Construction Supply Chain Planning: the Value of Collaboration and Integration

by

Walid ELMUGHRABI

THESIS PRESENTED TO ÉCOLE DE TECHNOLOGIE SUPÉRIEURE
IN PARTIAL FULFILMENT FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY
Ph.D.

MONTREAL, JANUARY 11, 2021

ÉCOLE DE TECHNOLOGIE SUPÉRIEURE
UNIVERSITÉ DU QUÉBEC

BOARD OF EXAMINERS

THIS THESIS HAS BEEN EVALUATED

BY THE FOLLOWING BOARD OF EXAMINERS

Mr. Amin Chaabane, Thesis Supervisor
Department of systems engineering at École de technologie Supérieure

Mr. Thien-My Dao, Thesis Co-supervisor
Department of mechanical engineering at École de technologie Supérieure

Mr. Alain April, President of the Board of Examiners
Department of Software Engineering and Information Technologie at École de technologie Supérieure

Mr. Mustapha Ouhimmou**,** Member of the jury
Department of systems engineering at École de Technologie Supérieure

Mr. Georges Abdul-Nour, External Evaluator
Department of industrial engineering at Université du Québec à Trois-Rivières

THIS THESIS WAS PRESENTED AND DEFENDED

IN THE PRESENCE OF A BOARD OF EXAMINERS AND PUBLIC

DECEMBER 14, 2020

AT ÉCOLE DE TECHNOLOGIE SUPÉRIEURE

FOREWORD

This thesis produced the following journal articles and conference papers:

a) Decision-making in Construction Logistics and Supply Chain Management: Evolution and Future Directions. *A conference paper. 7th International Conference on Information Systems, Logistics and Supply Chain ILS Conference 2018, July 8-11, Lyon,* (Published);

b) Present focuses and future directions of decision-making in construction supply chain management: a systematic review. *International Journal of Construction Management* (Published);

c) Collaborative supply chain planning and scheduling of construction projects. *IFAC World Congress July 11-17, 2020, Berlin, Germany.* (Published);

d) Collaborative supply chain planning and scheduling of construction projects. *Construction Innovation Journal* (Submitted);

e) From a literature review to a conceptual framework for inventory management in Construction Supply Chain Management. *Construction Management and economic Journal.* (Submission soon).

ACKNOWLEDGMENTS

Along the way, several people have contributed in a variety of ways to this research. Firstly, I would like to express my sincere gratitude to my advisor Prof. Amin Chaabane for the continuous support of my Ph.D. study and related research, for his patience, motivation, and immense knowledge. His guidance helped me in all the time of research. I could not have imagined having a better advisor and mentor for my Ph.D. study.

Besides, I would like to thank my co-supervisor, Prof. Thien-My Dao, for his insightful comments and encouragement. I would like to thank my committee members Prof. Alain April, Prof. Mustapha Ouhimmou, and Prof. Georges Abdul-Nour for their insightful comments.

In addition, I would like to thank my family, my wife, for their wise counsel and sympathetic ear. You are always there for me.

I am very grateful to the Libyan Ministry of Education for providing financial support throughout my Ph.D. program.

I would also like to thank my colleagues in the Numerix laboratory for all the great times we shared and provide a friendly environment that I had the pleasure to work in it.

Planification de la chaîne d'approvisionnement de la construction: la valeur de la collaboration et de l'intégration

Walid ELMUGHRABI

RÉSUMÉ

Dans le secteur de la construction, l'amélioration de l'efficacité logistique est essentielle pour mettre en œuvre les principes de la gestion des chaînes d'approvisionnement (SCM). En se basant sur la revue de la littérature, on a trouvé les principales décisions actuellement qui portent sur la logistique de la construction et la SCM. Ces décisions sont définies pour trois phases critiques d'un projet d'approvisionnement: préparation, planification et conception, achat et exécution. Cette thèse porte sur le développement de la logistique dans la construction tout en prenant en considération les décisions prises en matière de logistique de la construction, pour modéliser et utiliser de la meilleure façon les processus de d'approvisionnement dans l'industrie de la construction. Une revue de littérature systématique est utilisée pour identifier les priorités actuelles et discuter des futures orientations de la prise de décision dans la gestion de la chaîne d'approvisionnement du secteur de la construction (CSCM). Les résultats montrent qu'à présent, les applications du CSCM se concentrent principalement sur la gestion du matériel et des ressources utilisant la chaîne d'approvisionnement interne. Les décisions stratégiques relatives à la création de partenariats, à la planification basée sur la technologie de l'information et à la planification basée sur la logistique ne sont pas prises au stade initial de la planification et de la conception. Pour le développement futur de l'application du CSCM, on propose un cadre d'étude permettant d'exploiter les trois points essentiels, La planification et la conception collaboratives avec des techniques avancées, l'approvisionnement et la construction et la livraison du projet.

En outre, l'intérêt des chercheurs et des professionnels à l'égard de la CSCM s'est accru récemment avec l'élaboration théorique et la mise en œuvre de Building Information Modelling (BIM). Le BIM fournit non seulement une conception avancée des projets de construction, mais il aide les parties prenantes à gérer la chaîne d'approvisionnement de la construction (CSC). La gestion des stocks est l'un des piliers essentiels de la CSCM. Afin de consolider, évaluer et développer les possibilités de recherche futures par l'identification des lacunes en matière de recherche dans ce domaine, l'objectif principal chapitre est: Premièrement, proposer une analyse documentaire sur la gestion des stocks dans le contexte du CSC. Deuxièmement, dites plutôt fournir un cadre conceptuel et consolide la recherche dans ce domaine, qui se compose de trois parties : Le premier partie est lié à la nature des données et des informations nécessaires pour mettre en œuvre des politiques d'inventaire efficaces. La deuxième partie est liée à la collaboration étendue entre les parties prenantes du CSC pour la gestion optimale des stocks dans le CSC. La troisième partie est liée à l'incertitude et aux risques pour obtenir des politiques d'inventaire réalistes et applicables. Ce chapitre deux est utile à la fois pour les professionnels du CSCM et les chercheurs, puisqu'il décrit les diverses connaissances de la recherche dans ce domaine.

Par ailleurs, on propose un modèle intégré pour la planification de la chaîne d'approvisionnement de la construction collaborative (CSC) qui traite le problème intégré de l'ordonnancement des projets et de la commande des matériaux. L'objectif principal est de parvenir à une meilleure coordination et, par conséquent, de réduire le coût total de la CSC. Plus précisément, nous considérons un CSC à deux échelons composé d'un manufacturier, d'un entrepôt et de plusieurs sites de construction ou de multiples projets de construction indépendants. Les projets ont besoin de différents matériaux fournis par le même fabricant avec une capacité limitée. Le début de chaque activité est subordonné à la disponibilité des matériaux sur les sites de construction. Un modèle de programmation linéaire mixte (MILP) est proposé dans le but de réduire les coûts totaux d'approvisionnement tout en permettant la collaboration entre les contractants. Le modèle a été mis en œuvre à l'aide du IBM ILOG CPLEX Optimization Studio. Le modèle proposé est analysé par une étude numérique pour montrer les avantages de la planification collaborative dans la gestion des projets de construction. Le modèle de décision aide également à trouver les séquences de projets de construction pratiques ainsi que la commande, la fabrication et plans d'inventaires pour les participants SC.

Mots-clés : chaîne d'approvisionnement, logistique de construction, modèles d'inventaire, collaboration, modélisation des informations du bâtiment

Construction Supply Chain Planning: The Value of Collaboration and Integration

Walid ELMUGHRABI

ABSTRACT

In the construction sector, improving logistics efficiency is essential to implement supply chain management (SCM). Based on the literature review, we found the main decisions currently focused on construction logistics and SCM. These decisions are defined for three critical phases of a supply chain project: preparation, planning and design, procurement, and execution. This thesis focuses on developing logistics in construction while considering decisions making to construction logistics for modeling and making the best use of supply chain processes in the construction industry. A systematic literature review methodology is utilized to identify the present focuses and discuss future decision-making directions 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 supply chain (SC) integration. Strategic decisions related to building partnerships, IT-based planning, and logistics-based planning are not conducted at the early planning and design phase. For future CSCM application trends, a framework is proposed to leverage the three essential points, the collaborative planning and design with advanced techniques, procurement, and construction and delivery of the project.

Besides, Academic and practitioners' interest in Construction Supply Chain Management (CSCM) has increased recently with the theoretical development and implementation of Building Information Modelling (BIM). BIM provides an advanced construction project design, but it assists stakeholders in the management of the construction supply chain (CSC). Inventory management is one of the essential pillars of CSCM. To consolidate, evaluate and develop the scope of future research opportunities by identifying research gaps in this field, the main objective of this chapter is: First, it offers a literature review on inventory management in the context of the CSC. Second, it provides a conceptual framework map and consolidates the research in this field, composed of three parts. The first one is related to the nature of data and information necessary to implement efficient inventory policies. The second is associated with the extended collaboration between CSC stakeholders for inventory optimization in CSC. Finally, the third part relates to the uncertainty and risks to obtain realistic and applicable inventory policies. The review chapter is useful for both practitioners in CSCM and academics as it outlines the diverse knowledge of research in this area.

Therefore, we propose an integrated model for collaborative construction supply chain (CSC) planning that deals with the integrated problem of project scheduling and material ordering. The main objective is to achieve more coordination and, therefore, to reduce the total cost of the CSC. More specifically, we consider a two-echelon CSC composed of a manufacturer, a warehouse, and multiple construction sites where multiple independent construction projects are planned. The projects need various materials provided by the same manufacturer with a limited capacity. The starting time of each activity is subject to the availability of materials in the construction sites. A mixed-integer linear programming (MILP) model is proposed to reduce the total SC costs while collaboration between contractors is possible. The model was implemented using the IBM ILOG CPLEX Optimization Studio. The proposed model is analyzed through a numerical study to show the benefits of collaborative planning in construction project management. The decision model also helps find practical construction projects' sequences and suitable materials ordering, manufacturing, and inventories plans for SC participants.

Keywords: supply chain, construction logistics, inventory models, collaboration, building information modeling

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

LIST OF ABREVIATIONS AND ACRONYMS

CSC	Construction Supply Chain
MILP	Mixed Integer Linear Programming
CSCM	Construction Supply Chain Management
GA	Genetic algorithms
GC	General Contractor
IT	Information Technology
BIM	Building Information Modeling
SC	Supply chain
SCM	Supply Chain Management
EOQ	Economic order quantity

INTRODUCTION

Supply Chain Management (SCM) was first introduced in the manufacturing industries. SCM refers to maximizing customer satisfaction and reducing cost. Supply chain components, including facilities, sourcing, inventory, transportation, and pricing decisions, play a significant role in an organization's success or failure (Aquilano & Smith, 1980). Usually, these decisions can be classified based on the frequency and the period during which a decision phase impacts. During the last decades, SCM has been increasingly applied to many sectors to improve business performance, improve the customer experience (response time), lower cost, and ensure better quality (Dodin & Elimam, 2001; Seuring, 2012).

In construction, the application of SCM concepts is frequently used to guide project managers in strategic planning to achieve strong partnerships with suppliers and obtain more operational construction efficiency (Azambuja & O'Brien, 2008). The importance of SCM in improving construction management has been recognized since the 1990s. In this specific period, the literature and research papers mostly discussed whether SCM should be applied for the construction industry or not, due to the differences between the manufacturing and construction sectors. In the 2000s, research studies focused on analyzing and exploring the relevant aspects of SCM in construction and the role that it can play in this field (Vrijhoef & Koskela, 2000).

Inventory decisions, which is one of the vital logistical drivers in the supply chain (SC), has been widely studied and applied in other industries such as manufacturing (Okuda, Ishigaki, Yamada, & Gupta, 2018), (Spiliotopoulou, Donohue, Gürbüz, & Heese, 2018) and (Taleizadeh & Noori-daryan, 2016). Inventory management control is also essential for the construction industry. It can be used not only to reduce materials and logistics costs for a specific project through better collaboration between the supply chain partners (Zou, 2012). In the context of the SC, inventory is a crucial driver for efficient material supply and distribution. A construction project has typically limited working space at the construction site. Thus, material inventories are kept at a minimum level. The Just In Time (JIT) process is implemented in the construction supply chain to control inventory levels (Amornsawadwatana, 2011).

The construction industry is a necessary and vital sector for the worldwide economy; however, it is 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 low quality, resulting in an industry with constant and repeated problems to manage (Aloini et al., 2012). In construction networks, clients, consultants, contractors, designers, subcontractors, and suppliers are key nodes in a complex network that interact with each other, connected by interfaces embracing knowledge transfer, information exchange, and financial and contractual relationships. Nevertheless, these networks are noted with inefficient collaborations; for instance, the splitting up of design and construction, absence of integration and coordination between different functional disciplines, and poor communication (Behera et al., 2015). Major problems occurring in relationships among stakeholders of construction projects are summarized in Figure 0.1.

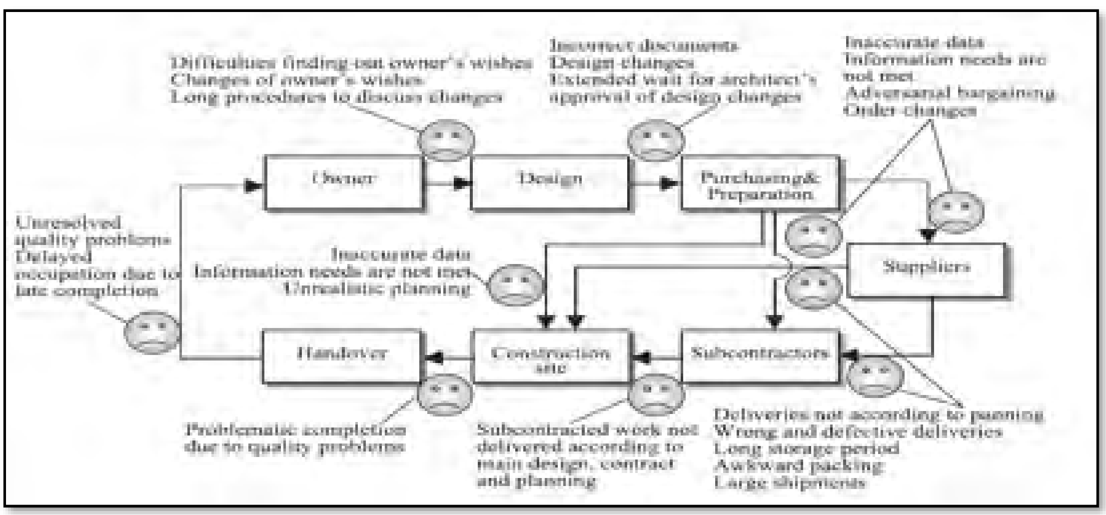

Figure 0.1 Major problems in construction relationships
Taken from Xue et al. (2005) & Behera et al. (2015)

The lack of sharing of information within the construction project is a critical problem. It represents a significant source of delays, errors, and duplications on projects (Validyanathan , 2009). According to Winch (2010), construction projects are heavily dependent on inventory management. If the inventory is not craftily deployable, the cost of construction is heavily affected. Variable material is also variably priced, and managing inventory is a necessary factor for the effective delivery of a project. However, a study by Gould & Joyce (2009) suggests that effective inventory management in construction enhances the concept of collaboration.

The interaction of management and information sharing is one approach to diagnose a problem. Each construction project contains information to be processed because many projects do not have the information to process their project activities; thus, an advanced system for sharing information is needed. The information provided needs to be limited to the building project itself but may include past-related projects' components and properties to enhance efficient modeling. For example, projects that used conventional material for a long-lasting lifecycle can be used for similar projects but with micro improvements. A supplier integrated into the project that was not formerly available in past projects can subsidize additional material delivery.

Various researchers have provided their ideas and models to enhance the construction supply chain's performance, such as the integrated model, single product model, optimal model, simulation model, and process model. Although these models are useful, the construction managers are still dealing with increasing supply chain management challenges, specifically modular construction. One of these issues is limited storage available on-site and cause negative aspect to increase costs. Therefore, with the complexity of projects arising, construction projects are required to optimize material inventory. This involves the inventory analysis necessary for a specific construction site and production pattern to detect any weaknesses in the inventory process and improve material usage and assignment to sites. Additional research is required to designate an innovative approach to optimize inventory and minimize cost.

0.1 CSC barriers and challenges in saving cost

Construction is a productive process with various and complex interfaces between participants and various obstacles generated by the absence of these partners' coordination. SCM presents several beliefs to address this fragmentation and decrease it. Even though SCM in the manufacturing industry has been extensively investigated and explained, utilizing these same principles to the construction industry presents waste and obstacles in CSC are widely existing and persistent (Papadopoulos, Zamer, Gayialis, & Tatsiopoulos, 2016).

Construction has been changed in the last two decades because of the development of technology. However, many problems still arise in the construction process, especially in the CSC, which is always challenging. Several research studies have assessed that construction is still inefficient, and many difficulties can be observed. Thus, the supply chain in construction cannot effectively use stakeholders if common challenges in implementation lead to a lack of communication, collaboration, and information transfer between partners. Therefore, lack of coordination and integration between various functional disciplines and low communication impact factors causing performance-related problems, such as low productivity, cost and time overrun, conflicts, and disagreements. Major issues are observed at the interfaces of different participants or stages involved in the CSC. These problems are caused by shortsighted and independent control of the CSC.

The study of Xue, Li, Shen, & Wang (2005) found that the general problems generate at the interfaces of different stages involved in the CSC. Therefore, the high fragmentation leads to the separation of design and construction, lack of coordination and integration between various functional disciplines, and poor communication, leading to delay in the project and increased costs. The figure below shows the problems between stakeholders that lead to delay and increase the project's costs. Serpell & Heredia (2004) recognized the challenges and the effects in CSC, and it is affected by many problems as has been reported by several authors. Most of these problems are not generated in the conversion process, but the different supply chain interfaces. Some of the problems are as follows:

- shortage of coordination, collaboration, and commitment between suppliers and clients within the supply chain;
- project design problems (many changes and inconstant information);
- poor quality of materials and components;

- deficient communication and information transfer;
- insufficient management within the supply chain (poor planning and control);
- lack of effective methods for measuring the performance of the different parties within the supply chain.

Therefore, ECLLP (2013) addressed the challenges that prevented to achieve saving cost in the CSC, which are:

- an expected bounce in costs linked to demand and supply requirements increased by industry consolidation and decreased levels of investment;
- business behaviors during the SC that decrease purposes or motivation for collaborative and supportive behaviors, driven by current business requirements;
- high level of fragmentation in the supply chain, especially related to multiple subcontractors;
- unsuitable risk transfer down the SC, possibly including loss of solution growth on-site construction.

Table 0.1.1 Causes of waste and delay in the construction sector

Stage	Cause of waste
Design	Design changes, errors in design, poor coordination and communication, unclear specification
Procurement and Operation	Ordering errors, difficulties to order small quantities damage during transportation, difficulties for trucks to access construction site, insufficient methods during loading, and unloading materials. inappropriate site storage. unused materials and equipment on site

Inadequate planning may cause material shortages that delay the project schedule or a substantial increase in inventory costs by producing or supplying materials earlier than needed at the construction site (Tserng, Yin, & Li, 2006). Material procurement and storage on construction sites need to be adequately planned and executed to avoid the negative impacts of material shortage or excessive material inventory on-site. Due to the SC participants' lack of collaboration, strategic decisions related to building a partnership, IT-based planning, and logistics-based planning are not conducted in the planning and design phase. This common practice reduces the effectiveness and the flexibility of the CSC ability. To move forward, external SC integration of contractors, manufacturers (Fabrication), and suppliers in the future SCM application trend is essential for efficient decision-making across the construction phases. For the trend, SC planning decisions, IT planning, and logistics planning are proposed to be conducted during 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. Also, BIM can compute fluctuations in inventory manipulation based on crew size and inventory quantity.

0.2 Research problem description and motivation

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. Thus, due to an increase in urbanization, construction companies focus on warehouse management services to optimize their construction activities because of the limited storage available on the construction site. Material procurement and storage on construction sites need to be properly planned and executed to avoid the negative impacts of material shortage or excessive material inventory on-site.

Projects in the construction industry over run the time and the allocated budget. Based on a study by McKinsey&Company (2017), they reported that "*still large projects across asset classes typically take 20 percent longer to finish than scheduled and are up to 80 percent over budget*". Furthermore, construction sites in urban areas have limited storage. In the construction industry, it is common for large amounts of construction materials to be stored at a construction site or the manufacturing plant because contractors or producers want to acquire or supply those materials before they are needed. The materials inventory always bothers construction project managers and their suppliers because it incurs additional inventory costs and causes serious construction problems, such as site congestion and, in some cases, deterioration of the quality of the materials (Tserng H. Ping, Yin Samuel Y. L., et Li Sherman 2006). Finally, the construction industry suffers from a lack of innovation, integration, collaboration, and information sharing. Logistics planning and optimization models are not well adapted to the recent developments of technologies such as BIM.

Accordingly, the literature review aims to highlight successes and improvement areas in inventory management to aid managers in construction projects. Therefore, based on the preliminary literature review, we have considered the following gaps in defining existing priorities and future directions for construction logistics and SCM:

- inadequate planning that may cause material shortages that delay the project schedule. A substantial increase in inventory costs by producing or supplying materials earlier than they are needed at the construction site. Recent research has not provided a structure for classifying CSC inventory models;
- lack of research suggesting potential decision-making approaches in construction SCM, particularly in the thorough definition of strategies and techniques that meet current construction management practices and technical development standards. No research proposed a conceptual framework for the inventory system in the construction field;
- lack of collaboration and integration, thereby increase CSC costs and decrease construction productivity.

