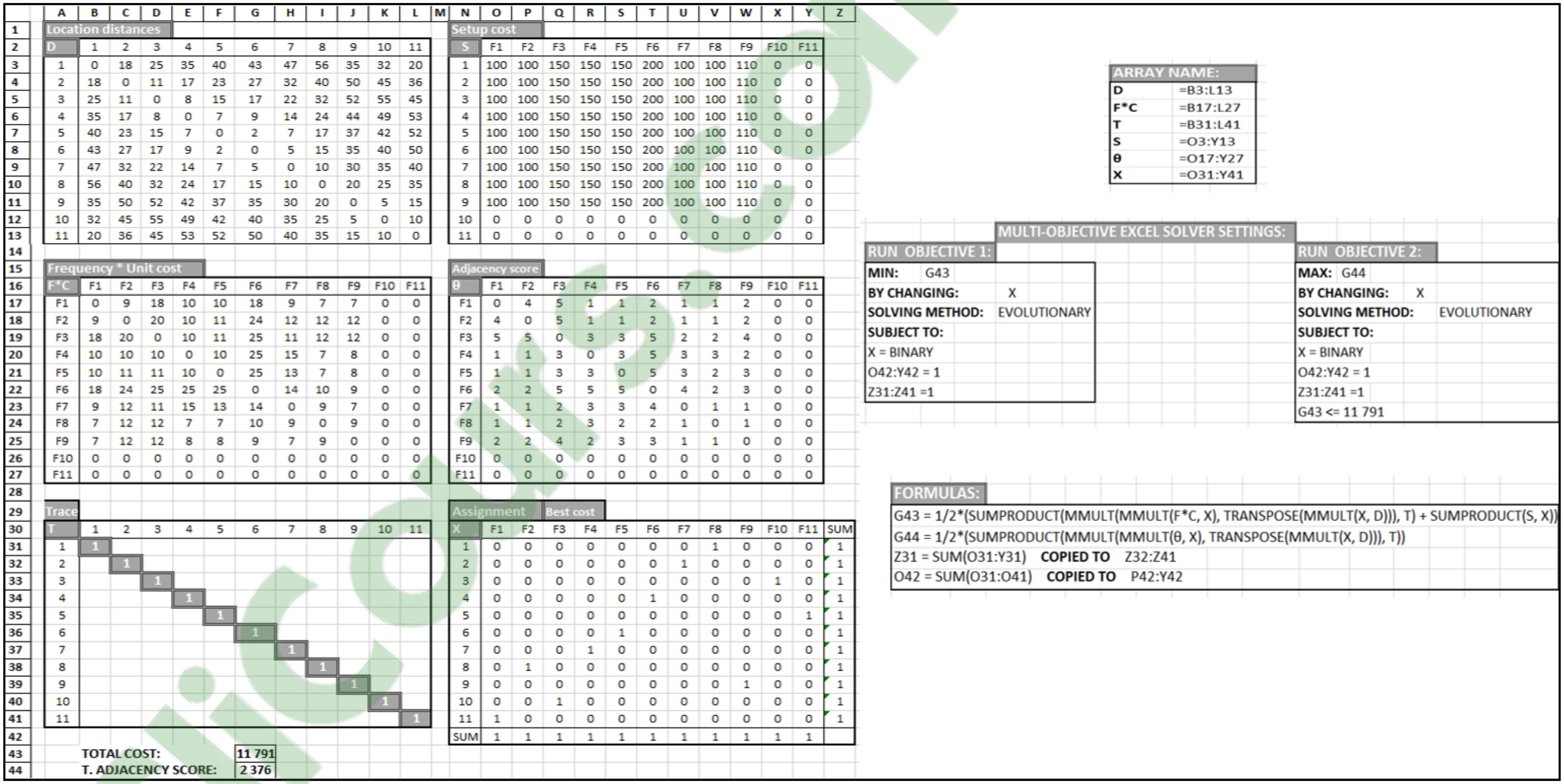
```
+@SUM(materialt2(M):@SUM(suppliert2(S):@SUM(PERIOD(T):EPt2(M,S,T)*o(M,S,T)))
)
+@sum(materialt2(M):@sum(suppliert2(s):@sum(period(t):l(m)*o(m,s,t))))
+@sum(materialt2(M):@sum(suppliert2(s):@sum(period(t):EPt2(m,s,t)*o(m,s,t))));
!TC is the total transportation cost for both material from the supplier to the warehouse ,and
from the construction site;
TC=
+@SUM(materialt1(M):@SUM(suppliert1(S):@SUM(PERIOD(T):(TS(M,S)*A(M,S,T)))))
+@SUM(materialt1(M):@SUM(suppliert1(S):@SUM(PERIOD(T):DCt1(M,S)*X(M,S,T))))
+@SUM(materialt2(M):@SUM(suppliert2(S):@SUM(PERIOD(T):DCt2(M,S)*o(M,S,T))))
+@SUM(materialt1(M):@sum(suppliert1(M):@SUM(PERIOD(T):I(M)*y(M,T))));
! HC is handling cost at the TPL warehouse for material 1;
HC=    @SUM(materialt1(M):FW(M)*W(M))
+@SUM(materialt1(M):@SUM(suppliert1:@SUM(PERIOD(t)|(T       #GT#1):0.5*IW(M,T-
1)+H(M))))
+@SUM(materialt1(M):@SUM(suppliert1(S):@SUM(PERIOD(T):0.5*A(M,S,T)*Q(M,S)*
H(M))))
+@SUM(materialt1(M):@SUM(PERIOD(T):@SUM(suppliert1(S):0.5*IW(M,T)*H(M))));
! material 1 checking cost at the warehouse;
VC =
@SUM(materialt1(M):@SUM(suppliert1(S):@SUM(PERIOD(T):V(M)*A(M,S,T)*Q(M,S))
));
!**********************                    CONSTRAINTS
***************************************************************************
*******;
! the flow balance equation at the TPL warehouse for material M1;
@FOR(materialt1(M):@FOR(PERIOD(T)| T #Ge#2 #and# (T #lt#n):
IW(M,T) = IW(M,T-1) +@sum(suppliert1(s):A(M,s,T)*Q(M,s))-Y(M,T)));
 !initial inventory for material 1;
@FOR(materialt1(M):@FOR(PERIOD(T)| T #EQ#1:
```

```
IW(M,T) = In(M)+@sum(suppliert1(s):A(M,s,T)*Q(M,s))-Y(M,T)));
! at the end of the planning period all material M1 must be consumed;
@FOR(materialt1(M):@FOR(PERIOD(T)| T #EQ#4:
Y(m,T)= IW(m,T-1) +@sum(suppliert1(s):A(m,s,T)*Q(m,s))));
!safety stock constraint;
@FOR(materialt1(M):@FOR(PERIOD(T)| (T #GE#2) #and# (T #lt#4):
 IW(M,T-1) +@sum(suppliert1(s):A(M,s,T)*Q(M,s))>= Y(M,T) +SS(M)));
@FOR(materialt1(M):