0.3 Research questions

The present study attempts to answer these crucial questions:

[RQ1]: What are the characteristics of existent inventory management models applied in the construction sector? What are their limitations, and how this affected Construction Supply Chain (CSC) integration?

We answer [RQ1] in Chapter 2. A comprehensive literature review of inventory models applied in CSC is proposed to identify the research gaps. We develop a typology for the selected inventory models. The typology is used to classify and review the extensive research of inventory models in the construction sector.

[RQ2]: What are the present focuses and future decision-making trends in construction logistics and SCM during the major construction stages? What are the future trends of SCM applications in the construction industry?

We answer [RQ2] in Chapter 3. We identify the present focuses of decision-making in construction SCM and the relationships existing between the SC actors during the major construction stages. Therefore, we propose a new conceptual framework for the inventory system in construction projects. The proposed framework suggested BIM as a technology enabler for the improvement of construction logistics and SC performances.

[RQ3-A]: How to model the integrated Construction Supply Chain considering different contractors working at different construction sites and on different projects?

We answer [RQ3-A] in Chapter 4. Proposing an integrated model for collaborative CSCs planning that deals with the integrated problem of project scheduling and material ordering. The main objective is to achieve more coordination and, therefore, to reduce the total cost of the CSC.

[RQ3-B]: What is the role of collaboration between the different members in reducing the whole construction supply chain's cost?

We answer Research [RQ3-B] in Chapter 4. We carried out a comparative study between the integrated and non-integrated CSC.

0.4 Thesis scope and objectives

Several research studies have assessed that CSC is still inefficient, and many difficulties can be observed. The lack of collaboration between partners is still the major problems that lead to a delay in delivering projects and increase costs. The major objective of this research is to reduce cost and time for CSC. Therefore, this study aims to close this gap by proposing a novel model for the optimization of joint production of modular products of material, scheduling, and inventory management in CSCs. Moreover, this study demonstrates how to coordinate production, scheduling, and inventory management for concurrent projects. This study is specifically targeting the following objectives:

- a comprehensive literature review of CSC to identify the gaps and research problem. We develop a typology for inventory management in construction. The typology is used to classify and review the extensive research of inventory optimization models;
- identifying the present focuses of decision-making in construction SCM and the relationships existing between the SC actors during the major construction stages and proposing future SCM applications in the construction industry. Therefore, proposing a collaboration framework for the inventory system in construction projects;
- developing a MILP model for collaborative CSC planning and scheduling of independent construction projects. Proposing a novel model for the optimization of joint production modular products, scheduling, and inventory management in CSCs.

0.5 Research methodology

This thesis utilizes a literature review to achieve one of the research objectives, which is performed by following content analysis provided by Seuring and Gold (2012), consisting of four steps: material collection, descriptive analysis, category selection, and material evaluation. Both qualitative and quantitative methodologies are used to support each other to get research results efficiently (Bryman and Bell 2015).

Step (1): Literature review for problem identification

A comprehensive literature review of CSC to identify the gaps and research problem. We develop a typology for inventory management in construction. The typology is used to classify and review the extensive research of inventory optimization models. We found that the construction industry has been limited in optimization inventory models and slower compared to other industrial sectors. Thus, it is suggested to focus on the inventory management system in CSC.

Material collection

To perform this thesis, academic papers published in reputable peer-reviewed journals and internationally important conferences are used. To reach the credibility of the literature review, trustful databases are chosen: Emerald, SCOPUS, Springer Link, Wiley, and international scientific conferences in the field of construction management: IEEE-Xplore. As mentioned in the introduction, the period from 2000 to the present has witnessed many academic papers focusing on the implementation of SCM in construction.

Descriptive analysis

The descriptive analysis for the general information of collected documents (years of publication, publications by country, and journals/conferences/publishers) is conducted. The descriptive analysis is also responsible for analyzing the important contents of the 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, construction phases, and optimization inventory models in the construction sector.

Category selection

The collected documents are categorized using three groups (dimensions) of classification criteria, which are general information, research type, and inventory model classification. Each group of the category selection reflects each critical aspect of the contents presented in all collected documents.

Material evaluation

To guarantee the review's quality, validity, and reliability, a crosschecking process is conducted for the document classification. The content analysis of the documents must be reviewed until a consensus is achieved.

Step (2): Providing a detailed description of the main areas and proposing a collaboration framework:

Identifying the present focuses and discussing the future directions of decision-making in CSCM, which is performed by following content analysis, consists of four steps: material collection, descriptive analysis, category selection, and material evaluation. Thus, based on identifying the gaps, we propose a collaboration framework for the inventory system in construction projects.

Step (3): Development of a new optimization model:

For the first step, we define the relevant issues: assumptions, executive objective, and constraints. We propose an integrated model for collaborative CSC planning that deals with the integrated problem of project scheduling and material ordering. The executive objective of the model takes into account the optimization for the CSC costs. The model validation with a numerical example shows that the proposed model performs better results in total cost. This implies that the optimization model for the integrated model can improve the construction logistics performance and deal with the practical requirements of the current issues in the construction industry.

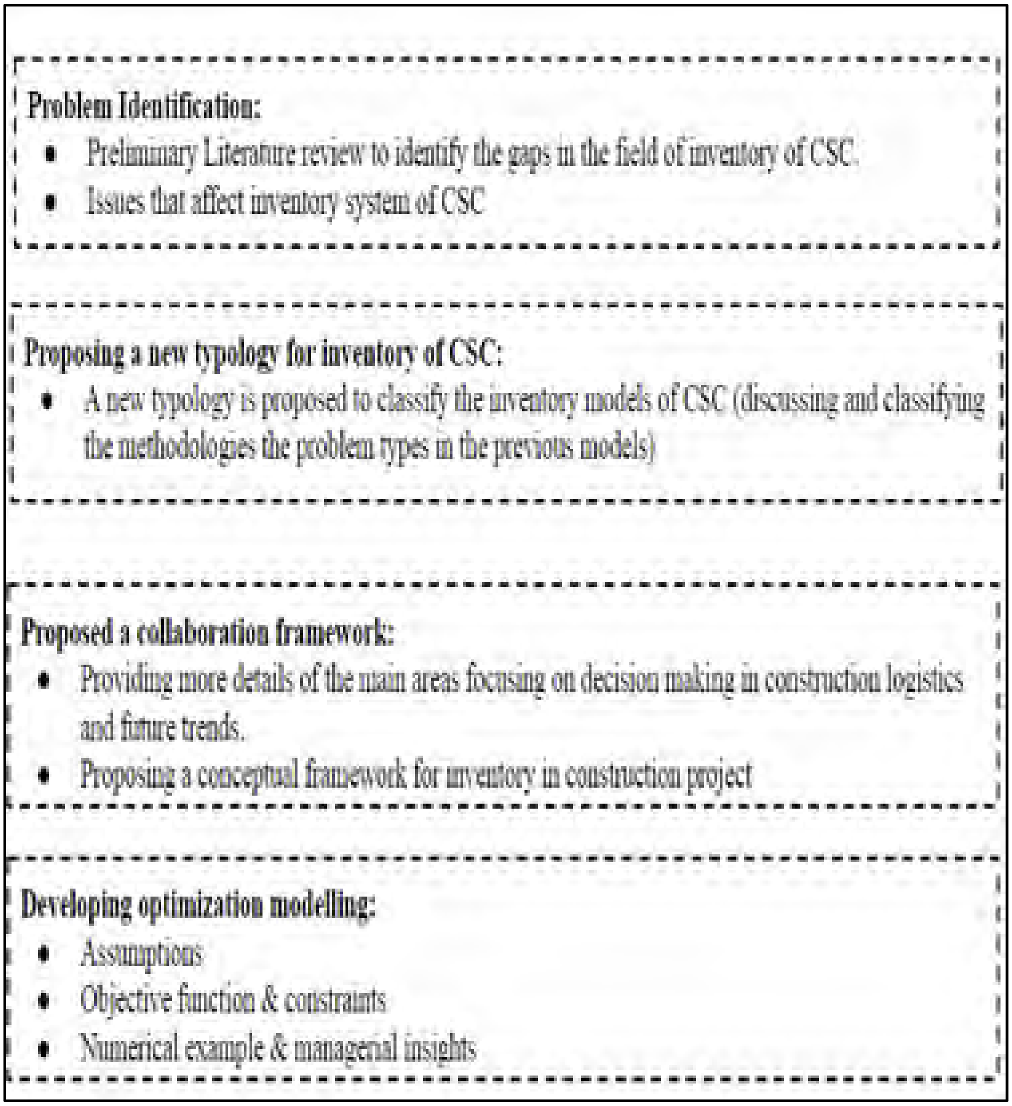

Figure 1.2 Research Methodology

0.6 Thesis contributions

This study aims to fill the research gaps found in the field of construction logistics and SCM. We provide a detailed description of the main areas of necessary enhancements to inventory optimization models in CSCs. Based on our best knowledge, we found no studies that have been done to classify the inventory models. Therefore, it offers a new typology on inventory management in the context of the CSC. Highlights the background of the research problem and identify the gaps. The literature review on this topic begins by looking into the worldwide CSC inventory models' performance and issues. The discussion was narrowing into a detailed literature review of the inventory models in the construction industry. First, we find that recent research has not introduced any mechanism for classifying CSC inventory models. Therefore, a lack of research proposes a collaboration framework for the construction sector's inventory models, which meet current construction management, practices requirements, and technological advances. Thesis objective 1.

Identifying the present objective of decision-making in the construction SCM and the relationships between SC actors during the main construction phases, study and suggest potential developments in SCM applications in the construction industry to meet the new requirements of construction practices technical development. Therefore, based on the typology and the present decision focuses, we propose a new conceptual collaboration framework to integrate all the CSC members and enhance SC network performance. Thesis objective 2.

A new mixed-integer linear programming model is proposed to reduce the total SC costs while collaboration between contractors is possible. The model was implemented using the IBM ILOG CPLEX Optimization Studio. The proposed model is analyzed through a numerical study to show the benefits of collaborative planning in construction project management. The decision model help also in finding efficient construction projects' sequences. The main objective is to achieve more coordination and, therefore, to reduce the total cost of the CSC. Thesis objectives 3A and 3B.

In conclusion, Construction Supply Chain Management (CSCM) is a promising approach to successfully achieve integration between the several disciplines of the chain (i.e., internal and external suppliers, designers, vendors, contractors, subcontractors, and internal and external clients). The value of integrating entities along Supply Chains (SCs) has been widely studied in many industries and services, except in the construction industry. However, SCM's importance in improving construction management has been recognized since the 1990s (Le et al., 2018). The construction projects face many issues because of the lack of collaboration amongst the SC participants. In the next chapter, a literature review of inventory management in the construction SC. Therefore, provided a typology of the inventory models and presented the models' description and attributes. At the end of this chapter, the research gaps are identified to facilitate the research questions and objectives.

0.7 Thesis structure

A brief overview of the thesis structure is described below:

Chapter 1 has provided a literature review of CSC inventory models to identify the gaps and research problems. Based on our best knowledge, we found there is no studies have been done to classify the inventory models. At the end of this chapter, research gaps identified, the coordination of production and inventory management, and multi-project scheduling has not been studied in previous research.

In chapter 2, we develop a typology for inventory management in the construction supply chain. The typology explained the inventory systems' problems and utilized them to classify and review inventory optimization models' extensive research. The result found that most scholars in construction supply chain management usually limit their research on the improvement of specific processes and activities. Therefore, we suggest BIM as a technology enabler for inventory management in the construction supply chain.

Chapter 3 identifies the recent development in decision-making in the construction SCM and proposes a new collaboration framework for the construction projects' inventory system. The proposed framework suggested BIM as a technology tool for the improvement of construction logistics and SC performances. To enhance CSC collaboration and integration. The proposed framework for construction supply chain management towards collaboration and integration has been proposed to answer the second research question. A conceptual framework has been developed with the SC members' integrated consideration in construction to enhance managing the construction supply chain and increase the SC performance.

Chapter 4, this chapter aims to answer the third research question. Chapter 4 presents a new mixed-integer linear programming model intending to reduce the total SC costs while collaboration between contractors is possible. Based on the literature review and the proposed framework, a mathematical model is proposed. The proposed model is analyzed through a numerical study to show the benefits of collaborative planning in construction project management. Therefore, sensitivity analysis is presented to see the impact of changing penalty and inventory holding cost on the total SC cost.

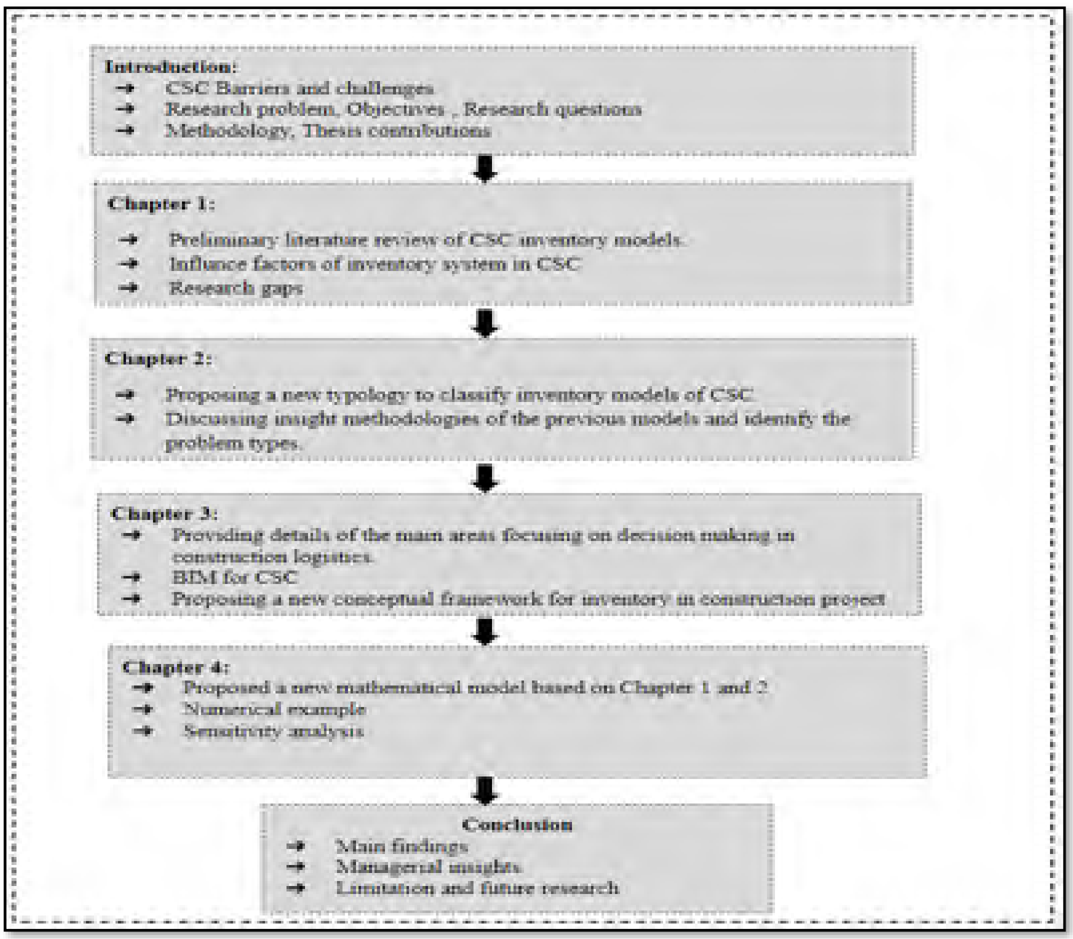

Figure 0.3 Overview of the thesis structure

CHAPTER 1

LITERATURE REVIEW

1.1 Background of optimization models of inventory in construction

The construction supply chain plays a most important role in the construction market competition. Construction supply chain management assists enterprises by helping them to achieve more competitiveness, increase profits, and have more control over the different factors and variables within the project. This chapter discusses the literature review about the inventory in the construction supply chain. The construction industry involves a multi-echelon supply chain with so many stakeholders. The industry faces many problems due to poor inventory management—these projects overrun the time and the allocated budget.

The supply chain of construction projects includes various stages and levels. Suppliers of the construction industry provide raw material (i.e., steel and aluminum) and other labor and equipment used at the construction sites. Inventory management plays an essential role in the procurement and management of supply requirements in construction projects. Interestingly, Fu (2014) inspired by the previous implementation of this approach in the pipe network design, water distribution network, and slope stability analysis, found the impact of activity amount on total cost is obvious, while the effect of network complexity is negligible. Material factor exerts a more significant influence on total cost than renewable resource strength for a given project. This is relevant because of the integration of project scheduling and batch orders.

The value of integrating entities along Supply Chains (SCs) has been widely studied in many industries and services, except in the construction industry (Golpîra, 2019). However, the construction industry is among the most important branches playing a key role in a country's economic growth especially due to its relation to other economic sectors. Therefore, the study proposed a MILP model to support the operation of a general multi-project multi-resource multi-supplier of CSC. The model considered the Vendor Management Inventory (VMI) strategy and addressed the supply and decision sharing strategy to integrate the CSC network design and facility location problems. This study's limitations were on the system's cost, and there is no transshipment between temporary facilities on site and the model designed in a deterministic environment.

Inventory theory from the supply chain perspective has already been widely studied and applied in other industries such as manufacturing, but it has started lately in the construction industry. Related research mostly emphasizes strategic importance analysis at the macroscopical level. Many research types primarily aim for a specific goal, such as quantity or cost in logistics planning and analysis from qualitative analysis (Zou, 2012). Efficient planning of materials procurement can result in significant improvements in construction productivity and project profitability. Previous research studies focus on aspects of material procurement: effect of material procurement on construction labor productivity; principles of site material management; just-in-time in construction projects; 4-dimensional visualization for material management; decision support systems for economic material purchasing; data exchange and integration for material procurement; and so on. For example, Polat, Arditi, & Mungen (2007) propose a simulation-based decision support system to support contractors in optimizing the rebar management system in the context of uncertainty. Said & El-Rayes (2010) developed an optimization model for construction logistics planning to optimize material procurement costs (ordering cost, stock-out cost, layout cost, and financing cost). Liu & Tao (2015) build a multi-objective optimization model for material purchasing in a three-echelon CSC. The model considers production cost, ordering cost, holding, agent cost and lead-time crashing costs as decisive variables. The table 1.1 helps to understand different elements of inventory models in the construction domain, which were presented and discussed by different authors.

Table 1.1 Inventory Models: Comparison between different contributions

Author (s)	No of suppliers	No of products	Project type	Material type
(Tserng et al., 2006)	Single	One material	Precast Concrete building project	Steel rebar
(Sajadieh et al., 2009)	Multi	Multi	Numerical Example	Not specified
(X. Feng & Zhang, 2010)	Not specified	One material	Residential building	Cement
(Ko, 2010)	Single	One material	Shopping mall	Precast Concrete
(Xue, Shen, Tan, Zhang, & Fan, 2011)	Single	One material	Numerical Example	Rebar
(H. Said & K. El-Rayes, 2011)	Multi	Multi	Numerical Example Multi-story building	Rebar, Masonry, Drywall, Tiles
(Zou, 2012)	Single	One material	Not applicable	Not specified
(Xie, 2013)	Not specified	One material	Not applicable	Formwork
(Fu, 2014)	Multi	Multi	Numerical Example	Not specified
(Said & El-Rayes, 2014)	Multi	Multi	Numerical Example Hypothetical Example of 10 story building	Concrete reinforcement steel, masonry blocks, drywall panels, and ceramic tiles
(Qiurui Liu & Tao, 2015)	Single	Multi	Numerical Example	Not specified
(Tabrizi & Ghaderi, 2016)	Multi	Multi	Numerical Example	Not specified
(Lu et al., 2016)	Multi	One material	A dam construction of a large-scale hydraulic	Fly-ashes
(Q. Liu et al., 2017)	Multi	Multi	Hydro-power station	Cement, Steel, Dinas, Lumber prefabricated

Author (s)	No of suppliers	No of products	Project type	Material type
(Xu & Zhao, 2017)	Multi	One material	Power station construction	Cement
(Hsu, Aurisicchio, & Angeloudis, 2017)	Single	Multi	Hospital project	Bathroom Pods
(Meng, Yan, Xue, Fu, & He, 2018)	Single	One material	Numerical Example	Reinforced bar (HRB 400E 28 mm
(C. Feng, Ma, Zhou, & Ni, 2018)	Multi	One material	Hydropower construction project	Rough gravelly soil
(Hsu, Angeloudis, & Aurisicchio, 2018)	Single	Multi	Residential construction	Different types of Bathroom Pods
(Jaśkowski, Sobotka, & Czarnigowska, 2018)	Multi	Multi	Construction of a road subbase	Natural crushed stone or Recycled Concrete
(Deng, Gan, Das, Cheng, & Anumba, 2019)	Multi	Multi	SC network of five project sites and 15 suppliers in different locations	Different types of materials
(Golkhoo & Moselhi, 2019)	Single	Multi	Numerical Example Office buildings	Reinforcing steel
(Golpîra, 2019)	Multi	Multi	Not specified	Not specified

Lu, Wang, Xie, & Li (2016) emphasized the demand and supply of material in the construction projects, discussing the management of risk to improve the construction project productivity and cost-efficiency. The model is prompted by the desire to alleviate the challenges associated with the control of the stochastic inventory in the construction industry. The model was, however, limited because of not considering uncertainty and disruption in the supply chain. Other research focused on the utilization of modern models.

For example, the Building Information Modelling Hisham Said & El-Rayes (2014), concluded the development of an automated multi-objective construction logistics optimization system designed to support the contractors in integrating and planning material supply and site decisions. This study's limitations were difficulties in improving user interfacing capabilities by visualizing optimal site layout plans and locations of material storage areas inside building spaces and incorporating an online collaboration environment to facilitate easy share and exchange of information between the contractors and their suppliers. Walsh, Hershauer, Tommelein (2004) discussed the delivery time for long-lead construction material. They used a simulation model for optimizing supply chain relationships in construction and explored the impact of holding construction materials at the appropriate location within the supply chain. They found that the JIT management system could reduce inventory levels and the related costs; however, their research limitations were, this strategy can be problematic to deploy in a long SC.

Therefore, Tserng, Yin, & Li (2006) established an optimal model that minimized the integrated inventory cost and used it to create a decision-support system for buyers and suppliers of steel rebar to plan supply and production. Although the model was useful, it is limited because it did not analyze decisions based on production, inventory, and construction labor for the integrated supply chain model. Sajadieh et al. (2009) & Fu (2014) discussed problems in project scheduling and material ordering for construction projects. They argued that project scheduling integrated with material ordering leads to issues that affect various aspects of the construction projects, especially pertaining to cost and resources management. Further, Sajadieh et al. (2009) suggest that traditional inventory construction planning strategies are based on non-aligned planning from the start of a project becomes problematic during construction project execution. With this, Fu (2014) identified other costs such as renewable resources costs and back-ordering costs, which were the traditional method in construction projects.

Therefore, Lu et al. (2016) focused on analyzing stochastic inventory control of the construction material and developed a general safety-stock determination approach under nonstationary stochastic demand and random supply yield. The purpose of this study is to present a general approach to construction material safety-stock determination that is capable of improving the overstock or understock situation. Lu et al. (2016) also emphasized using an inventory buffer to investigate the influence of material inventory on construction projects' variability.

Further, Sajadieh et al. (2009) and Fu (2014) emphasized the importance of integrating scheduling projects and material ordering into the construction project. For this purpose, Sajadieh et al. (2009) focused on Project Scheduling Material Ordering (PSMO) by proposing a MIP - Mixed Integer Programming model. In their paper, the PSMO problem investigated by Dodin & Elimam (2001) was extended by developing a Genetic Algorithm (GA) approach to find the optimal solution for large-scale problems. Liu, Xu, & Qin (2017) focused on integrating operations in the CSC. Uncertainty is one of the most challenging factors in real-world CSCs. There are many inherent uncertainties in the supply chain of the construction industry. An integrated multi-objective purchasing and production-planning model is constructed and applied to a hydropower construction project. The results illustrate that efficient integrated operations are critical for CSC performance. The optimization results also indicate that considering uncertain rush orders and delay times improves CSC efficiency.

The study of Fu (2014) used various variables such as decision variables, intermediate variables, and parameters associated with the scheduling and ordering to minimize the total cost, which is composed of renewable resource cost, material cost, ordering cost, inventory holding cost, backorder cost and delay penalty or reward for early completion. Tserng et al. (2006) mentioned that high variability in the construction environment leads to high-cost variation, particularly in the material cost using a wide spectrum of mathematical formulations. However, instead of using GA, Fu (2014) used a Hybrid Algorithm, which combined the harmony search with the GA due to the complexity of the project scheduling and material batch ordering problems. The difference between both algorithms can be analyzed according to the way it handles different tasks. Accordingly, Sajadieh et al. (2009) found that GA effectively handles batch-ordering while HA is best for project scheduling.

According to Russell, Howell, Hsiang, & Liu (2013) study, they discussed the time buffer, which is defined as the extra time during complete inventory control procedure, which is suggested to be essential for the construction project because it accommodates and compensates for project uncertainties and potential variations between management levels for the inventory control of the construction project. Horman & Thomas (2005) emphasized material buffers in construction, discussing buffer's deployment's impact on project variability. However, the researchers did not focus on evaluating the performance of the employees employed in construction projects. In addition, focusing on displaying categories of responsiveness of different types of buffers and the utilization of cost in these mechanisms for providing a different level of response is justified by the researchers because project variability can be affected by the deployment of buffers but has not evaluated the impact on construction labor performance. The researchers also suggest new construction project management thinking (i.e., the theory of constraints and lean construction) recommend managing buffer size carefully to analyze the relationship between inventory buffers and construction labor performance. The researchers depicted that the production system concentrates on Just-In-Time (JIT) processes so that effective delivery of material at the site can be managed along with prompt installation as per the construction project's requirements.

Contrarily Tabrizi & Ghaderi (2016) addressed inventory allocation by presenting a mathematical model for optimizing the simultaneous planning of material procurement and project schedule. They utilized mixed-integer programming as a tool for optimizing the robustness of scheduling and material costs. The proposed model achieves its objective by using the modified multi-objective differential evolution algorithm and the Taguchi method to enhance the robustness of the results. Further, the bi-objective mathematical model analysis presented by this research shows that it can maximize the scheduling process while minimizing the construction material costs. However, the model does not address the discount strategies' impact on the material's cost and the scheduling process.

Other researchers integrated the inventory model using transportation, inventory, information, and facilities drivers, all of which affect the supply chain of construction. In this case, Ko

(2010) focused on preparing a framework for precast fabricators so that inventory can be reduced and proposed a framework that includes three main components: buffer evaluation, due adjustment, and scheduling. This study proposed a framework to reduce the level of finished goods inventory using three steps. The first step is to evaluate a time buffer using fuzzy logic. Fabrication due dates are then adjusted using the inferred buffer according to the production strategy. Finally, production sequences are arranged using a multi-objective genetic algorithm.

Russell et al. (2013) developed a survey. It was administered to project managers, superintendents, and foremen to identify the most frequent and severe reasons for adding time buffers to construction task durations. They confirmed the time buffers in construction are widely used, but that without considering just in time delivery, the time lags can create a loss on projects. Fu (2014) posited that traditional methods do not work for project integration and include trade-off costs in terms of renewable resource costs, material cost, ordering, and back-ordering costs, holding costs of materials, and cost of finishing early or late. Along with this, the backorders also harm the inventory as they often increase construction projects' costs.

Therefore, construction project managers use mathematical analysis, which also depicted that with the exponential distribution of the lead-times, the outstanding orders' age information could be irrelevant for the dynamic rationing decisions. H. Said & El-Rayes (2011) Offer a novel optimization model for the efficient procurement and materials storage on project sites that can improve the productivity and the profitability of the construction project. They developed an automated multi-objective construction-logistics optimization system using data from BIM and construction schedules to enhance the exploitation of interior storage spaces in a building. The system mines geometric data of interior and exterior site areas to systematize the available storage space's computation.

Kumar & Cheng (2015) also propose an automated framework of dynamic site layout using BIM data to identify actual travel paths of on-site personnel. Hamdan, Barkokebas, Manrique, & Al-Hussein (2015) presented a framework that integrates BIM with simulation to deliver an inventory planning and management tool. This tool can be applied to reduce inventory costs and increase the performance of the supply chain. Golkhoo & Moselhi (2019) Presented an automated method as a part of a significant Materials Management System (MMS) to generate an optimized material delivery schedule. The proposed method can make trade-offs and optimized balance among elements of material cost. It can also consider the construction projects' dynamic nature by following up the progress reflected in the last up-to-date schedule. This method can guide contractors or material professionals in procuring material with the least cost and without early, late, excess, and insufficient purchasing.

1.2 Influence factors of inventory management of construction industry

1.2.1 Capacity on construction site

Feng et al. (2018) Proposed three types of uncertainty sources that are inherent to supply chains, resulting in excess inventory in the supply chain: supplier performance, manufacturing process, and customer demand. In real-world construction projects, CSC design is driven by the construction plan. The supply capacity of the upstream partners (such as the manufacturers, suppliers, and transporter) may restrict the project construction. Therefore, the study presented a novel Stackelberg-game model within bi-level multiple objective multistage programming to solve the inherent conflicts to deal with uncertainty and support decision-maker to reallocate material on site. Based on the ABC approach, Fang (2011) stated that there are four cost elements related to the logistics of precast concrete units between the supplier’s factory and the construction site, and they are procurement, stocking at the supplier’s yard and/or intermediate warehouse, transportation, and loading and stocking on site. Therefore, by comparing the total construction logistics cost, the contractor and supplier can determine the optimal storage quantity at the supplier’s yard, central warehouse, and construction site to meet the construction demand at the lowest cost.

1.2.2 Demand

Uncertainty is defined as the inability to assign probabilities to future events or the difficulties to accurately predict decisions' outcomes (Ganbold & Matsui, 2017). Therefore, demand uncertainty in construction refers to the extent of the change and unpredictability of the material needed on site. Demand variation in construction plays a vital role in delivering the project on the due date. Delay in delivering materials and equipment to construction sites is often thought of as a contributory cause of cost overruns and project delivery in developing countries.

Scheduling, and material demand, both play main factors that lead to deviations from the planned initially and incurring additional costs. Since delays in construction schedules are almost inevitable, and changes in the demand often have a severe impact on the upstream logistics, their effect must be carefully taken into consideration. Hsu et al. (2018) proposed a technique for predicting the demand uncertainties on the construction site using probabilistic historical data analysis. Demand uncertainty results in a combination of lower quality, excess capacities in the construction site, excess inventory, and waste; thus, it increases the overall cost. In addition, numerous uncertain factors caused by large scale, complex processes, and multiple participants also make it challenging to effectively manage a construction project.

1.2.3 Environmental

Material supply in the construction industry is different from the manufacturing industry. Material demand problem sometimes occurs due to external events, such as delays in the permit, inspection, material quality, availability of material, labor, weather, etc. that can affect the project completion date—organizations faced with uncertainties from its task environment. To respond to the uncertainties, construction companies internalize fewer resources and capabilities while increasing their integration with SC partners. As construction operations are prone to risks due to, e.g., weather, worker absenteeism, and turnover, the actual demand for materials may fluctuate (Jaśkowski, 2018). Hsu et al. (2018) presented an optimization model on the site demand variation aroused from the various disruptions such as inclement weather, workers productivity fluctuations, late transportation, and crane's operation reliability issues. All disruptions are assumed to be independent of one another and characterized by their occurrence probability. The results demonstrate how the optimal supply chain configuration is established, considering multiple schedule deviation factors.

1.2.4 Construction productivity

Active management in construction means the efficient utilization of workers, materials, and equipment. Improving productivity on-site is a primary concern for any construction company. Although a high number of publications exist concerning construction productivity, there is no agreement on a standard productivity measurement system. Researchers have concluded that it is difficult to obtain a standard method to measure labor productivity because of project complexity and the unique characteristics of construction projects (Robles, 2014). Low worker motivation and morale, low worker productivity, personal conflicts among workers, labor shortage, slow mobilization of labor, Strike, unqualified/inexperienced workers lead to delay the project (Golpîra, 2020). Some researchers stated that the daily construction output measured construction industry productivity carried out by workers and equipment on different tasks and is expressed as the daily assembly quantity of material on the site (Hsu et al., 2018). Therefore, productivity on-site has a significant impact and leads to delay because labor productivity is behind the project schedule.

1.2.5 Transportation

Efficient logistics in urban areas is crucial for construction companies since building materials account for 30–40% of all construction costs, and the space on site is highly constrained (Guerlain et al., 2019). Chen and Nguyen (2019) Mentioned that location should be considered a critical input in the selection process of the material. Transportation cost is affected by the transportation distance and location of material, accounts for 10% to 20% of some industrial projects' total budget. Therefore, transportation cost could be deemed as the dominant decision variable in the transportation planning of construction material. Manavazhi & Adhikari (2002)

Presented a survey study collected from different projects related to delays in highway projects in Nepal. The study identified the factors associated with time delays and also their effects. Organizational weakness, government regulations, and transportation delays were critical. Xie & Palani (2018) stated that control of supply chains traditionally focused on operations, distribution, inventory, and transportation functions at the firm level. Deng et al. (2019) Presented a mathematical model to support decision-making for the allocation of consolidation centers in congested regions with long transportation distances. In the modular products transportation process are transported from the warehouse to construction sites according to the daily demand for each product at each location on a just-in-time basis (Hsu et al., 2018). Therefore, the study stated that the weather, delays in the delivery of construction components is another commonly identified cause of disruption for original assembly timelines.

Thus, Effective planning to deal with these issues is vital for the managers of construction projects. 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 (Phuoc Luong Le et al., 2018). The next section shows the proposed framework for the construction domain's inventory system that considers integration at the early stage of the construction project. At the construction phase, the GC is responsible for making decisions related to on-site operations: IT-based decisions (building a 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 significant in this phase to ensure the construction's schedule, cost, and quality.

1.3 Research gaps

Construction SCM refers to the management of complex systems in which the performance relies on a set of hundreds of decisions delivered by multiple independent firms. Based on the above literature review, we recognize the following gaps in implementing the previously presented models. Although there is a rich literature about CSC collaboration, the coordination of production and inventory management and multi-project scheduling has not been studied in previous research. Inadequate inventory planning may cause material shortages that delay the project schedule. A substantial increase in inventory costs by producing or supplying materials earlier than they are needed at the construction site. Lack of collaboration and integration thereby increase CSC costs and decrease construction productivity. Therefore, recent research has not proposed any typology study to classify inventory system models in the construction sector; therefore, we found no framework was proposed to address the issues of inventory system in the construction sector.

Accordingly, the current literature review aims to highlight successes and improvement areas in inventory management to aid managers in construction projects. In inventory management, various researchers have provided their models such as:

- the Integrated Model of Said & El-Rayes (2014): Presented the development of a new automated multi-objective construction logistics optimization system (AMCLOS) that would support the contractors in optimally planning material supply and storage;
- the Single-Product Model of Xu & Zhao (2017): Examined supplier selection and dynamic inventory (SSDI) problems for the supply of construction materials;
- Walsh, Hershauer, Tommelein, & Walsh (2004) and Samer Bu Hamdan, Beda Barkokebas, Juan D. Manrique, & Mohamed Al-Hussein (2015) presented a simulation Models for Inventory Management. The model reduces the length and variability of the delivery time for long-lead construction materials to improve overall project lead-time.

The aim of these models is to enhance the supply chain management of construction projects. Although these models are useful, construction managers are still dealing with the issues in the CSC, which include:

- limited storage available on the construction site, thereby increase storage costs and decrease construction productivity;
- inadequate planning that may cause material shortages that delay the project schedule;

- a substantial increase in inventory costs by producing or supplying materials earlier than they are needed at the construction site.

1.4 Conclusion

The inventory management system is considered the major aspect for the construction communities focused on effectively managing the supply and distribution of the material. Motivated by the inventory control and needs of the managers involved in the construction projects, the literature review has focused on exploring the construction projects' inventory system. For this purpose, the focus was laid on evaluating the previous research to develop an effective understanding of the inventory system's needs and requirements that require an effective inventory control practice. Various researchers have provided their ideas and models such as the integrated model, single-product model, optimal model, simulation model, and process model to enhance construction supply chain management. Although these models are effective, the construction managers are still dealing with supply chain management issues. Some of these issues are unpredictable such as weather condition and hazards at the sites, which still needs to be handled effectively.

CHAPTER 2

TYPOLOGY OF CSC INVENTORY MODELS

2.1 Introduction

Inventory management is one of the major concerns for the managers involved in the construction projects. Few authors and scholars also discuss the subject related to the inventory system in construction. They have utilized different inventory models to help the managers on construction for project scheduling and material ordering. This chapter focuses on theses research related to the inventory models of the construction supply chain management. The models used by the researchers are classified and summarized in this section for evaluating the importance and effectiveness of the inventory models in the construction projects. Kanimozhi & Latha (2014) research was related to material management. The literature review indicated that material management is one of the critical aspects of the construction industry (Akintoye, McIntosh et al. 2000, Zou, and Zhang et al. 2007). One of the most reason for cost overrun is poor material management (M. Abas 2016). According to Zou (2012), proper inventory mechanism leads to reduce the overall cost. Proper order cycle, quantity stocks, lead-time, and safety stock need to be calculated for inventory cost minimization.

Poor planning and material management decrease labor productivity (Patil and Pataskar 2013). As sufficient stock is necessary for achieving project performance parameters, ABC and Economic Order Quantity (EOQ) analysis is performed to overcome stock-out. (Madhavi, Mathew et al. 2013) emphasized the problems related to the improper material procurement process. Construction project cost may vary depending on the material, workforce, subcontractor, overhead cost, and other general issues. Material procurement is the variance major contributor to cost variance. S.Sindhu (2014) used ABC analysis to classify the different inventory items. The data was collected via a questionnaire and analyzed through Statistical Package for Social Sciences (SPSS).

Project scheduling and material ordering for the construction projects problems have been discussed by (Sajadieh et al., 2009) and (Fu, 2014). When integrated with the material order, the researchers argued that project scheduling leads to realistic problems, affecting various attributes of construction projects such as cost and resources. In this context, Sajadieh et al. (2009) mentioned the traditional strategy used by the construction project managers to approach project scheduling and material ordering as two separate factors. The researchers cited that the managers used to carry out the project schedule as the first phase of the construction project to consider the activities schedule as a familiar parameter used to determine the material order. Fu (2014) identified some of the other costs, such as renewable resource costs and back-ordering costs, which were also traditional construction projects. Fu (2014) presented a mathematical model for calculating the cost of holding inventory and the backorder cost. The researcher utilizes mixed integer programming to implement the mathematical model, which is critical for optimizing the construction projects' scheduling and the construction material's procurement. The researchers use the genetic algorithm and the hybrid algorithm combined adapted harmony search to enhance the optimization process's robustness. More description and attributes regarding the construction supply chain's inventory models are available in Appendix I, Table-A I-1, p.99.

Table 2.1 Models description and attributes

Author (s)	Research problem	Solution Method/ Algorithm	Key Model Attributes	Applied
(Tserng et al., 2006)	Integrated inventory cost and the vendor management inventory policy	Concept of constraint programming	Production and supply operations model presented to minimizes the inventory cost.	Supplier, & GC
(Sajadieh et al., 2009)	Project scheduling and material ordering	Genetic algorithm approach	MIP model to integrate project scheduling with material ordering.	GC

Author (s)	Research problem	Solution Method/ Algorithm	Key Model Attributes	Applied
(X. Feng & Zhang, 2010)	Inventory control based on supply chain management and Vendor managed inventory	Exact method	The model is applied to determine the economic and rational stocks.	GC
(Ko, 2010)	Precast fabrication inventory	Multi-objective GA	Proposing a framework to reduce the level of inventory	Supplier
(Xue et al., 2011)	Value of information sharing under different inventory policies to reduce inventory cost	Exact method	The value of information sharing under different inventory policies	GC
(H. Said & K. El-Rayes, 2011)	Material logistics & site layout planning in congested construction sites	GA	Optimize site logistics costs & minimizing project-scheduling criticality.	GC
(Zou, 2012)	Inventory management Based on Inventory Theory	Exact	Adopt EOQ model to optimize the inventory.	GC
(Xie, 2013)	Inventory management based on storage theory	Exact	Solve the problem of the optimal scheme of inventory with the storage theory.	GC

In this Chapter, a new typology is developed for inventory models based on the previous literature review of CSC inventory models. The typology is used to classify and review the extensive research of inventory models in the field of construction.

2.2 Methodology of the previous inventory models

In this section, we discuss the generic scientific aspects of the classified models. This concerns the second part of our classification. Therefore, we discuss problem types of inventory models. Inventory is one of the major aspects for the construction communities focused on managing the material's supply and distribution effectively. The fact that 65% of the previous models develop approximate methodologies shows the complexity of CSC analysis. Metaheuristic algorithms, namely the Particle Swarm Optimization (PSO) and the Genetic Algorithms (GA) were used as the basis for approximate optimization. Among different developed versions of the genetic algorithm, the Non-dominated sorting genetic algorithm (NSGA-II) has proved more efficient to solve multi-objective problems.

Tserng et al. (2006) utilized constraint programming to solve the production and supply operations model to minimize the integrated inventory cost. Ko (2010) proposes a framework to reduce the level of Precast Fabrication inventory using three steps. The first is the time buffer evaluation. The second is a due-date adjustment, and the third is production scheduling that arranges production sequences. Fuzzy logic and multi-objective genetic algorithm were adapted to achieve this goal. H. Said & El-Rayes (2011) utilized GA to optimize construction logistics decisions in a congested construction site, including material ordering, stock-out, carrying, and layout decisions while minimizing schedule criticality.

Fu (2014) developed an integrated mixed integer-programming model of project scheduling and batch ordering and then presented a hybrid algorithm that combines harmony search and GA to solve the problem. Therefore, Hisham Said & El-Rayes (2014) used GA as a tool to implement the multi-objective optimization of construction logistics planning in the developed automated system for integrating and planning material supply and site decisions. Liu & Tao (2015) used PSO algorithm to find the optimal order quantity, reorder point, and lead time simultaneously to minimize each construction partner's total cost in the CSC. Tabrizi & Ghaderi (2016) applied the NSGA-II and a modified version of the multi-objective differential evolution (MODE) algorithm as the solution methodologies for the PSMO problem, presented as a robust mixed-integer programming model. The performance of the NSGA-II and MODE was tested against that of the e-constraint method, but this method was applied just for the small-sized projects since the PSMO problem falls within the NP-Hard problems class.

Lu et al. (2016) developed a general approach to determine the safety stock of construction material then used the fixed-point iteration method to calculate the time-varying base-stock level and safety-stock level. Liu et al. (2017) applied GAs (a hybrid multi-objective genetic algorithm that combines NSGA and an elitist multi-objective evolutionary algorithm) to obtain the optimal purchasing quantity and production quantity. Xu & Zhao (2017) proposed an interactive PSO algorithm, the bi-level PSO (BLPSO) algorithm, to cope with the dynamic bi-level supplier selection and dynamic inventory model. C. Feng, Ma, Zhou, & Ni (2018) developed a hybrid algorithm combining an evolved GA and PSO to solve the novel Stackelberg game optimization model for integrated production-distribution construction system in the construction supply chain.