 In(M) +@sum(suppliert1(s):A(M,s,1)*Q(M,s))>= Y(M,1) +SS(M));
!supplier1 capacity constraint;
@FOR(MATERIALt1(M):@for(suppliert1(s):@sum(period(t):
A(M,s,T)*Q(M,s) +X(M,s,T)) <= Ut1(M,s)*SLECt1(M,S)));
!supplier2 capacity for m2;
@FOR(MATERIALt2(M):@for(suppliert2(s):@sum(period(t):
o(M,s,T)) <= Ut2(M,s)*SLECt2(M,S)));
! the material M1 demand constraint;
@FOR(materialt1(M):@FOR(PERIOD(T):
@sum(suppliert1(S):X(M,s,T)) + Y(M,T) >= D(M,T)));
! the material M2 demand constraint;
@FOR(materialt2(M):@FOR(PERIOD(T):
@sum(suppliert2(S):o(M,s,T))  >= g(M,T)));
!  the construction site capacity constraint ;
@FOR(MATERIALt1(M):@FOR(PERIOD(T):
@sum(suppliert1(s): X(M,s,T))  <= Z(M,T)-Y(M,T)));
! the construction site capacity ;
@FOR(MATERIALt2(M):@FOR(PERIOD(T):
@sum(suppliert2(s): o(M,s,T))  <= J(M,T)));
!if the material M1 is not stored at the warehouse, no delevery is made of material M1 to the
warehouse;
@FOR(materialt1(M):@FOR(PERIOD(T):
```

```
 @FOR(suppliert1(s):A(M,s,T) <= W(M)*4500)));
! MATERIAL M1 is not sent directly if it's stored at the warehouse
;@FOR(materialt1(M):@FOR(PERIOD(T):
 @FOR(suppliert1(s):x(M,s,T) <= (1-W(M))*45000)));
!if the material M1 is not stored at the warehouse, no delevery is made of material M1 from
the warehouse to the construction site;
@FOR(materialt1(M):@FOR(PERIOD(T):
 @FOR(suppliert1(s):y(M,T) <= W(M)*4500)));
!for each material only one supplier is selected ;
@for(materialt1(m):@sum(suppliert1(s) : slect1(m,s)) = 1);
@for(materialt2(m):@sum(suppliert2(s) : slect2(m,s)) = 1);
! binary variables constraints;
@FOR (materialt1(M):@for(suppliert1(s): @BIN(slect1)));
@FOR (materialt2(M):@for(suppliert2(s): @BIN(slect2)));
@FOR (material(M): @BIN(W));
! int variables constraints;
@FOR (material_period(M,T) :@GIN(Y(M,T)));
@FOR (material_period(M,T) :@GIN(IW(M,T)));
@FOR (materialsupplierperiod(M,s,T) :@GIN(A(m,s,t)));
@FOR (materialsupplierperiod(M,s,T) :@GIN(X(m,s,t)));
@FOR (materialsupplierperiodt2(M,S,T):@GIN(O(m,s,t)));
END
```