Jaśkowski et al. (2018) put forward a mixed-integer linear programming model for optimizing supplies of materials. Material prices were expressed as fuzzy values with triangular membership functions. To solve the problem, the fuzzy model was converted into a three-objective linear program with crisp coefficients. The proposed way of converting and solving the fuzzy linear program produced solutions that reduce the total inventory cost in an uncertain environment. Golkhoo & Moselhi (2019) proposed GA-MLP (Multi-Layer Perceptron) method to generate an optimized material delivery schedule. MLP was utilized to improve GA by generating memory to overcome local minima encountered in applying GA for optimization. The proposed automated method has been validated through a numerical example, and the obtained results demonstrate that GA-MLP outperforms GA in optimizing construction material inventory. Babak H. Tabrizi (2018) used meta-heuristics to deal with the PSMO problem include NSGA-II and migrating birds' optimization (MBO) algorithm. Habibi et al. (2019) provided an integrated framework for the PSMO problem with sustainability considerations. The presented model falls within the NP-Hard problems class. Two multi-objective meta-heuristic algorithms, namely NSGA-II and MOPSO (Multi-Objective PSO), were modified to serve as solution methods. For small problems, the performance of these methods was compared with that of the second version of the augmented e-constraint (AUGMECON2) method, but for larger problems, where the exact method was unable to produce a solution within a reasonable time, these two algorithms were compared with each other. The results showed that regardless of problem size, NSGA-II outperforms MOPSO in the majority of evaluation metrics.

Therefore, exact analysis is presented in 30% of the previous studies and the mathematical approach was used as a basis for the optimization. X. Feng & Zhang (2010) & Zou (2012) adopted the Economic Ordering Quantity model to optimize the inventory while (Xie, 2013) used the storage theory. Finally, Meng et al (2018) adopted the Dynamic Programing Method for reducing construction material cost by optimizing buy-in decision.

2.3 Typology

In Table 3.1, we present the typology. The typology is to classify construction supply chain inventory models in different construction projects. The first column names the typology dimension, the second column the possible values, the third column is the explanation and the fourth column shows the number of papers. The principal parts of a table are shown in Table 2.2. More details regarding inventory models' typology in construction is available in Appendix Table A I-2, p.99.

Table 2.2 Inventory models classification

Typology dimension	Value	Explanation	No of papers
The problem under investigation:			
Specification: Echelons		Number of echelons	
	1	Single echelon	14
	2	Two echelon	7
	3	Three echelon	2
Structure	Relationship between items		
	C	Convergent material structure: One successor, multiple predecessors	9
	D	Divergent material structure: multiple successors, one predecessor	3
	G	General material structure: multiple (successors, predecessors)	3
	S	Serial material structure: one successor, one predecessor	8
Time	Moments in time where relevant events occur		
	C	Continuous: actions possible at any point in time	6
	D	Discrete: actions at specific points in time	17
Information	Level of information needed to perform the computations		
	L	Local: single node only	2
	G	Global: everything	21
Resources specification:	Restriction on availability of resources		
Capacity	F	Bounded storage / processing capacity	16
	I	Infinite capacity (no constraint)	1
	U	Unspecified	6

Typology dimension	Value	Explanation	No of papers
The problem under investigation:			
Delay	Time it takes to deliver an item (including production times, excluding stock-out delays)		
	C	Constant	14
	G	General stochastic	6
	U	Unspecified	5
Market specification	Exogenous demand for an item		
Demand	C	Deterministic.	17
	G	General stochastic	6
	N	Normal	2
Customer	Attributes (reactions to disservice, advanced demand)		
	B	Backordering	3
	G	Guaranteed service	14
	L	Lost sales	1
	U	Unspecified	5
Control type specification	Prescribed type of replenishment policy		
Policy			
	B	Echelon base stock	1
	b	Installation base stock	1
	S	Echelon (s , S)	1
	F	Fixed time policy	8
	O	Other	9
	U	Unspecified	3
Lot-sizing	Constraint on release quantity		
	F	Flexible: no restriction	4
	Q	Fixed order quantity	8
	O	Other	10
	U	Unspecified	1
Operational flexibility	Capability to use other means of satisfying unexpected flexibility requirements than originally foreseen		
	N	None	14
	R	Routing flexibility	2
	U	Unspecified	7

2.4 Problem types

This section specifies which types of problems have been studied and what the main achievements have been. We structured this following the dimensions of our typology. Since papers may study several problem types simultaneously, the sum of percentages of type classes may exceed 100%. For each dimension, we identify avenues for further research. This research should close the gap between the assumptions made so far and the assumptions required to apply the models developed in real-life situations.

2.4.1 Number of echelons

As the CSC involves different actors such as designers, suppliers, general contractors, sub-contractors, and the owners, it is of interest how many echelons the systems studied in the literature. We found that 61% of the previous papers consider one-echelon systems, 30% of the articles consider two-echelon systems, and 9% of the articles consider three-echelon systems. We can conclude that most papers are one-echelon systems, which shows that extending the analysis to two or more than two echelons is by no means trivial. We need specific assumptions to consider multi-echelon systems because the CSCs are complex.

2.4.2 Structure

From the previous literature review of optimization models of inventory in construction, 61% of the models have a one-echelon system. The supply chain is composed of one or multiple suppliers and a construction site or a construction company ruled by a general contractor responsible for delivering the materials for different construction sites. Therefore, 43% of the models considered serial structure, delivering one or multiple materials from one-supplier to a construction site or a construction company, and 57% considered a convergent structure, collecting one or different types of materials from different suppliers for a construction project. In addition to the one-echelon system's components, most of the 30% of the models represent the two-echelon systems considered either a warehouse, material management, or a consolidation center.

Tserng et al. (2006) studied a subcontractor for steel rebar supply required by forecasters and delivered to different contractors (divergent structure). Hsu et al. (2017) & Hsu et al. (2018) considered a supply chain with a divergent system where they chose modular products as the planning material assembled on sites after being stored in a warehouse. The latter models represent 43% of the total number of papers with a two-echelon system; they have a general structure, from different suppliers to different construction sites after being stored in a warehouse, material management, or a consolidation center. The rest of the models (14%) have a convergent structure, different suppliers, storage, and a construction site.

In contrast, models with a three-echelon system only concern 9% of the models we classified, and they are with a serial structure. In their supply chain network, Liu & Tao (2015) & Liu et al. (2017) took into account the owner of the project in addition to the supplier and the general contractor. Moreover, Liu & Tao (2015) considered a third-party inventory contractor between the supplier and the general contractor because of the large volume of building material and the owner pay for the inventory management for the inventory contractor. According to the study of Liu et al. (2017), material flows are from the supplier to the owner, and then the raw materials are shipped from the owner to the fabrication contractor in the CSC. The fabrication contractor produces the semi-fabricated units, and then the semi-fabricated units are shipped from the fabrication contractor to the general contractor. In the end, the general contractor delivers the construction project to the owner.

To conclude, most of the publications considered a convergent or a serial structure no matter how many echelons the system is, which means that only a few papers consider delivering to different construction projects. The results show that extending the analysis to divergent systems is by no means trivial. Still, more research on general structures is needed to deal with material purchasing and inventory of a construction supply chain and develop optimization models to reduce each actor's costs and ensure the whole supply efficiency.

2.4.3 Time

Based on the previous optimization inventory models, around 74% of the models assumed discrete-time which means 26% of the papers assume continuous time. For large-scale problems, meta-heuristic algorithms have been demonstrated to offer high computational efficiency, and the particle swarm optimization (PSO) algorithm and the genetic algorithm (GA) have proven to be the most practical methods, with the GA being inherently discrete and the PSO being inherently continuous (Feng et al. 2018). Discrete-time assumptions are motivated by the underlying planning systems, such as MRP (Sajadieh et al., 2009) & (Golkhoo & Moselhi, 2019).

2.4.4 Information

Most of the optimization models assume global information with 91 %, which means 9 % of the papers assume local information. This might be surprising initially, but it is a consequence of the proposed integrated models in the selected models, which require global information to manage the inventory in an integrated supply chain. To analyze the material supply chain in the construction industry, Tserng et al. (2006) & X. Feng & Zhang (2010) adopted the Vendor Managed Inventory (VMI) method from the manufacturing industry, which is a cooperative inventory management model that in the context of the integrated supply chain.

Managing the inventory levels efficiently helps to enhance the supply chain's performance and reduce the total cost of inventory management. The GC should provide the supplier with information about the required materials, the project schedule, and the current inventory situation to supply materials on time and meet the level of inventory service and avoid delays on construction projects. Ko (2010) & Liu et al. (2017) proposed an integrated purchasing and production planning model that integrates purchasing and production planning for reducing fabrication inventory in a CSC of a company making prefabricated products. H. Said & El-Rayes (2011) & Hisham Said & El-Rayes (2014) used integration to optimize the construction material management planning, which includes supply and storage optimization. These optimization models integrated the process of CSC management to reduce the total cost. Xue et al. (2011) investigated the value of information sharing under different inventory policies at the firm-level in the case of whether supplier shares supplying information or not and concluded that contractors should encourage cooperation with their suppliers to save construction costs and increase their service level. Liu & Tao (2015) mentioned explicitly in their assumptions that the information is shared on the CSC.

Fu (2014) & Tabrizi & Ghaderi (2016) proposed and integrated project scheduling and material ordering optimization models for the construction project. They mentioned that traditional methods of CSCM do not consider the different trade-offs that exist among several costs. They emphasized that taking the trade-off influence into account highlights that project scheduling and material ordering are inseparable and must be treated simultaneously in an integrated manner to coordinate project time, cost, and procurement management. Although supply chain research has seen a large number of contributions on gaming and information issues over the last decade, there is still a research gap concerning complex supply networks that go beyond two-echelon serial systems ((Xu & Zhao, 2017) ; (C. Feng, Ma, Zhou, & Ni, 2018)). CSC still lacking exchange information among stakeholders to increase the performance of the supply chain. Other issues affect CSC's performance, which are the limited capacity on-site and the change in demand for materials.

2.4.5 Capacity and demand

In the construction sector, managing the necessary quantity of inventory plays a significant role in restocking materials and avoiding excess on-site. Capacity in the construction site is limited because of the results; it comes as no surprise most of the publications considered systems with a bounded capacity of 70% because of the capacity constraints on-site. However, 26% of the previous models did not mention and specify capacity information. Only the study of Liu & Tao (2015) considered infinite capacity and assumed that the inventory level decreases linearly during the construction process. Therefore, Xu & Zhao (2017) stated that inventory level could not exceed the storage capacity on-site because of the limited capacity constraint. Lu, Hui, et al. (2018) noted that the quantity of material allocated to each activity could only equal its actual demand or zero at any period. Hsu, Angeloudis, & Aurisicchio (2018) considered capacity constraints and assumed that the sum of all the stored products' volume is always smaller than the warehouse capacity.

On the other hand, the demand in construction varies. However, we found that 74% of the papers assume deterministic demand, and around 26% of the papers assume general stochastic demand. Therefore, only 8% of the considered papers did not specify demand. (Zou, 2012) considered the material consumption speed of each period is different, that means based on the productivity on the construction site for each period. Xu & Zhao (2017) considered the demand for each period for each project is known. Indeed, materials are obstacles for construction project managers and their suppliers, incur additional inventory costs, and cause serious construction problems, such as site congestion and deterioration of the materials' quality (Tserng et al., 2006).

The study of Lu et al. (2016) focused on the analysis of the stochastic inventory control problem of construction material and develops a general safety-stock determination approach under nonstationary stochastic demand and random supply chain the purpose of this study is to present a general approach of construction material safety-stock determination that can improve the overstock or understock situation. Therefore, they emphasized using the inventory buffer concept to investigate the influence of material inventory on construction projects' variability. The model was, however, limited because of not considering uncertainty and disruption in the supply chain. Hsu, Angeloudis, & Aurisicchio (2018) proposed an optimization model of logistics processes in modular construction deals with variations in the demand on construction sites. Deng et al. (2019) presented a mathematical model to support decision-making for allocating consolidation centers in congested regions with long transportation distances. In modular construction, products are transported from the warehouse to construction sites according to each product's daily demand at each location on a just-in-time basis. However, the variability of construction project and uncertainty in the material supply chain is still needed to draw more consideration.

2.4.6 Customer response to stock-out

The majority of publications over time (59 %) used a guaranteed service approach, which implies that all demand is satisfied. 14% considered backorder type customers. In 4% of all papers, demand not met in time is lost, and the rest of the publications did not mention their response. In practice, customer responses to stock-outs vary. In business-to-consumer (B2C) environments, most customers choose another product or another retailer. With online sales, this has become easier than before. In business-to-business (B2B), delivery time is negotiated when products are not available on time.

2.4.7 Optimal polices

As in most other fields, researchers have strived to find optimal control policies. In inventory management, it is commonly assumed that costs for holding inventory are linear in time and number on hand. In contrast, penalty costs are linear in time and number of backorders. Besides holding and penalty costs, fixed order costs are considered. Though other objective functions have been considered, we restrict ourselves to this cost structure, as it concerns the vast majority of papers devoted to the quest for optimal policy structures. In our analysis, we distinguish between serial, convergent, divergent, and general structures. Major challenges regarding optimal policies concern systems with finite capacity. It is fair to say that, for general structure, there is no hope to find optimal policies. In our classification, we have indeed classified the solutions from models under the GSM assumption as optimal. On the other hand, the optimality of a solution should be viewed in the context of the model's application.

2.5 Research gaps

From the Literature review, it can be said that the researchers emphasized discussing the solutions for inventory problems in the construction project with a similar purpose, which is to reduce cost and time and increase profitability for the construction project. In this context, various researchers such as Sajadieh et al. (2009) & Fu (2014) emphasized analyzing the construction managers' traditional approaches to manage the inventory. For this purpose, they have also used the GA and HA algorithms. However, from the critical analysis of the traditional approaches, it can be said that these methods are time-consuming and complex for the managers of the construction projects.

Along with this, the use of information technology in inventory management is one of the effective methods that could enable the managers to monitor the supply and need for materials and analyze the backorders in the construction. The involvement of technology could also enable the construction managers to emphasize reducing the cost and enhancing the effectiveness of the inventory so that the project's overall performance could be increased effectively. The researchers emphasized various models for determining the demands of the customers and variables that impact the inventory system of the construction project.

From the critical analysis of the models and the evidence offered by the researchers, it can be said that the inventory models could help the managers of the construction project to manage the tasks effectively using proper strategic planning and material ordering. The authors pointed to the need for improved scheduling and Just-in-time deliveries. Digital tools, including simulation or optimization, web-based system for logistics or solutions based on BIM were proposed. Other solutions include using a separate logistics company, increased standardization or pre-assembly, and methods to size the material inventory or safety stock optimally (Seppänen & Peltokorpi, 2016).

As presented above, recent studies in the literature have attempted to develop various models to facilitate the optimization for inventory systems in construction. Despite their significant contributions to the body of knowledge in construction management, the existing studies still have the following gaps:

- previous studies in CSC focus on optimizing logistics costs related to material purchasing, transportation, and storage. However, most of the studies ignore the role of the integrated problem of project scheduling and material ordering;
- although some previous studies confirm the benefits of the integration for construction logistics, there is a lack of study developing the optimization model for construction

logistics with considering the value of collaboration between stakeholders to minimize total CSC cost;

- While BIM has become essential within all phases of the construction project, there have been no studies proposed framework on how it can be CSC stakeholders collaborate to reduce the inventory cost;
- there is also a lack of study developing the optimal models for the integrated CSC operations, which considers finished modular construction products shipped to construction sites.

To have clear understandings of construction logistics and SCM as well as fill the above gaps, it was important to classify the inventory models and identify the problem types in each model, the relationships existing between the SC actors during the major construction stages. Although scholars widely studied the theories of purchasing and supply operations in construction, the optimization for SC collaboration among members has not yet been fully explored for the industry. Thus, this thesis's proposed optimization model for collaborative construction supply chain (CSC) planning deals with the integrated problem of project scheduling and material ordering for modular products. The main objective is to achieve more coordination and, therefore, to reduce the total cost of the CSC.

2.6 Conclusion

Over the last decades, researchers attempted to apply different models to optimize inventory for better construction project execution. However, the application has been limited and at a slower speed than that in general applications. From the typology, it can be said that the researchers emphasized discussing the solutions for inventory systems in the construction projects with a similar purpose, which is to reduce cost and increase profitability. In this context, various researchers emphasized analyzing the traditional approaches to manage the inventory. For this purpose, they have also used the GA and HA algorithms. The results show a lack of a clear framework that deals with the issues in managing the inventory.

The use of information technology in the management of the inventory is one of the effective methods that could enable the managers to monitor the supply and need of materials along with analyzing the backorders in the construction project, thereby allowing the construction managers to emphasize the reduction of the cost and enhancing the inventory effectiveness. However, the collaboration of SCM systems in construction is not often realized in its full capacity and potential. This is one reason why the construction industry invited BIM to resolve site conflicts. In the next chapter, we will propose a collaborative framework to consolidate research limitations and gaps and offer a solution to overcome inventory issues because of the integration of all CSC members. Partners will predict risks of disruption to production and design buffers to guard against those risks. The next chapter discussed decision-making in the construction SCM and proposed a new collaboration framework for the inventory system in construction projects.

CHAPTER 3

COLLABORATIVE FRAMEWORK FOR INVENTORY MANAGEMENT IN CONSTRUCTION PROJECTS

3.1 Towards collaboration framework

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, SCM concepts are 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. In this specific period, Papers mostly discussed the controversial issue of 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 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 efficiency in performance: Lean concept is adopted to improve CSC collaboration (Eriksson 2010); logistics modelling using simulation (Vidalakis et al. 2011) and logistics optimization using meta-heuristics algorithms (Hisham Said & El-Rayes, 2014) & (Kumar and Cheng 2015). Recently, CSC integrated with building information modelling (BIM) is another proof that the adoption of logistics and SCM in the construction sector continues to evolve with technological progress (Papadonikolaki et al. 2015).

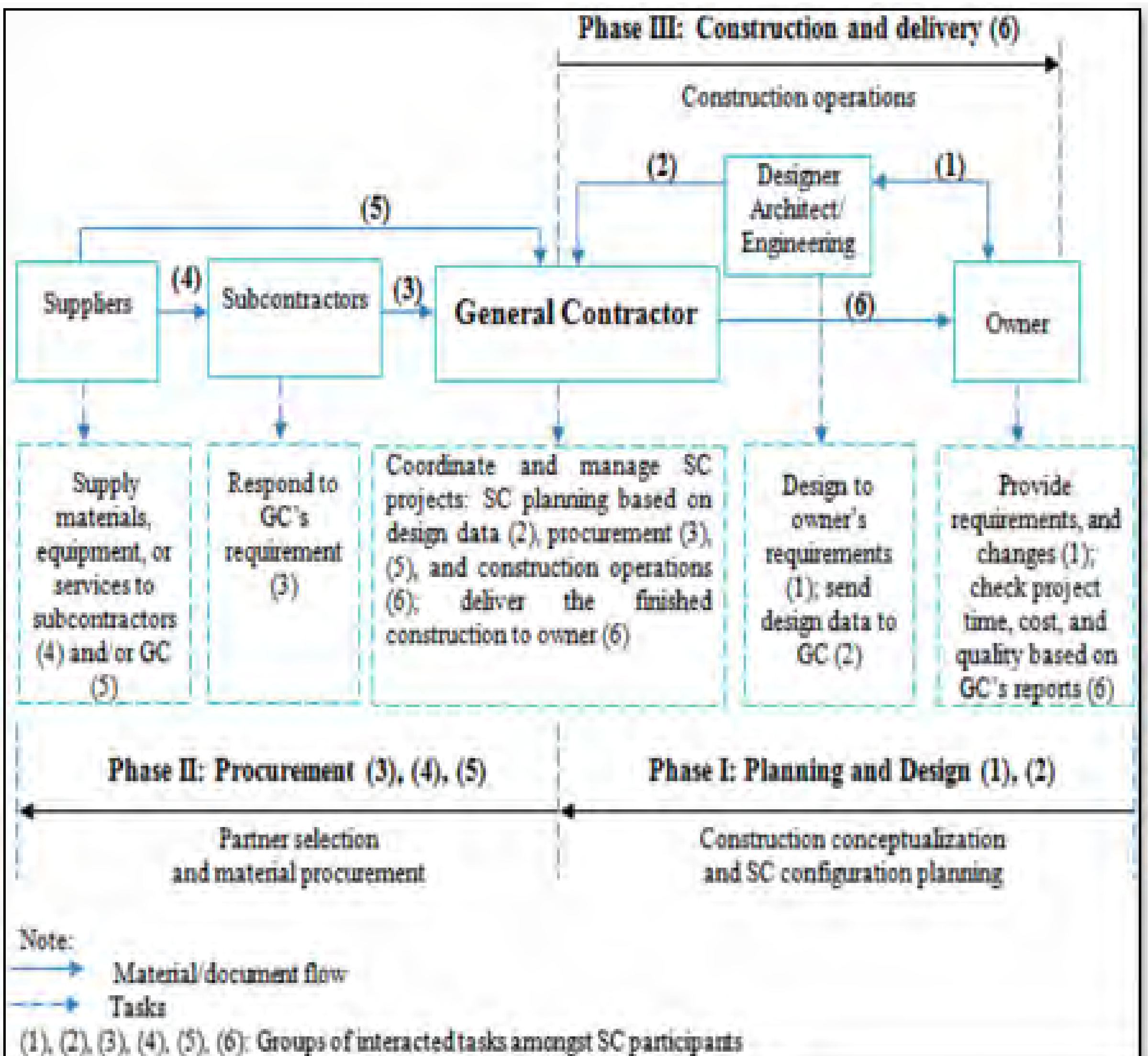

Figure 3.1 Phases of the construction process with participants' tasks.

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 of design and construction, the absence of integration and coordination between different functional disciplines, and 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. 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 to improve construction networks since it is not clear who will gain the benefits of improving 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 their own business's efficiency to achieve immediate economic advantages rather than to improve the network performance. It is suggested that the stakeholders should consider the global efficiency of the 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 construction management research has not proposed any framework to classify construction supply chain decision-making or suggest when they should be integrated along with the construction phases (Azambuja and O'Brien 2009). To fill this gap, this chapter 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.

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) with the tasks. 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.

3.2 Present focuses of decision making in CSCM

This section contributes to the illustration and discussion about the present focuses of decision-making in CSCM for the reviewed papers. It answers the research question – RQ1: 'What are the focuses of decision-making in CSCM and the relationships existing between the SC participants during the major construction phases mentioned in the reviewed literature?' Table 3.1 shows the decision focuses on CSCM across three major construction phases mentioned by recent scholars.

At the strategic level, eight papers aim at the decision of identifying CSC configuration, nine papers focus on the decision of developing tools and methods for CSC planning and management, and five papers consider the identification of CSC risks as an important decision at the phase 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.

Table 3.1 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 3.1 presents detailed descriptions of CSC decisions.

Focused decisions, for CSCM in accordance with each phase of the construction project, which are proposed by the reviewed literature. At the phase 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 feedback to the designer and calls for the designer's contributions during the stage of CSC network planning.

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.

Table 3.1 Descriptions of CSC decisions

Decision level	Decision	Descriptions
Strategic	CSC configuration	To configure and allocate CSC factors, participants, procedures, tasks, material & 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.
	Tools and methods Development	Develop methods and tools for process planning, process controlling, and performance measurement of CSC network.
	CSC risks identification	Identify, assess risks, raise mitigation and contingency strategies, and respond efficiently to recognized threats as they arise.
	Building partnerships	Apply CSCM to achieve long-term and supportive partnerships between actors in a global perspective in order to improve construction performances, and create client value at a lower cost.
	Building construction information system	Develop IT systems to link all stakeholders and resources of the network, provide real-time data, and accelerate the innovations in the construction industry.
Tactical and operational	Production planning	Make the production plan and control for construction processes; and provide information throughout the construction project to all stakeholders' requirements.
	Supplier selection	To apply efficient methods for supplier evaluation and selection.
	Purchasing materials	To establish and employ the efficient models to optimize the material procurement and storage.
	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.
	Site-layout planning	To improve the on-site performance through optimizing the arrangement of temporary facilities in which transportation distances of on-site personnel and equipment are minimized.
	Controlling information flow	To control information flows in order to leverage the construction stakeholders' collaborations and avoid the instability in construction execution.
	Material handling	To convey, elevate, position, transport, package and store materials. It is straightly associated with site layout planning.

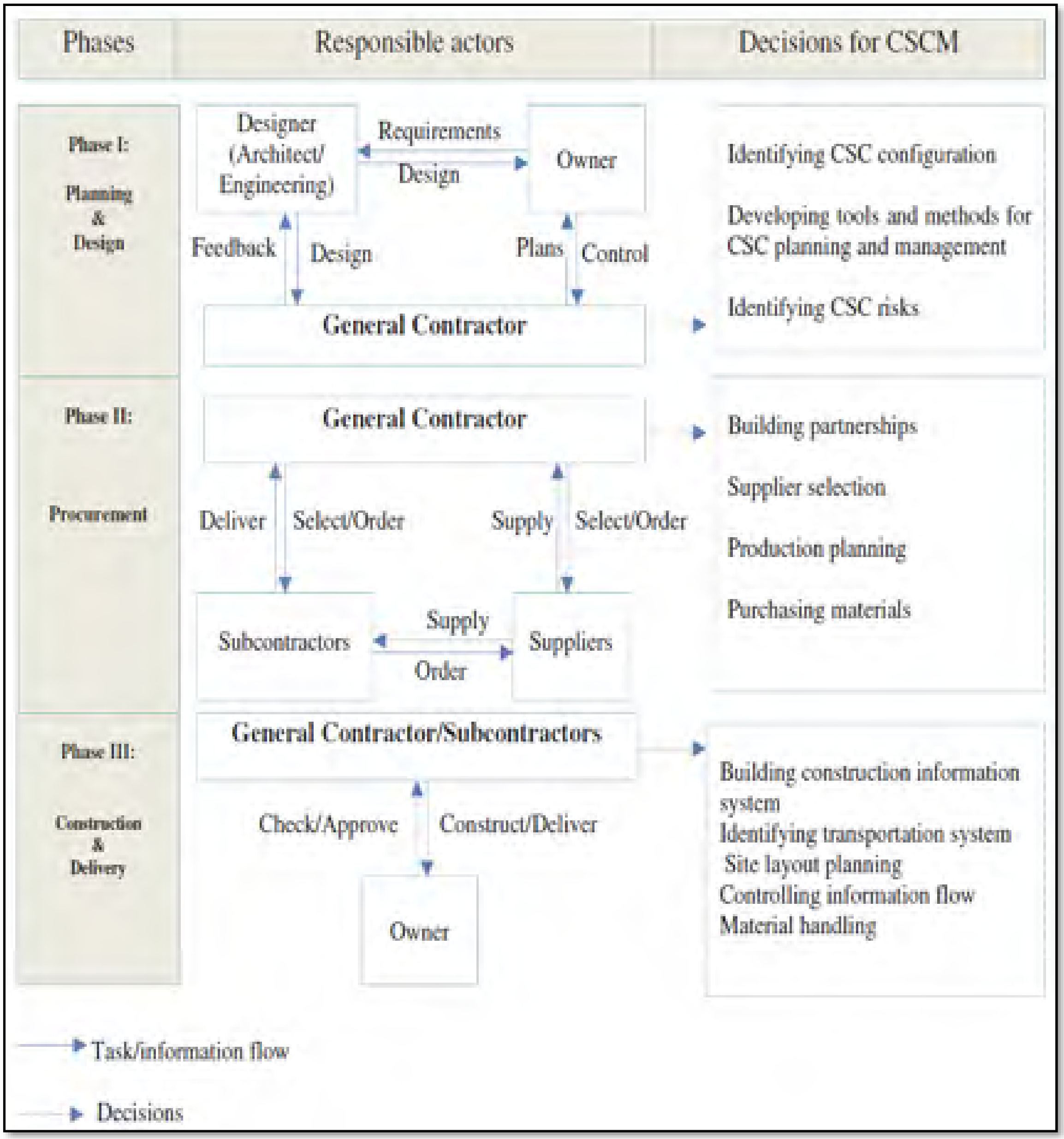

Figure 3.2 Decision focuses on each phase of construction project

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 among the GC, the designer, and the owner for the planning and design; thus, it results in the inefficiency in construction planning and design. Therefore, propositions are made as follows:

- **p1-** during the planning and design phase, 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;

At the phase of procurement, the General Contractor focuses on the decisions of building partnerships, supplier selection, production planning, and purchasing materials. The strategic decision of building alliances with key partners requires 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 phase needs the collaboration of the General Contractor, the subcontractors, and the suppliers to ensure the reliability of materials supply process and sub-construction delivery, and mitigate the risks of supply delays.

- **p2 -** during the phase of procurement, the collaboration between the General Contractor, 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 phase of construction, the General Contractor 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 General Contractor and subcontractors work together on-site to finish the construction; thus, their corporations are very important in this phase to assure the schedule, cost, and quality of the construction. To make the construction phase 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 General Contractor.

- **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 decision (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 phase of planning and design to leverage the quick responses to the uncertainties occurring on the construction site;
- **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 phase to leverage the quick responses to the uncertainties occurring on the construction site.

3.3 Evolution and trends in CSCM application

Among the literature sample, there are few papers, which discuss the evolution and trends of SCM application in construction (Vrijhoef & Koskela 2000; Dainty et al. 2001; Xue et al. 2005; Albaloushi & Skitmore 2008; Azambuja & O'Brien 2009; Tennant & Fernie 2014; Behera et al. 2015; Papadonikolaki et al. 2015; Simatupang & Sridharan 2016; Lin et al. 2017). The timeline Figure 3.3 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 & Johnson 2015).

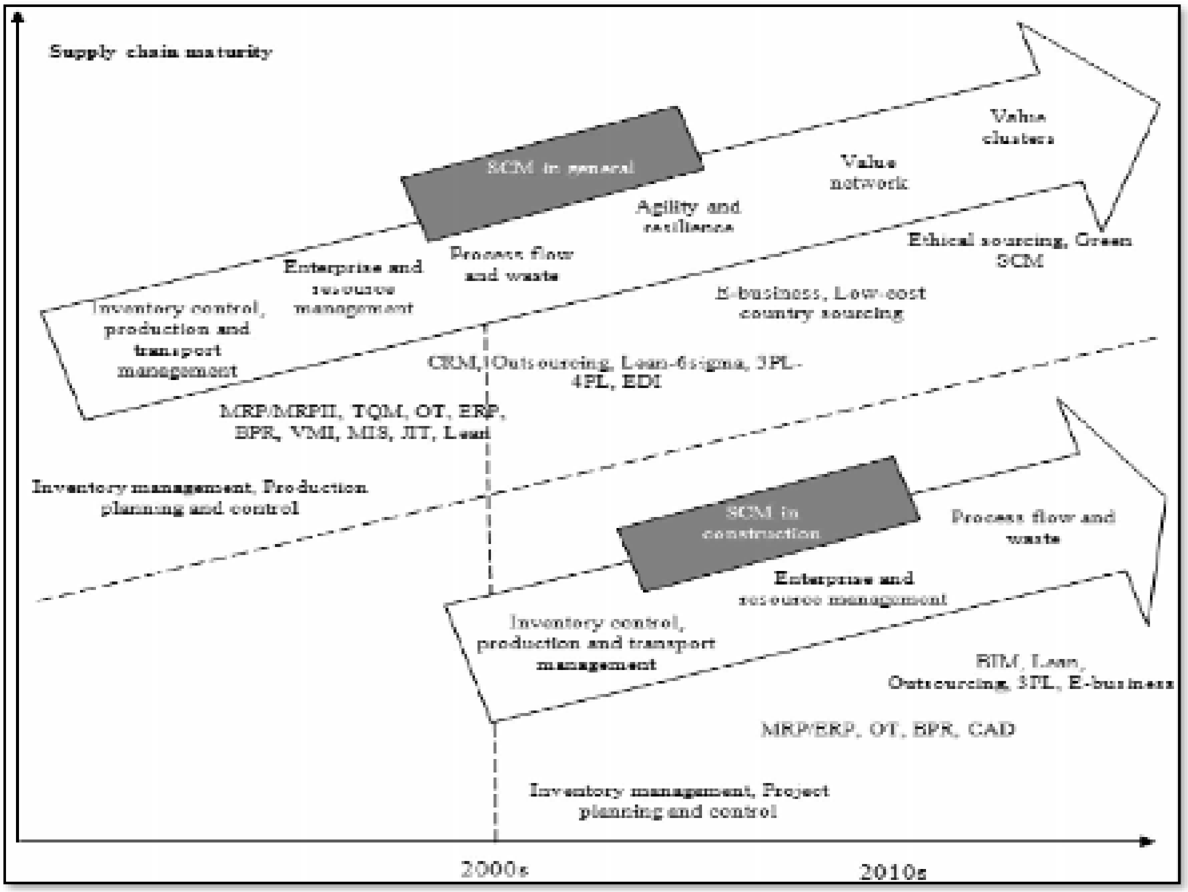

Figure 3.3 Evolution of SCM strategies and techniques in general & in construction.

As shown in Figure 3.3, 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; 3PL-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 3PL to process the customer orders. In such case, the relationship between the 3PL 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 2008). 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 & 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 CSCM 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 CSCM 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; 3PL; E-business) to control and improve the process flow and eliminate the construction wastes (Albaloushi & Skitmore 2008; Papadonikolaki et al. 2015; Dave et al. 2016; Simatupang & Sridharan 2016; Lin et al. 2017). For the efficiency in the process flow and waste elimination, the trend in CSCM 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 & O'Brien 2009; Hisham Said & El-Rayes, 2014; Tennant & 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.

3.4 Building information modelling (BIM)

3.4.1 BIM and planning process

The planning and management of SCs require well specifying the participating members and the relationships amongst them. CSCs normally consist of various members and are complex in structure. Representing CSCs using a network model can help understand the complexity, support re-configuration, identify the bottlenecks, and prioritize company's resources, as well as additional values to the management of construction projects (J. C. Cheng et al., 2010b).

The application of Building Information Modeling BIM is to create the project plan and budget, provide collaboration between the design team, choose and manage sub-contractors, and to optimize the client's skills and satisfaction (Bryde, Broquetas, & Volm, 2013). Based on (Yan & Damian, 2008), by using BIM, there are some benefits such as improving creativity, quality, and sustainability and decrease the time and cost. Therefore, BIM can reduce resistance problems, decreasing in rework and improvement in engineering efficiency, improved job site communications, excellent quality, design, and an early generation of the steady budget for the project as practical of BIM models. Decreasing the uncertainty of working with traditional version data, exchange information simply with team members, even though virtually, observing and manage the activities of construction projects (Janssen, 2014).

On the other hand, when using BIM, there are some challenges, which is: poverty of using BIM by operators, BIM keeps hold on improving and make a difference in the process is needed since more task is done in advance to save cost and work through construction (Yan & Damian, 2008). The BIM model and the plan connected to result in a specific plan; for each material utilized in the building is precisely recognized when it is needed at the construction site. When consolidated BIM with the plan is called the 4D model, with the 4D model, it is possible to find difficult schedule sequences, so, by using 4D model makes it possible to carry out materials JIT at the construction site (Bryde et al., 2013). Deliveries can be planned by the information that includes in BIM such as sizes; weight and number of the materials with this information can calculate the amount and type of trucks needed.

BIM as a process can be seen as a virtual process that includes all sides, disciplines, and facility system within a single virtual model, enabling all stakeholders to cooperate more precisely and effectively than traditional processes (Azhar, Khalfan, & Maqsood, 2012). BIM has been solved most of the issues that were prevailing in the supply chain.

Table 3.2 BIM has addressed certain issues of CSC

Issue of supply chain	Application in construction practice	BIM Solutions
Lack of transparency in the material and component information	Placing of a material order for a subcontractor can be delayed because of the lack of transparency of the data. BIM reduces this.	Information is fully transparent for the project team and necessary parties of the supply chain as they can be accessed by them through the software at any point.
Reduction of variability	Orders given by the client most probably do not fully communicate to almost all the parties. So, there is variability in data.	Variability has been reduced by given identical data for all the users of BIM regarding one project. Changes are updated on all the other users' accounts.

Issue of supply chain	Application in construction practice	BIM Solutions
Synchronization of material flows	Material production, supplying, and delivery process do not synchronize. Therefore, transportation costs get high.	Materials for assembly have been Synchronized
Poor management of critical resources	Mostly in design & build contracts, where the contractor is selected with the basis of tender price, it is very difficult to determine the critical resources.	BIM has the facility to link with project management soft wares like the last planner, clearly identifies the critical path and reduces the workload of critical resources.
Configuration of the supply chain	For every new project, a new supply chain is formed, and the connection between previous supply chains is very low. Therefore, the configuration of all those new supply chains has built up everything from the beginning. Mostly the relationships.	Configurations van be evaluated by BIM five-dimensional models
Poor communication between supply chain members	Interconnection between supply chain members is very low, mostly due to the fragmentation of the industry.	BIM is interconnected with all the parties, and once a change occurred it is automatically changed and communicated with the whole group of model users
Waste and pollution increment	Current supply chain is full of waste and pollution mainly due to the non- collaboration work and lack of knowledge about the actual scope of work.	Waste and pollution is minimized as the whole concept is drawn on the software package.
Time-consuming	When the information flow gets slow, doubtful and non-trust worthy it consumes a lot of time. Traditional methods always take more time to identify the problem and find solutions.	BIM works as work packages under a pre-determined schedule; therefore the work is done faster.
Additional costing for unforeseen events	Unawareness about the cost uncertainties is a major problem nowadays.	Cost has been introduced as the 5th dimension of BIM for early cost warnings
Different parties of supply chain use different data in the same manner	For a particular one item most probably architect, quantity surveyor and engineer works with three different drawings.	BIM makes sure everybody work with the same data. Integration of all the components quickly passes a transformation.

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, Nadeem, Mok, & Leung, 2008). Many authors have already attempted to propose the frameworks and models using data from BIM to facilitate the dynamic planning of construction logistics. Cheng et al. (2010) proposed a Service-oriented architecture model to facilitate the flexible synchronization of CSCs by employing internet services, internet portal, as well as open data-source technologies. Jung & Joo (2011) promoted the important role of BIM as CSC information system, which leverages relationships of construction participants and integrates all the corporate tasks consisting of planning, design, controlling general management, and research and development. Maghrebi et al. (2013) proposed a model for integrating BIM with CSC to control and reduce delays in construction material delivering. Hisham Said & El-Rayes (2014) developed an automated multi-objective construction logistics optimization system (AMCLOS) to support the contractors in the optimization of material procurement and storage. AMCLOS automatically retrieves project data of space and sequence from available scheduling and BIM electronic files for optimizing material handling and site layout decisions. Papadonikolaki et al. (2015) proposed a model, which merges product model, process model and organizational model into a graph-based model to represent and analyze a BIM-based CSC project. Kumar and Cheng (2015) developed an automated framework for creating dynamic site layout models by utilizing data from BIM.

A trend in BIM implementation is expanding 3D data into an nD information modeling, since BIM is a source of plentiful data associated with the facility (geometric and functional data) throughout the whole life cycle of construction projects (Ding, Zhou, & Akinci, 2014). This leverages dynamic and virtual exploration of scheduling, costing, sustainability, maintainability, and safety. The nD modelling distributes useful data to all construction participants to track the necessary information in a matching system, which results in cohesive and efficient construction performances. Besides, the development of cloud computing technology recently creates a breakthrough in data storage and sharing platform, enhancing cooperation and collaboration and leveraging effective real-time communication among the network participants (Wong, Wang, Li, & Chan, 2014). Nevertheless, the technology is fairly novel to be applied for the construction industry. Researchers expect that the implementation of cloud-based BIM can generate opportunities to share different disciplines and interchange the essential data for making important decisions during stages of construction projects (Porwal & Hewage, 2013).

With the complexity of projects arising, project management methods are required to optimize the procurement and allotment of material inventory. Construction material organization involves storage supply and onsite logistics that will be affected by management decisions. This study optimizes the benefits of management material costs and making decisions by integrating Building Information Modelling (BIM) system that has been used by contractors and design teams. One of the main issues of using BIM and the use by a few stakeholders is the level of detailed data that the decision-making process is based on. BIM is designed to help understand the logistics and optimization of planning material storage and supply to reduce as much material waste as possible. BIM will illustrate the latest automated logistics systems granting users the ability to optimize building materials for building and machinery applications. BIM's inventory management system objective is to forecast the results of acquiring inventory at the time of construction, its drawbacks, and the materials' delivery process. With the trend in BIM systems becoming a globally accepted practice, project managers are tasked with reinforcing BIM applications. Besides interpreting BIM characteristics, its applications are critical for forecasting onsite problems and providing solutions.

3.4.2 Benefits of selecting BIM for project practices

BIM can be selected for technology tracking in supply chain operations to resolve project objectives during required prompt material deliveries and material application and installation. Buildings erected nowadays are designed digitally as well as for the relationships between the building and its occupants within internal systems used for monitoring facilities. Prompt productivity encourages BIM as its advancement of software adoption. BIM is designed with the capacity to behave as an altering factor to visualize industrial changes and their demands, putting forward sustainable design.

The digital illustration in BIM software resolves ahead of time the supply chain and logistics operations (Watson, 2011). This study invokes the negative factors of onsite delivery as well as positive factors. Surely positive are the more favorable conclusions by using BIM software, as its intent in design is resolved. However, a positive outcome computed by BIM cannot be formulated without forecasting the negative aspects of inputting specific factors. The purpose of BIM resolution is to be prepared to face challenges in the event projects travel from their intended scheduling. With BIM, the project can be resolved in a controlled manner and by understanding the forecasted negative results, can be handled effectively. A ranged of problems can be focused on throughout the SCM system where risk management is discovered. As a result, a framework designed to bridge the gap between risk management and material delivery on site.

Therefore, risk management has been mostly defined by time and cost estimates indicating underperformance and miscommunication. Companies are known for merging within a supply chain arrangement to collaborate skill efficiency and attitude on the project. Hence, BIM software benefits by selecting specific personnel suitable for specific tasks introduced to each project. However, the collaboration of SCM systems in construction is not often realized in its full capacity and potential. This is one reason why the construction industry invited BIM software to resolve site conflicts. Many conflicts, either onsite or offsite, are due to material delivery issues. For example, a subcontractor is scheduled to begin its work scope on a particular date when their respective material delivery is delayed or the former subcontractor has not completed the work.

Evidently, many standards and procedures are utilized for information and data mining within BIM software. The support of top management and organizational capacity are predetermined factors playing critical roles implementing BIM software to resolve logistics. They assist with coordination and communication along the technical aspects of learning curves. BIM implementation captures change management when necessary or when existing site conditions are impractical. BIM can be inputted with the mitigating features by management in order to compute where the project will be affected by material delivery and then improve with efficiency (Jung & Joo, 2011).