APPENDIX II

SPREADSHEET-BASED MULTI-OBJECTIVE SITE LAYOUT OPTIMIZATION.



Location distances

D	1	2	3	4	5	6	7	8	9	10	11
1	0	18	25	35	40	43	47	56	35	32	20
2	18	0	11	17	23	27	32	40	50	45	36
3	25	11	0	8	15	17	22	32	52	55	45
4	35	17	8	0	7	9	14	24	44	49	53
5	40	23	15	7	0	2	7	17	37	42	52
6	43	27	17	9	2	0	5	15	35	40	50
7	47	32	22	14	7	5	0	10	30	35	40
8	56	40	32	24	17	15	10	0	20	25	35
9	35	50	52	42	37	35	30	20	0	5	15
10	32	45	55	49	42	40	35	25	5	0	10
11	20	36	45	53	52	50	40	35	15	10	0

Setup cost

S	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11
1	100	100	150	150	150	200	100	100	110	0	0
2	100	100	150	150	150	200	100	100	110	0	0
3	100	100	150	150	150	200	100	100	110	0	0
4	100	100	150	150	150	200	100	100	110	0	0
5	100	100	150	150	150	200	100	100	110	0	0
6	100	100	150	150	150	200	100	100	110	0	0
7	100	100	150	150	150	200	100	100	110	0	0
8	100	100	150	150	150	200	100	100	110	0	0
9	100	100	150	150	150	200	100	100	110	0	0
10	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0

Frequency * Unit cost

F*C	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11
F1	0	9	18	10	10	18	9	7	7	0	0
F2	9	0	20	10	11	24	12	12	12	0	0
F3	18	20	0	10	11	25	11	12	12	0	0
F4	10	10	10	0	10	25	15	7	8	0	0
F5	10	11	11	10	0	25	13	7	8	0	0
F6	18	24	25	25	25	0	14	10	9	0	0
F7	9	12	11	15	13	14	0	9	7	0	0
F8	7	12	12	7	7	10	9	0	9	0	0
F9	7	12	12	8	8	9	7	9	0	0	0
F10	0	0	0	0	0	0	0	0	0	0	0
F11	0	0	0	0	0	0	0	0	0	0	0

Adjacency score

θ	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11
F1	0	4	5	1	1	2	1	1	2	0	0
F2	4	0	5	1	1	2	1	1	2	0	0
F3	5	5	0	3	3	5	2	2	4	0	0
F4	1	1	3	0	3	5	3	3	2	0	0
F5	1	1	3	3	0	5	3	2	3	0	0
F6	2	2	5	5	5	0	4	2	3	0	0
F7	1	1	2	3	3	4	0	1	1	0	0
F8	1	1	2	3	2	2	1	0	1	0	0
F9	2	2	4	2	3	3	1	1	0	0	0
F10	0	0	0	0	0	0	0	0	0	0	0
F11	0	0	0	0	0	0	0	0	0	0	0

Trace

T	1	2	3	4	5	6	7	8	9	10	11
1	1										
2		1									
3			1								
4				1							
5					1						
6						1					
7							1				
8								1			
9									1		
10										1	
11											1

Assignment **Best cost**

X	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	SUM
1	0	0	0	0	0	0	0	1	0	0	0	1
2	0	0	0	0	0	0	1	0	0	0	0	1
3	0	0	0	0	0	0	0	0	0	1	0	1
4	0	0	0	0	0	1	0	0	0	0	0	1
5	0	0	0	0	0	0	0	0	0	0	1	1
6	0	0	0	0	1	0	0	0	0	0	0	1
7	0	0	0	1	0	0	0	0	0	0	0	1
8	0	1	0	0	0	0	0	0	0	0	0	1
9	0	0	0	0	0	0	0	0	1	0	0	1
10	0	0	1	0	0	0	0	0	0	0	0	1
11	1	0	0	0	0	0	0	0	0	0	0	1
SUM	1	1	1	1	1	1	1	1	1	1	1	

TOTAL COST:	11 791
T. ADJACENCY SCORE:	2 376

ARRAY NAME:

D	=B3:L13
F*C	=B17:L27
T	=B31:L41
S	=O3:Y13
θ	=O17:Y27
X	=O31:Y41

MULTI-OBJECTIVE EXCEL SOLVER SETTINGS:

RUN OBJECTIVE 1:

MIN: G43
BY CHANGING: X
SOLVING METHOD: EVOLUTIONARY
SUBJECT TO:
X = BINARY
O42:Y42 = 1
Z31:Z41 =1

RUN OBJECTIVE 2:

MAX: G44
BY CHANGING: X
SOLVING METHOD: EVOLUTIONARY
SUBJECT TO:
X = BINARY
O42:Y42 = 1
Z31:Z41 =1
G43 <= 11 791

FORMULAS:

G43 = 1/2*(SUMPRODUCT(MMULT(MMULT(F*C, X), TRANSPOSE(MMULT(X, D))), T) + SUMPRODUCT(S, X))
G44 = 1/2*(SUMPRODUCT(MMULT(MMULT(θ, X), TRANSPOSE(MMULT(X, D))), T))
Z31 = SUM(O31:Y31) **COPIED TO** Z32:Z41
O42 = SUM(O31:O41) **COPIED TO** P42:Y42

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