3.5 Collaborative planning and design with advanced techniques

The Planning and design phase is critical and has a major impact on CSC performance, which produces the strategies for the following activities of construction management and execution. It usually requires the integration of GC, owner, and designer into construction design and development processes. Nevertheless, to achieve more efficiency in CSCM, it is suggested that the involvement of the key suppliers and sub-contractors in the phase of construction planning and design can increase the productivity and supply commitments and decrease the risk of non-compliance. Besides, as mentioned in the previous proposition (P4), planning-based decisions should be conducted at this phase 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 phase of planning and design.

Besides, decisions related to construction IT planning, logistics planning (transportation, site layout, and material handling) are also proposed to deploy at this phase 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 external integration. 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 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.

At this phase, Building Information Modelling (BIM) is strongly recommended as a data source for the SC participants to create, share, and use data together. 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 improve design coordination and 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 ensure the well-competent requirements. The GC uses the design data for 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, and material handling) require optimal solutions to reduce construction costs 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 Modelling (ABM), Simulation, and Mathematical programming (linear programming, integer programming, dynamic programming, stochastic programming, multi-objective optimized modelling, game theory, and 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 model developer's corporate objectives. ABM can be used to achieve the agreed solutions of logistics through the process of negotiation and interaction amongst the SC participants. 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 uncertainties occurring in the construction execution. 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. These techniques are useful in construction and logistics planning by optimizing the construction logistics cost, including ordering, carrying, shortage, layout costs, optimal material supply and storage, creating dynamic site layout models, or minimizing transportation costs.

3.6 The proposed framework for future inventory system

A range of problems can be focused on throughout the SCM system, where the risk of inventory management is discovered. As a result, a framework is designed to bridge the gap between inventory management and material delivery on site. Companies are known for merging within a supply chain arrangement to collaborate skill efficiency and attitude on the project. Hence, the BIM system benefits by selecting specific personnel suitable for specific tasks introduced to each project. The balance between onsite and offsite inventory is determined by a consistent flow of material to reduce costs. Therefore, there is a considerable amount of literature claiming that the Construction Consolidation Centre (CCC) can improve logistics practices and limit these problems. Implementation of a consolidation center solves problems due to the lack of storage space on construction sites (Deng et al., 2019).

Poorly planned logistics can result in late project delivery as well as the following problems:

- increased cost and use of storage on the site;
- increased health and safety risks to site workers due to increased material handling;
- create obstacles for contractors on the project site.

A CCC is a distribution facility through which material deliveries are shipped to construction sites and can take the right material at the time of the request to the right place. Besides, providing a dry and safe place to avoid materials being damaged, reducing the environmental effect of material transportation and reducing the level of tied-up capital and worker risks in the construction site (Lundesjo, 2011).

The proposed framework in Figure 3.4 based on the results obtained from the literature review. The basic idea is to use BIM to achieve more collaboration and integration between SC members among different phases of the construction process. The new framework is focused specifically on future inventory systems in the construction sector to avoid the congestion of materials on the construction site as well as to reduce the inventory cost. A trend in BIM implementation is expanding 3D data into nD information modelling since BIM is a source of rich data associated with construction projects' whole life cycle. BIM is proposed as IT because of its ability to compute inventory manipulation fluctuations based on crew size and inventory quantity. BIM can be selected for technology tracking in supply chain operations to resolve project objectives during required prompt material deliveries and material application and installation. During the planning and design phase, the integration between the General Contraction, the Owner and the Designer contributes to CSC network planning and design efficiency through the decisions focused on identifying CSC configuration; developing tools and methods for CSC planning and management; and identifying CSC risks.

Therefore, BIM can accelerate the construction inventory process and simultaneously improve quality. However, conventional inventory methods need to evolve as many components are created offsite and then transported to the site. Manufacturing rates often rebound within specific ranges because of the variable numbers of crewmembers. The inventory production process is to be analyzed through a simulation model for computing the problem's probability. The data to be input has to be accurate to gain accurate BIM results to leverage the data. Combining BIM and the process simulation to develop and facilitating a model to optimize inventory management and construction planning.

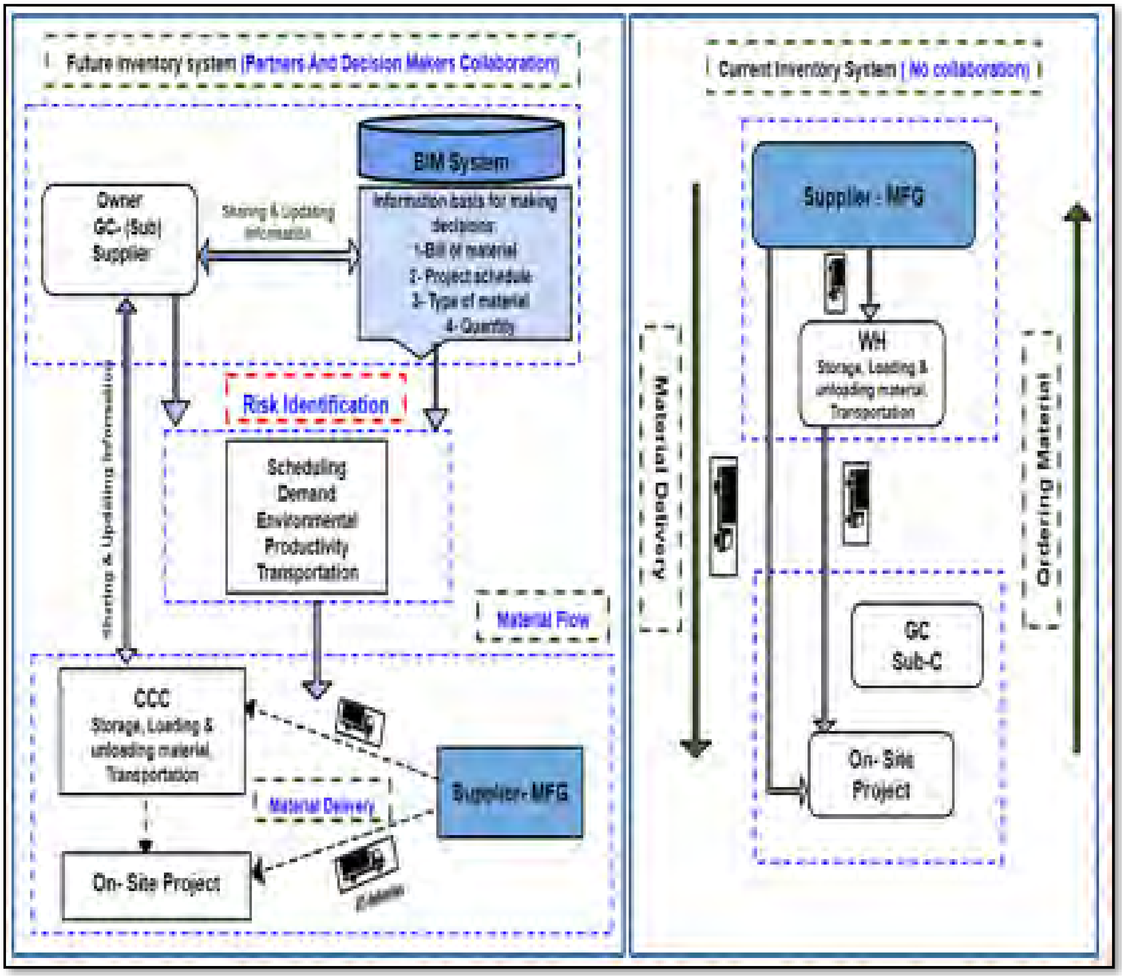

Figure 3.4 The role of BIM in inventory management of CSC

To reduce the impact of unseen risk factors that may affect the progress of any construction project, it is essential to have tools to predict the influence of major risk factors in advance identifying and understanding the risk events that affect CSC and developing models that automatically detect changes in the probability distributions of risk factors in the planning and the operation phases. To achieve more efficiency in CSC, it is suggested that the involvement of the key owner, supplier, CC, and contractors in the phase of construction planning and design can increase the productivity and supply commitments and decrease the risk of non-compliance. At this point, BIM is strongly recommended as a data source for the SC participants to create, share, and use data together (Hisham Said & El-Rayes, 2014) & (Kumar & Cheng, 2015).

The BIM provides a full range of construction project information (such as construction schedule, material quantity, and on-site inventory). The analysis layer then uses the provided data (e.g., cost analysis or network analysis) to support CSCM tasks. Furthermore, the CCC operator makes up consolidated loads and delivers them on a Just-In-Time (JIT) basis. Materials shipping from MFG to CCC occurs where inventory is only held at CCC with consideration to transportation, inventory holding, and fixed and variable processing costs. This way provides a just-in-time delivery system, smoothing the flow of materials and delivering usable quantities to trade different contractors. The BIM monitoring model's objective is to overcome the main challenge in the supply chain process of material tracking. Therefore, providing the managers with reliable information on material status, whether the inventory is located at the site or elsewhere along the supply chain (Irizarry, Karan, & Jalaei, 2013).

3.7 Conclusion

This chapter aimed to fill the research gaps identified in the field of construction logistics and SCM. First, we identify the decision-making in construction SCM with detailed specification of methods and tools that meet new construction management practices and the technological progress. Besides, we found that recent research has not proposed any framework to address the issue of CSC's inventory system. Therefore, it is essential to have tools to predict the influence of major risk factors in advance identifying and understanding the risk events that affect CSC and developing models that automatically detect changes in the probability distributions of risk factors in the planning and the operation phases. The next chapter, proposing a supply chain model where inventory management and scheduling decisions are integrated through collaborative mechanisms to achieve more coordination and, therefore, to reduce the total cost of construction supply chains.

CHAPTER 4

COLLABORATIVE SUPPLY CHAIN PLANNING AND SCHEDULING OF CONSTRUCTION PROJECTS

4.1 Introduction

Construction supply chains are a complex network with different relationships and resources, product/services, logistics, information, and money flows. Moreover, construction projects planning and execution involve many participants from several organizations requiring intensive communication efforts to efficiently deliver the project. The use of a project-oriented management procedure is adding more obstacles since each project is unique. Supply Chain Management (SCM) in construction represents a significant construction opportunity (Le et al., 2018). However, the construction industry's lack of collaboration is one of the significant issues that the industry is facing. Work in a silo "goes with the fear of losing one's territory and not accepting the benefits of this type of collaboration, particularly when it comes to saving time and money."

Supply chain collaboration could drive massive cost-saving, provide real-time supply chain collaboration, and increase the ability to deliver the project one-time. In construction, the application of SCM concepts is frequently used to guide project managers in strategic planning to achieve strong partnerships with suppliers and obtain more operational construction efficiency (Azambuja & O'Brien, 2008; Hsu, Aurisicchio, & Angeloudis, 2017). 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 project scheduling (Vaidyanathan & Howell, 2007). Project scheduling integrated with material ordering leads to issues that affect various aspects of the construction projects, especially about cost and resources management, including inventory management. Traditional inventory construction planning strategies based on non-aligned planning from the start of a project becomes problematic during construction project execution (Sajadieh et al., 2009). Concerning this, a research study identified other costs, such as renewable resource costs and back-ordering costs, which were introduced to tackle the limitation of traditional inventory management methods in construction projects (Fu, 2014). A recent study proposed a MILP model to support the operation of a general multi-project multi-resource multi-supplier of CSC (Golpîra, 2020). The model considered the Vendor Management Inventory (VMI) strategy and addressed the supply decision sharing strategy to integrate the CSC network design and facility location problems. Another study emphasized material buffers in construction, discussing the impact of buffers' deployment on project variability (Horman & Thomas, 2005). The results highlight the importance of managing buffer size carefully and analyze the relationship between inventory buffers and construction labor performance. The problem of inventory allocation was addressed by presenting a mathematical model for optimizing the simultaneous planning of material procurement and the project schedule (Tabrizi & Ghaderi, 2016). Other researchers suggest more extensions to inventory management models in construction by adding transportation, information, and facilities drivers, which affect the CSC (Ko, 2010).

Analytical models have been frequently used to model the construction supply chain to optimize cost or minimize time subject to the project constraint. For example, H. Said & El-Rayes (2011) proposed a novel optimization model for the efficient procurement and materials storage on project sites that can improve the productivity and the profitability of the construction project. Hamdan et al. (2015) presented a framework that integrates BIM with simulation for inventory management to reduce inventory cost and increase the performance of the CSC. More recently, Golkhoo & Moselhi (2019) presented an automated method as a part of a significant materials management system to generate an optimized material delivery schedule. The literature reviewed raises construction project issues to do with the lack of collaboration amongst the SC participants. Each player has his schedule. Therefore, the collaboration between different supply chain players is critical to improving construction profitability (Dallasega et al., 2018). Although the rich literature in supply chain collaboration, to the best of our knowledge, the coordination of production, scheduling, and inventory management in the construction industry has not been studied in the past (Chen, Lei, Wang, Teng, & Liu, 2018).

4.2 Literature review

4.2.1 Project scheduling problem

One of the critical problems within the construction industry is project scheduling (Hartmann & Briskorn, 2010) and has been studied for decades; however, an integrated model that supports the construction project scheduling problem-solving method is still lacking. Delays in construction projects, cost overruns, and low quality have long been common issues within the construction sector (Larsen, Shen, Lindhard, & Brunoe, 2016). Construction scheduling is concerned with optimally sequencing activities over time and allocating resources accordingly (J. Zhou, P. E. Love, X. Wang, K. L. Teo, & Z. Irani, 2013). Construction scheduling is concerned with optimally sequencing activities over time and allocating resources accordingly (J. Zhou, P. E. D. Love, X. Wang, K. L. Teo, & Z. Irani, 2013). Construction projects consist of complex facets of work. Wrong decisions on selecting construction methods and allocating resources, such as crew size and equipment, may lead to cost overruns or project delay issues. Zhang, Li, & Tam (2006) proposed a heuristic algorithm investigating possible combinations of tasks while scheduling all tasks in the selected combination to minimize project duration. Therefore, resources are the most influential constraints in construction, as they determine the feasibility of a project schedule and whether it is optimal (P.-H. Chen & Weng, 2009). Resource management, regardless of the work location, is inefficient and can sometimes lead to a misleading schedule. Resources cannot be used, even if available, beyond the capacity of workplaces (Francis).

One of the biggest issues facing the construction industry is the fragmentation of communication and information sharing between partners. Wang, Lin, & Zhang (2020) presented an integrated information model for the resource-constrained project scheduling model to capture all the information required for construction scheduling. The construction schedule problem should be extended to include digital technologies to integrate project scheduling with the material supply chain. BIM brings collaboration and integration among SC members.

Inventory management and control are important for the construction industry. It can be used to reduce materials and logistics costs for a specific project through better collaboration between the SC partners (Zou, 2012) and avoid project delay.

4.2.2 Construction supply chain optimization models

Varieties of optimization models and techniques have been used to tackle inventory problems in the construction sector. Here, we give a detailed review of the previous solution methods applied to different models. Tserng, Yin, & Li (2006) utilized constraint programming to solve the production and supply operations model to minimize the integrated inventory cost. Fu (2014) developed an integrated mixed integer-programming model of project scheduling and batch ordering and then presented a hybrid algorithm that combines harmony search and GA to solve the problem. Therefore, it used GA to implement the multi-objective optimization of construction logistics planning in the developed automated system to integrate and plan material supply and site decisions. Liu & Tao (2015) used the PSO algorithm to find the optimal order quantity, reorder point, and lead time simultaneously to minimize each construction partner's total cost in the CSC.

The study of Tabrizi & Ghaderi (2016) applied the NSGA-II and a modified version of the multi-objective differential evolution (MODE) algorithm as the solution methodologies for project scheduling and material ordering (PSMO) problem, presented as a robust mixed-integer programming model. The performance of the NSGA-II and MODE was tested against that of the e-constraint method; this method was applied just for the small-sized projects since the PSMO problem falls within the NP-Hard problems class. Liu, Xu, & Qin (2017) applied GAs (a hybrid multi-objective genetic algorithm that combines NSGA and an elitist multi-objective evolutionary algorithm) to obtain the optimal purchasing quantity and production quantity for the multi-objective CSC Operations model. Xu & Zhao (2017) proposed an interactive PSO algorithm, the bi-level PSO (BLPSO) algorithm, to cope with the dynamic bi-level supplier selection and dynamic inventory model. Feng, Ma, Zhou, & Ni (2018) developed a hybrid algorithm combining an evolved GA and PSO is developed to solve the novel Stackelberg game optimization model for integrated production-distribution construction system in the CSC.

Logistics management is a part of SCM that plans, implements, and controls the efficient flows of material and related information and the inventory storage to meet customers' requirements. Jaśkowski, Sobotka, & Czarnigowska (2018) put forward a mixed-integer linear programming model for optimizing supplies of materials; material prices were expressed as fuzzy values with triangular membership functions and to solve the problem. The fuzzy model was converted into a three-objective linear program with crisp coefficients. Thus, the proposed way of converting and solving the fuzzy linear program produced solutions that reduce the total inventory cost in an uncertain environment. Golkhoo & Moselhi (2019) suggested a GA-MLP (Multi-Layer Perceptron) system to produce an optimal distribution schedule for products. MLP was used to enhance GA by creating a memory to solve local minima found while implementing GA for optimization. A numerical illustration validated the proposed automated approach, and the results obtained indicate that GA-MLP outperforms GA in maximizing the inventory of building materials. Tabrizi (2018) The meta-heuristics used to solve the PSMO problem include the NSGA-II and the MBO algorithm for migratory bird optimization. Habibi, Barzinpour, & Sadjadi (2019) presented an interconnected structure for sustainability considerations for the PSMO problem. The presented model falls under the category of NP-Hard problems, so two multi-objective meta-heuristic algorithms, namely NSGA-II and MOPSO (Multi-Objective PSO), were adjusted to serve as solution methods. For minor concerns, these algorithms were comparable to the second iteration of the Enhanced e-constraint method (AUGMECON2), although these two algorithms have been contrasted for large problems in which the same approach has struggled to offer the answer in a suitable period of time. The results show that NSGA-II dominates MOPSO in most assessment measures, regardless of the problem size.

Table 4.1 CSC inventory models

Author (s)	No of suppliers	No of products	Research problem	Solution Method
(X. Feng & Zhang, 2010)	Not specified	One material	Inventory control based on supply chain management and vendor managed inventory	Exact method
(Hisham Said & El-Rayes, 2014)	Multi	Multi	Construction logistics planning (supply and site activities)	GA
(Lu et al.,2016)	Multi	One material	Construction material safety stock under non-stationary stochastic demand and random supply yield	Fixed point iteration method
(C. Feng, Ma, Zhou, & Ni, 2018)	Multi	One material	Integrated production-distribution Construction System (PDCS) in CSC	GA/PSO hybrid algorithm
(Hsu, Angeloudis, & Aurisicchio, 2018)	Single	Multi	Optimization of logistics' processes in modular construction covering the manufacturing, storage, and assembly	Computational
(Jas'kowski, Sobotka, & Czarnigowska, 2018)	Multi	Multi	Material quantities	Fuzzy-linear programming
(Golpîra, 2019)	Multi	Multi	Integration of Facility location problem into the CSC network design	Computational

4.3 Research gaps and objectives

The previous literature review allows identifying gaps in this existing research and developing an integrated model for collaborative CSC. Therefore, there is a lack of study developing the optimal models to increase collaboration and reduce CSC costs. The proposed supply chain model is expected to serve as a decision methodology to achieve more efficiency in the construction sector. This chapter also demonstrates how to integrate scheduling and inventory management decisions to achieve a fully integrated project delivery method by using numerical experimentation and data-oriented optimization.

4.4 Problem statement and solution methodology

In practice, the inventory system in construction projects is restricted, which must be wisely utilized to deal with issues of approachability and congestion (Kumar & Cheng, 2015). This paper considers a multi-product and two-echelon CSC with one manufacturer, who provides finished modular construction products to the warehouse. The manufacturer and the warehouse are part of the leading focal company. The warehouse is responsible for delivering modular products to different construction sites (the consumers of finished products at a certain rate) managed by the same contractor.

Traditionally, each project is managed in an individual manner. In this study, we assume that a collaboration between the focal company and the contractor is possible, and it is beneficial for both parties. Such collaboration can be accomplished by modifying the operations in the production, inventory management in the warehouse, and the construction sites and the review of the project's schedules. All parties involved in the collaboration process have a common objective, which is the minimization of the overall cost of the construction supply chain, as shown in Fig 4.2, which captures the real CSC's critical components.

The previous literature review allows identifying gaps in this existing research and developing an integrated model for collaborative CSC. Two scenarios are explored. Scenario 1 is the original case situation where the two projects are managed independently (no collaboration). Scenario 2 is when collaboration is applied between the two projects (with collaboration).

Figure (4.1) presents the model development method, which is divided into three main steps: (1) Problem identification, which is based on the literature review, which is the basis of every research, for which it shows how connected a research is to previous studies and sets criteria for readers to assess the quality of a research. Thus, it helps to identify research focuses and stimulate new research directions. In this thesis, to identify the research gaps, we conduct a preliminary literature review of related studies in optimization inventory models in construction. (2) Building the optimization model and solution method, which take into account the issue of collaboration between SC members. First, we identify the parameters for project activities, material parameters, manufacturing and warehouse parameters, and transportation-related parameters. In terms of required information related to material quantity, BIM is used as a database to support all the required data. (3) model outputs by solving the optimization model with an objective function and constraints. Two scenarios were explored. Scenario 1 is the original case situation where the two projects are managed independently (no collaboration). Scenario 2 is when collaboration is applied between the two projects (with collaboration). The outputs from the two scenarios demonstrate that it is possible to achieve supply chain cost reduction with the collaboration mechanism of supply chain planning and scheduling of independent construction projects.

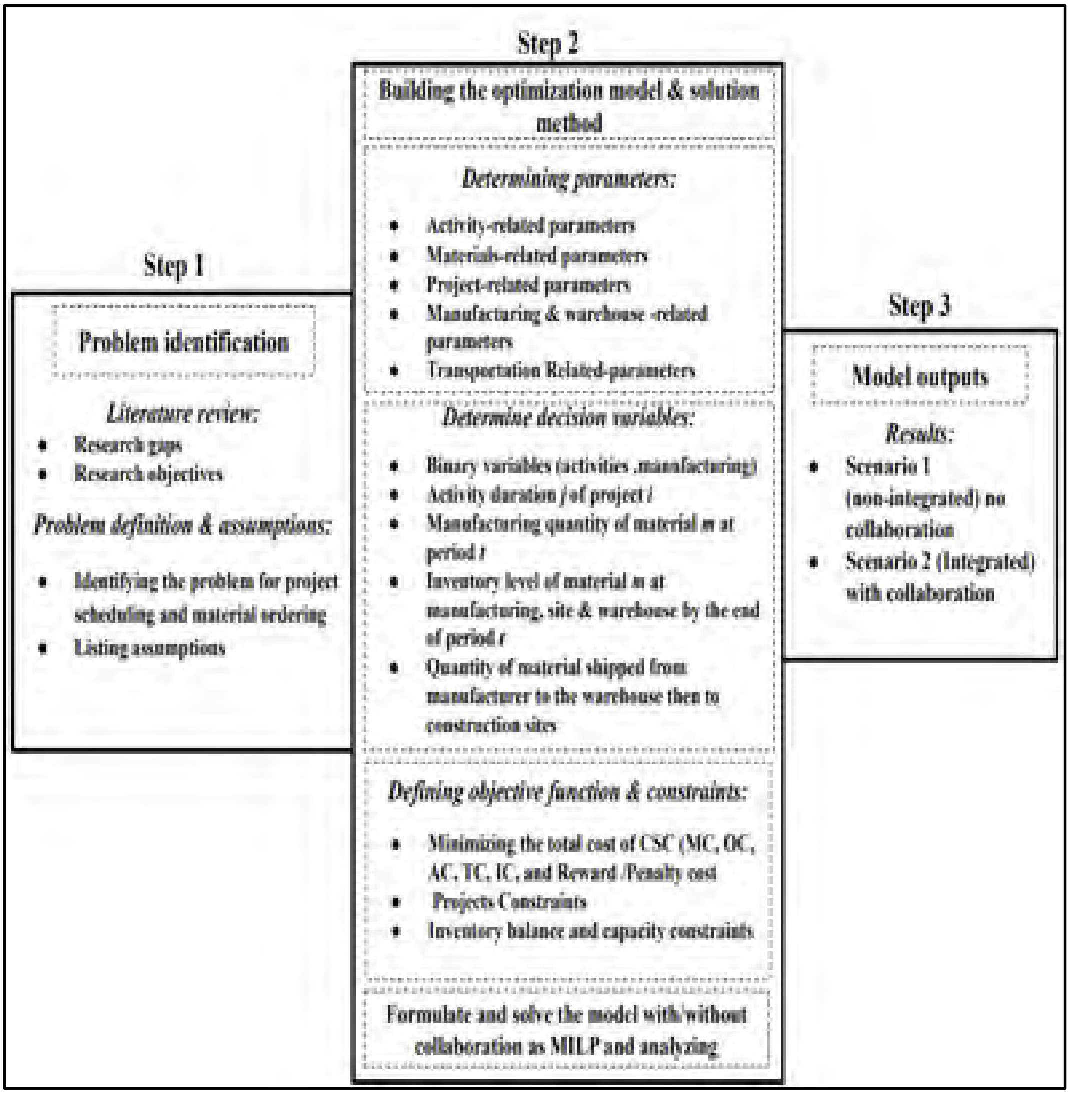

Figure 4.1 Developing CSC modelling method

4.5 Problem formulation and optimization model

The propose is to present supply chain planning and scheduling of independent construction projects. We develop a supply chain model where inventory management and scheduling decisions are integrated through collaborative mechanisms to achieve more coordination and, therefore, to reduce the total cost of construction supply chains.

4.5.1 Assumptions and notations

This study considers a multi-product and two-echelon CSC with one manufacturer, who provides finished modular construction products to the warehouse. The manufacturer and the warehouse are part of the leading focal company. The warehouse is responsible for delivering modular products to different construction sites (the consumers of finished products at a specific rate) managed by the same contractor. Traditionally, each project is managed individually. In this study, we assume that a collaboration between the focal company and the contractor is possible, and it is beneficial for both parties. Such cooperation can be accomplished by modifying the operations in the production, inventory management in the warehouse, and the construction sites and the review of the project's schedules. All parties involved in the collaboration process have a common objective, which is the minimization of the CSC's overall cost, as shown in Figure 4.1, which captures the critical components of the real CSC.

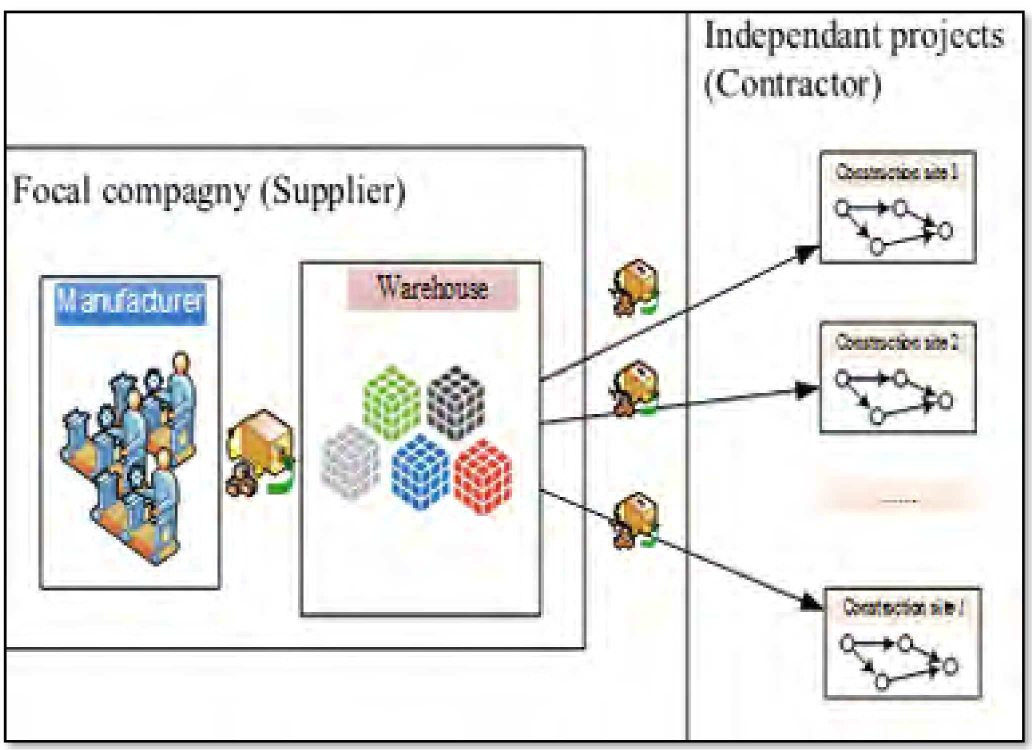

Figure 4.2 CSC members

A list of non-renewable resources (modular materials) is required and must be available on the construction site before starting the execution of each activity. The precedence relations of activities are finish-to start with zero lags. The first and last activities in each project are dummies and have a zero-completion time. Activity duration is a decision variable and can vary between the normal time and the crash time. To present the mathematical formulation we first introduce the following notations.

Sets and Indices:

$\boldsymbol{i}$: Index of construction sites (projects), $i = 1, 2, \ldots, I$.

$\boldsymbol{m}$: Index of materials, $m = 1, 2, \ldots, M$.

$\boldsymbol{t}$: Index of time, $t = 0, 1, 2, \ldots, H$.

$\boldsymbol{j, k}$: index for activities of project i, j, k = 1, 2,…, n_i

$\boldsymbol{P_{ij}}$: Set of activities preceding activity j in construction site *i*.

Construction sites parameters

Activity related parameters

$\boldsymbol{\alpha_{ij}}$: The crashing cost of activity j of project *i*.

$\boldsymbol{\beta_{ij}}$: The cost of reducing the duration of activity j by one period of project *i*.

$\boldsymbol{\mu_{ij}}$: Upper bound on the duration of activity j (normal time) of project *i*.

$\boldsymbol{v_{ij}}$: Lower bound on the duration of activity j (crash time) of the project *i*.

$\boldsymbol{H}$: Time horizon.

$\boldsymbol{L}$: Sufficient large number.

Materials related parameters

$\boldsymbol{oc_m}$: Ordering cost of material *m*.

$\boldsymbol{\delta_{mij}}$: Amount required from material m to process activity j in construction site *i*.

$\boldsymbol{vol_m}$: Volume of material *m* in m^3.

$\boldsymbol{cap_i^c}$: Maximum capacity of construction site *i* in m^3.

$\boldsymbol{h_i^c}$: Inventory cost per m^3 for one period in the construction site.

Project-related parameters

$\boldsymbol{d_i}$: Due date of the project of construction site *i* after which a delay penalty cost is paid.

$\boldsymbol{p_i}$: Penalty cost per period for having the project of construction site *i* late beyond d_i.

$\boldsymbol{r_i}$: Reward paid per period for completing the project of construction site *i* before d_i.

Manufacturer and warehouse related parameters.

$\boldsymbol{mr_m}$: Maximum manufacturing capacity of material m per period.

$\boldsymbol{mc_m}$: manufacturing cost per unit of material *m*.

cap^m : Maximum capacity of manufacture in m^3.

$\boldsymbol{h^m}$: Inventory cost per m^3 for one period at the manufacturer.

$\mathbf{SC_m}$: set-up cost for producing material m in each period

cap^w : Maximum capacity of the warehouse in m^3.

$\boldsymbol{h^w}$: Inventory cost per m^3 for one period in the warehouse.

Transportation-related parameters

$\boldsymbol{tc^{mw}}$Transportation cost of material from manufacturer to warehouse per truck.

$\boldsymbol{tc_i^{wc}}$ Transportation cost of material from warehouse to construction site i per truck.

$\boldsymbol{cap^{tmw}}$Capacity of a truck running from manufacturer to warehouse, in m^3.

cap^{twc} Capacity of a truck running from the warehouse to construction sites, in m^3.

Decision variables

$\boldsymbol{\varphi_{mit}}$: Binary variable, equal 1 if at least one unit of material m is ordered by construction site i in period t, and 0 otherwise.

$\boldsymbol{\varpi_{ijt}}$: Binary variable, equal 1 if activity j of project i is completed in period t, and 0 otherwise.

$\boldsymbol{\zeta_{ijt}}$: Binary variable, equal 1 if activity j of project i is started in period t, and 0 otherwise.

$\boldsymbol{\lambda_{ij}}$: Duration of activity j of project i.

$\boldsymbol{\chi_{mt}}$: Manufacturing quantity of material m in period t.

$\boldsymbol{\theta_{mt}}$: Binary variable, equal 1 if a unit of material m is manufactured in period t, and 0 otherwise.

$\boldsymbol{I_{mit}^{c}}$: Inventory level of material type m at construction site i by the end of period t.

$\boldsymbol{I_{mt}^{w}}$: Inventory level of material type m at the warehouse by the end of period t.

$\boldsymbol{I_{mt}^{m}}$: Inventory level of material type m at the manufacturer by the end of period t.

$\boldsymbol{\varepsilon_{mt}^{mw}}$: Quantity of material m shipped from the manufacturer to the warehouse at period t.

$\boldsymbol{\varepsilon_{mit}^{wc}}$: Quantity of material m shipped from warehouse to the construction site i at period t.

4.5.2 Model formulation

Based on the above-mentioned notations and assumptions, the total cost for the CSC can be obtained by equation (4.1) to (4.6). The objective is to minimize the total cost, which is equal to the summation of the Manufacturing Cost (MC), the Ordering Cost (OC), Activities Cost (AC), Transportation Cost (TC), and Inventory holding Cost (IC), and the Reward and Penalty of project completion (RPP). Where:

$$MC = \sum_{m=1}^{M} \sum_{t=0}^{H} (m_{cm}\chi_{mt} + SC_m\theta_{mt}) \tag{4.1}$$

$$OC = \sum_{m=1}^{M} \sum_{i=1}^{I} \sum_{t=0}^{H} O_{cm}\, \varphi_{mit} \tag{4.2}$$

$$AC = \sum_{i=1}^{I} \sum_{j=1}^{n_i} \left(\alpha_{ij} - \beta_{ji}\left(\lambda_{ji} - v_{ij}\right)\right. \tag{4.3}$$

$$TC = \sum_{m=1}^{M} vol_m \sum_{t=0}^{H} (\frac{tc^{mw}}{cap^{tmw}} * \varepsilon_{mt}^{mw} + \frac{1}{cap^{tmc}} \sum_{i=1}^{I} tc_{i}^{wc}\ \varepsilon_{mit}^{wc} \tag{4.4}$$

$$IC = \sum_{m=1}^{M} vol_m \sum_{t=0}^{H} \left(h^m I_{mt}^{m} + h^w I_{mt}^{w} + \sum_{i=1}^{I} h_i^c * I_{mit}^{c}\right) \tag{4.5}$$

$$RPP = \sum_{i=1}^{I}(\sum_{t=d_i+1}^{H} p_i(t - d_i + 1)\varpi_{in_it} - \sum_{t=0}^{d_i+1} r_i(d_i + 1 - t)\varpi_{in_it} \tag{4.6}$$

The constraints of the model are as follows:

Constraints related to projects:

$$\sum_{t=0}^{H} t\zeta_{ikt} + \lambda_{ik} \leq \sum_{t=0}^{H} t\zeta_{ijt} \; \forall i = 1, \dots, I;\; j = 1, \dots, n_i;\; k \in P_{ij} \tag{4.7}$$

$$\varpi_{i10} = 1, \quad \forall i = 1, \dots, I \tag{4.8}$$

$$\lambda_{in_i} = 0 \quad \forall\, i = 1, \dots, I \tag{4.9}$$

$$\sum_{t=1}^{H} \zeta_{ijt} = 1 \quad \forall\, i = 1, \dots, I, j = 2, \dots, n_i \tag{4.10}$$

$$\sum_{t=0}^{H} \varpi_{jt} = 1 \quad \forall i = 1, \dots, I;\; j = 2, \dots, n_i \tag{4.11}$$

$$\sum_{t=0}^{H} t\zeta_{ijt} + \zeta_{ij} = \sum_{t=0}^{H} t\zeta_{ijt} \quad \forall\; i = 1, \dots, I;\; j = 2, \dots, n_i \tag{4.12}$$

$$\mu_{ij} \leq \lambda_{ij} \leq v_{ij} \quad \forall\, i = 1, \dots, I;\; = 1, \dots, n_i \tag{4.13}$$

$$\varepsilon_{mit}^{wc} \leq L\varphi_{mit} \;\; \forall m = 1, \dots, M; i = 1, \dots, I;\; t = 1, \dots, H \tag{4.14}$$

Constraint (4.7) takes into consideration the precedence relation between the activities. Constraints (4.8) & (4.9) show that the first and last activities in all projects are dummies. Constraints (4.10) and (4.11) guarantee that each activity can only have one start and finish time. In addition, it forces the construction sites to finish the corresponding project during the time horizon H. Duration of each activity by considering its lower and upper bounds is calculated by equations (4.12) and (4.13). Constraint (4.14) ensures that if a material is shipped to the construction site (order was placed at that period).

Constraints related to inventory balance:

$$I^{w}_{mt} = I^{c}_{mi0} = 0\,, \qquad \forall m = 1, \dots, M;\ i = 1, \dots, I \tag{4.15}$$

$$I^{m}_{mt} = M, \quad \forall\, m = 1, \dots .\, M \tag{4.16}$$

$$I^{m}_{mt} = I^{m}_{m(t-1)} + \chi_{mt} - \varepsilon^{mw}_{mt} \quad \forall m = 1, \dots, M, \qquad t = 1, \dots, H-1 \tag{4.17}$$

$$I^{w}_{mt} = I^{w}_{m(t-1)} + \varepsilon^{mw}_{mt} - \sum_{t=1}^{H} \varepsilon^{wc}_{mit}\,, \quad \forall m = 1, \dots .\, M;\ t = 1, \dots, H-1 \tag{4.18}$$

$$I^{c}_{mit} = I^{c}_{mi(t-1)} + \varepsilon^{wc}_{mit} - \sum_{j=1}^{ni} \delta_{mij}\zeta_{ijt}\ \forall m = 1, \dots, M;\ i = 1, \dots, I;\ t = 1, \dots, H-1 \tag{4.19}$$

Constraints (4.15) to (4.19) balance the inventory in each period, considering that there is no initial inventory. Equation (4.19) is written, assuming that the required material for each activity must be available at the starting time of activity.

Constraints related to capacity:

$$I^{m}_{mt}\, vol_m \leq cap^m \quad \forall m = 1, \dots, M;\ t = 0, \dots, H-1 \tag{4.20}$$

$$I^{w}_{mt}\, vol_m \leq cap^w, \qquad \forall\, m = 1, \dots, M;\ t = 0, \dots, H-1 \tag{4.21}$$

$$I^{c}_{mit}\, vol_m \leq cap^{c}_{i} \quad m = 1, \dots .\, M, i = 1, \dots \dots, I, t = 0, \dots, H-1 \tag{4.22}$$

$$\chi_{mt} \leq mr_m \quad \forall\, m = 1, \dots, M;\ t = 0, \dots, H-1 \tag{4.23}$$

$$\chi_{mt} \leq L\theta_{mt} \quad \forall m = 1, \dots, M, \quad t = 0, \dots, H-1 \tag{4.24}$$

$$\sum_{m=1}^{M} \theta_{mt} \leq 1 \qquad \forall t = 0, \dots, H \tag{4.25}$$

Constraints from (4.20) to (4.22) ensure that the inventory in each period does not exceed the capacity. Constraint (4.23) states that the manufacturing rate is within a pre-defined range during the period. Constraint (4.24) forces θ_{mt} to be equal to one if $\chi_{mt} > 0$. Constraint (4.25) ensure that we can product only one material per period.

4.6 Numerical examples

4.6.1 Data

In order to illustrate the benefits of the proposed approach, a numerical experiment is carried out for two types of modular materials (m=2) and two construction projects (i=2). For this example, each construction project is composed of eight (8) activities where the first and the last activities are dummies and represent the project start and completion, respectively. The precedence relationships between all the activities are finish-to-start. The preceding project activities, the normal and crash time of each activity, the normal and crashing costs of the construction project activities are presented in the appendix. Table 4.2 shows the number of modular products required for each construction site per activity. Moreover, we suppose that the two construction sites have similar demands. More parameters related the example (see Appendix II, p. 104 and 105).

Table 4.2 The demand for materials of activities

δ_{mij}	j=1	j=2	j=3	j=4	j=5	j=6	j=7	j=8
m=1	0	2	1	2	2	2	1	0
m=2	0	2	2	2	1	1	1	0

The planning horizon is fixed to 20 periods, and the project due dates are equal to their critical path. We assume that the inventory cost in the construction site is higher than the inventory cost in the warehouse and the manufacturer since. The initial inventory must satisfy the demand for the first activities. The warehouse has relatively a non-limited capacity. Moreover, the capacity in the construction site is very limited.

4.6.2 Computational results

The proposed model was implemented using the IBM ILOG CPLEX Optimization Studio (version 12.7). The mathematical relationships were captured using the OPL mathematical modeling language. The case problem was solved with satisfactory solutions within 1 min on average. Two scenarios are explored. Scenario 1 is the original case situation where the two projects managed in an independent manner (without collaboration). Scenario 2 is when collaboration is permitted between the two projects (with collaboration). To compare the two scenarios, we have considered as a baseline, a model where the reward/ penalty is null to analyze the impact of integration on the project completion time and how flexibility in the project's completion time will help the CSC efficiency. When we analyze the results related to scheduling, we can notice that for scenario 1 (without collaboration), the two projects were completed within their respective due date, which is period 19 for the first project and period 16 for the second project (see Figure 4.2).

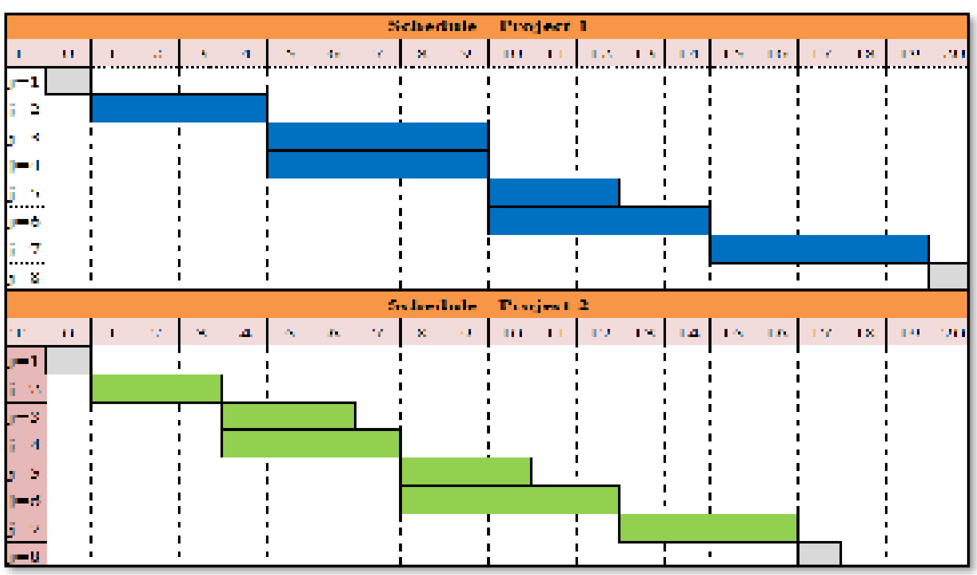

Figure 4.3 Gantt chart for projects activities in scenario 1

For scenario 2 (Figure 4.3), when we consider an integrated CSC, the first project is completed in time (period 19) without any change compared with scenario 1. However, the second project was delayed by two periods to finish in period 18. In this case, the contractor accepts to delay project 2 by two periods for the benefits that will ensure a more efficient CSC with a minimal cost and which is the case here if we compare the different costs between the two models.

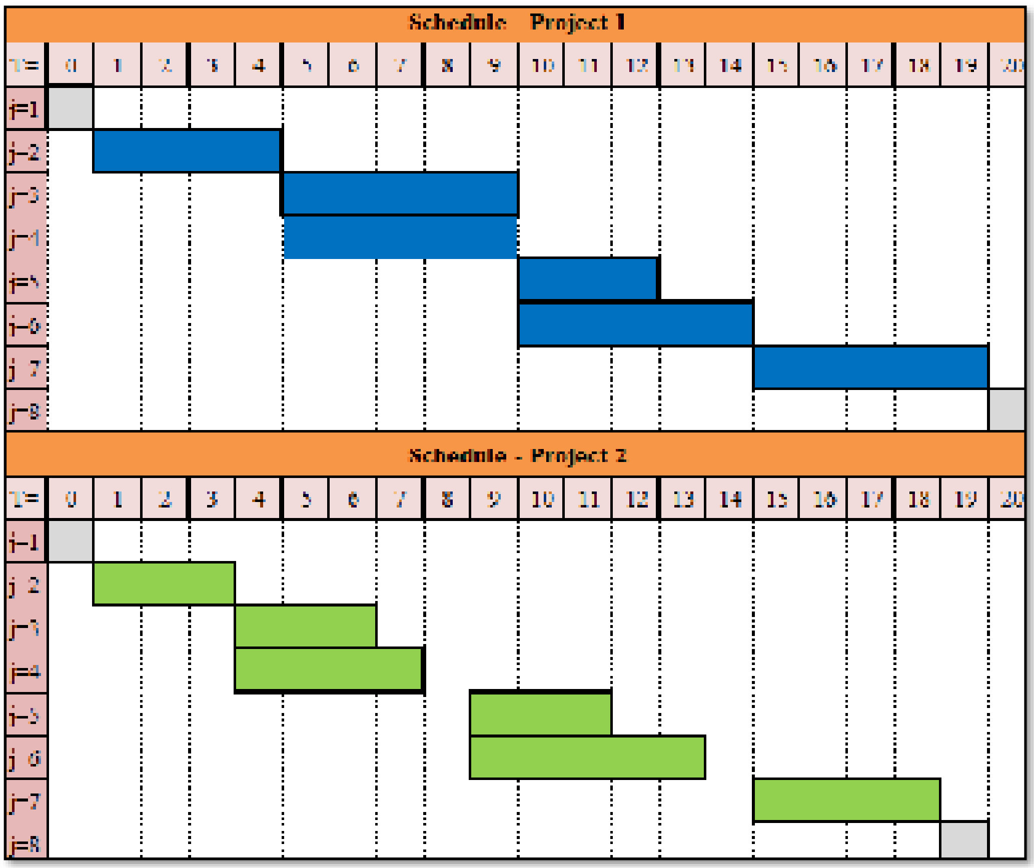

Figure 4.4 Gantt chart for projects activities in scenario 2

4.6.3 Benefits of the CSC with collaboration

The results for both scenarios are collected and compared with more details to understand the benefits of CSC collaboration. The logistic coordination and collaboration of the different projects in this specific case can bring a total of 3.07% savings. The high-cost reductions are observed in the setup-cost (2.61%) and inventory holding cost (0.47%).

Table 4.3 CSC cost comparison

	Scenario 2			Scenario 1			Scenario 2 versus	
	Project 1	Project 2	Projects (1+2)	Project 1	Project 2	Projects (1+2)	Cost saving ($)	Cost saving (%)
Manufacturing cost	6100	6100	12200	6100	6100	12200	0	0.00%
Setup cost	195	195	390	390	390	780	390	**2.61%**
Ordering cost	360	360	720	360	360	720	0	0.00%
Activities cost	385	325	710	385	325	710	0	0.00%
Transportation cost	145	145	290	145	145	290	0	0.00%
Inventory holding cost	100	90	190	130	130	260	70	**0.47%**
Reward	0	0	0	0	0	0	0	0.00%
Penalty paid	0	0	0	0	0	0	0	0.00%
Total Cost	7285	7215	14500	7510	7450	14960	460	**3.07%**

One of the main results provided by the optimization model for both projects is demand planning. Indeed, when collaboration is active, each project's final schedule helps the planner determine the demand plan based on the starting date of each activity and the products needed for each step. Having the quantity of the required material per activity for each construction site, the two projects' schedule, and the activities duration, we can generate the demand plan in the construction sites (Figure 4.4).

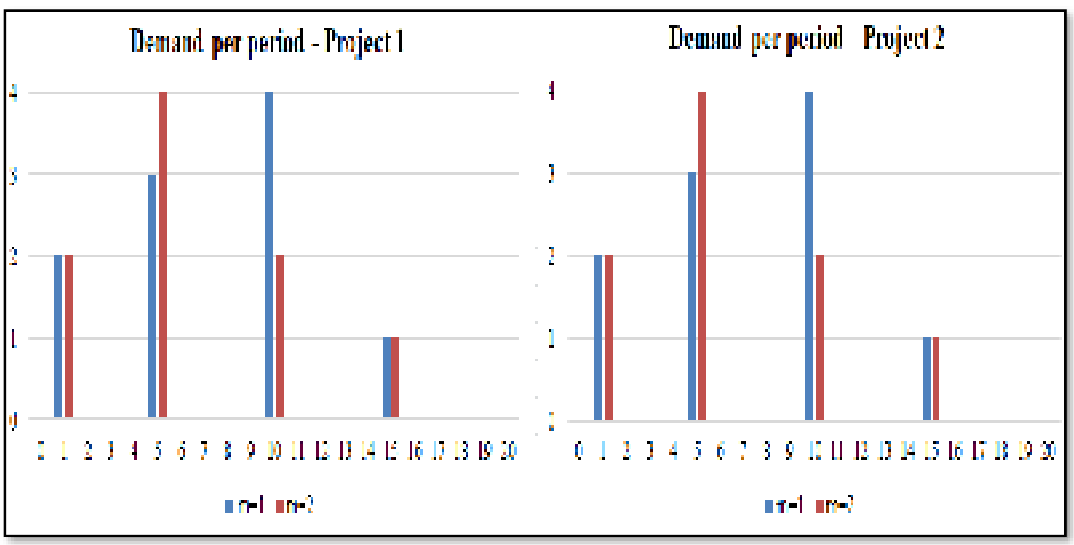

Figure 4.5 Demand planning per period – Scenario 2

The manufacturing quantities per period of each material required for the different construction sites with and without collaboration are illustrated in Figure 4.5. For instance, we can notice that when collaboration is active (scenario 2), the manufacturer produces the required quantities of material 1 (m=1) during five different periods while in scenario 2. Nevertheless, the manufacturer uses nine different periods to produce material 1 in scenario 2. Similar behavior is also observed for material 2. Therefore, when collaboration is active, the manufacturer succeeds in using the production capacity efficiently, and we observe a reduced setup cost and total cost for the whole supply chain members.

Figure 4.6 shows the inventory levels at the different construction sites for both scenarios. When there is no collaboration and information sharing between the two projects, the inventory cost is higher because due to the lack of coordination for materials management. Therefore, the lack of synchronization in demand planning and project sequencing generates higher inventory in the warehouse and increase the total CSC. The integrated master plan reduced the materials inventory in the warehouse and construction sites, which helps to reduce site congestion and achieve a lower cost for the entire CSC.

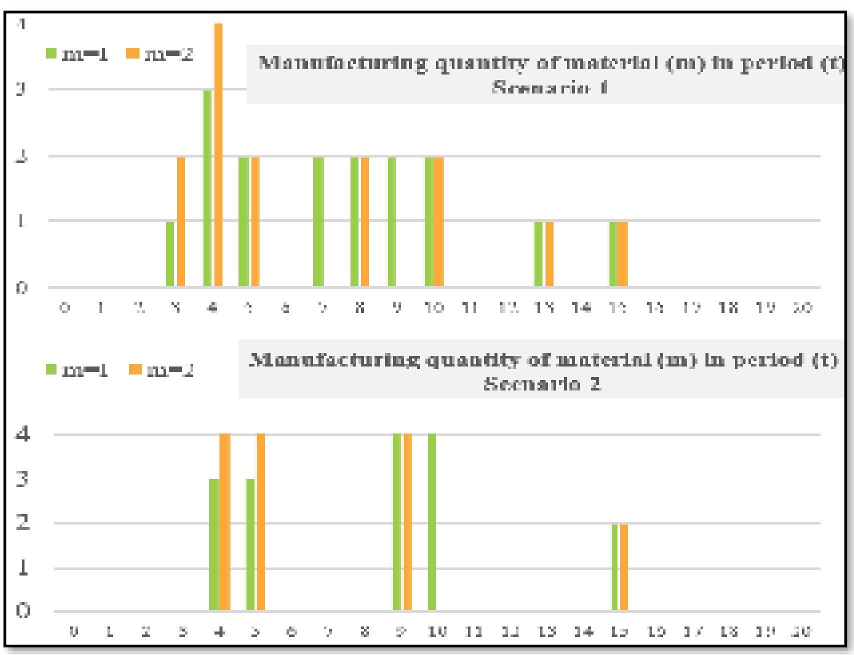

Figure 4.6 Manufacturing plan for scenarios 1 and 2

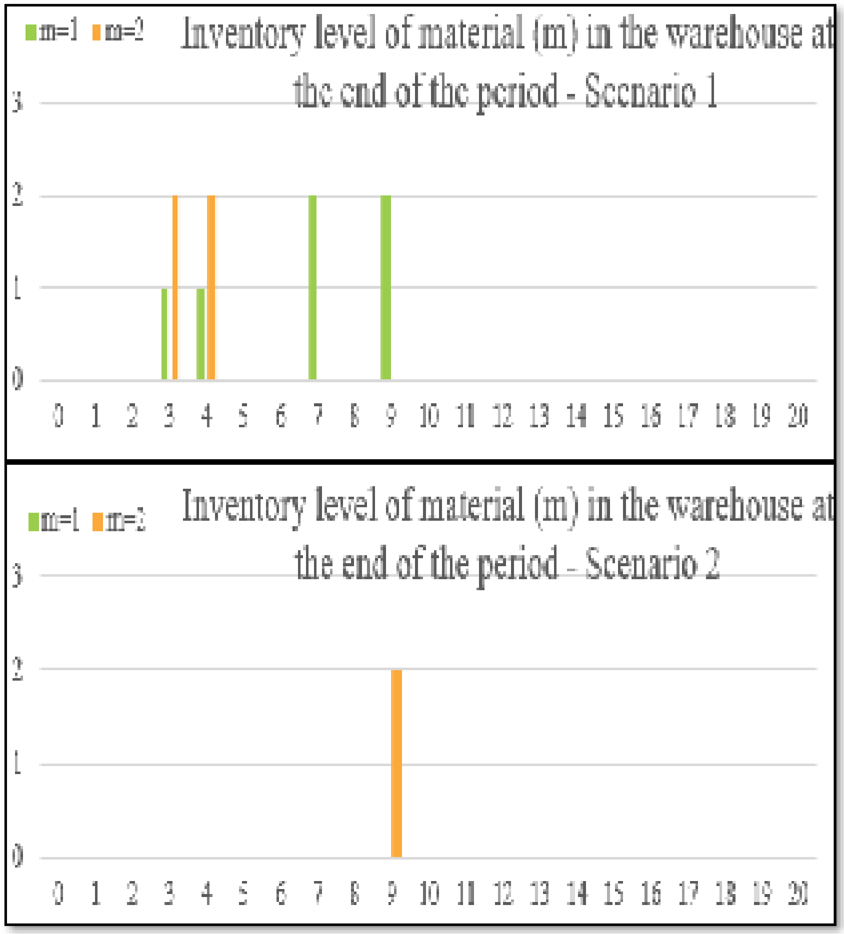

Figure 4.7 Inventory in the warehouse for scenarios 1 and 2

4.7 Managerial insights implications

4.7.1 Sensitivity analysis related to penalty

We also analyze the results when the penalty paid in case of project delay is increasing, and we notice that project 2 is still delayed by two periods in the case of a penalty that reaches \$10. When the penalty reaches \$20, project 2 is delayed by only one period. Finally, the project finishes on-time without delay when the penalty is higher than \$30. Project 1 is not delayed. A detailed analysis of the different costs shows particularly that the total cost remains under control and demonstrates the advantage of collaboration.

Table 4.4 CSC cost comparison under penalty variation

Penalty ($)	Total Cost ($) Scenario 2	Total Cost ($) Scenario 1	Cost-saving (%)
0	14 500	14 960	3,07%
10	14 520	14 960	2,94%
20	14 535	14 960	2,84%
30	14 540	14 960	2,81%
40	14 540	14 960	2,81%
300	14 540	14 960	2,81%
800	14 540	14 960	2,81%

The main cost reduction for high penalty values (more than 30 $) is obtained from a better inventory optimization, as shown in Figure 4.8.

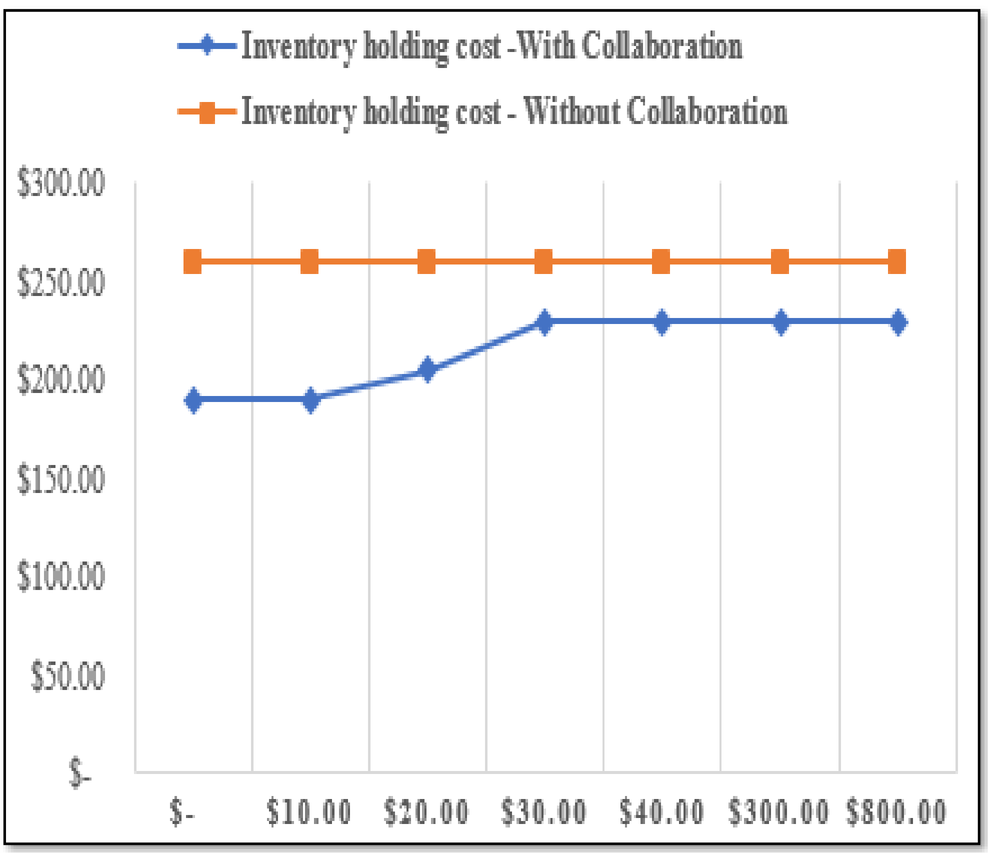

Figure 4.8 Inventory costs with penalty variation

4.7.2 Impact of changing the inventory holding cost

To show the impact of changing the inventory holding cost at the different levels of the CSC, we have considered tow cases. For the first case, we consider that the inventory holding cost at the manufacturer, in the warehouse, and construction sites are the same. This is the case that reflects the situation where projects are located in rural areas where the space for inventory is not very limited. For the second case, we assume that the manufacturer and the warehouse inventory holding costs are kept the same as in scenario 1, whereas we increase the inventory holding cost at the construction site. This situation reflects more the case where construction projects are in urban areas. When we compare the plans and results obtained for the first and second case, we can notice that while increasing the inventory holding cost at the construction site (other parameters remaining the same), the model with collaboration reduced the inventory level at the construction sites, which helps to reduce site congestion, and generated a lower total inventory cost for the entire CSC.

4.8 Impact of the number of projects

To show the benefits of the proposed approach, we also applied the proposed model in five construction sites, and we consider two types of modular materials. Two scenarios are explored. Scenario 1 where the two projects managed without collaboration and scenario 2 is when collaboration is possible between the five projects. To compare the two scenarios, we have considered as a baseline a model where the reward/penalty is null to analyze the impact of integration on the project completion time and how flexibility in the project's completion time will help the CSC efficiency. Table 4.5 shows the results for both scenarios. The results are compared with more details to understand the benefits of CSC collaboration. The logistic coordination and collaboration of the different projects in this specific case for modular products can bring 2.89 % savings. The high-cost reductions are observed in the setup-cost (2.77%) and inventory holding cost (0.41%).

Table 4.5 CSC cost (no penalty)

	Non-integrated	Integrated	Scenario 2 VS Scenario 1	
	Total scenario 1	**Total scenario 2**	**Cost-saving ($)**	**Cost-saving (%)**
Manufacturing cost	30,500 $	30,500 $	- $	0.00%
Setup cost	1,950 $	915 $	1,035 $	**2.77%**
Ordering cost	1,800 $	1,800 $	- $	0.00%
Activities cost	1,805 $	1,915 $	(110) $	-0.29%
Transportation cost	725 $	725 $	- $	
Inventory holding cost	650 $	495 $	155 $	**0.41%**
Reward	- $	- $	- $	0.00%
Penalty	- $	- $	- $	0.00%
Total cost	37,430 $	36,350 $	1,080 $	**2.89%**

4.9 Discussion and implications

We have considered a multi-echelon CSC made of one manufacturer, one warehouse, and different contractors working on various construction sites with different project activities. The proposed model's critical implication is to demonstrate the value of collaboration in the construction sector using SCM principles. The CSC participants can use the decision model to better coordinate activities sequencing and materials management for modular products, which contributes to cost reduction for all SC members. To succeed in using the collaborative model, SC members have to collaborate and share all the information needed to reduce the total CSC costs and prevent project delays. The proposed supply chain model is expected to serve as a decision methodology to achieve more efficiency in the construction sector. This model also demonstrates, by using numerical examples, how to integrate scheduling and inventory management decisions to achieve a fully integrated project delivery method. By proposing a new model for collaborative CSC planning, this proposed approach provides a solid base of development on achieving more coordination between CSC members.

4.10 Conclusion

This chapter proposed a new model for collaborative supply chain planning and scheduling of independent construction projects. A MILP model is developed considering one manufacturer produced modular products, one warehouse, and multi-construction sites. Numerical examples are used to demonstrate the value of collaboration in the construction sector using SCM principles. Better coordination of activities sequencing and materials management contributes to cost reduction for all supply chain members. This research can be extended in different ways. First, a numerical example with more activities and projects is important to evaluate computational complexity. Indeed, it is not difficult to see that the problem is NP-hard, and it is important to test some heuristics solution approaches for solving large instances. Second, the current model could be extended to include renewable resources and other objectives to evaluate CSC performance. Finally, we can develop this study for stochastic CSC in which the objective function is to minimize the expected total cost.

CONCLUSION

Over the last decades, researchers attempted to apply different techniques to optimize the construction supply chain management. However, the application has been limited and at a slower speed than that in general applications. We find the critical decisions, which are presently focused on construction logistics and SCM. These decisions are identified for three main stages of a CSC project: planning and design, procurement, and construction execution. Inventory management is one of the important pillars of CSCM. To consolidate, evaluate and develop the scope of future research opportunities by identifying research gaps in this field, classifying optimization models of inventory in construction and providing a conceptual framework map, and consolidating the research in this field. Besides, a new model for collaborative supply chain planning and scheduling of independent construction projects is proposed.

A MILP model is developed considering one manufacturer, one warehouse, and multi-construction sites. Numerical examples are used to demonstrate the value of collaboration in the construction sector using SCM principles. A better coordination of activities sequencing and materials management contributes to cost reduction for all supply chain members. This research can be extended in different ways. First, a numerical example with more activities and projects is important to evaluate computational complexity. Indeed, it is not difficult to see that the problem is NP-hard, and it is important to test some heuristics solution approaches for solving large instances. Second, the current model could be extended to include renewable resources and other objectives to evaluate CSC performance. Finally, we can develop this study for stochastic CSC in which the objective function is to minimize the expected total cost.

Contributions

We find that recent researches have not proposed any typology study to classify CSC inventory models. Based on our best knowledge, we first present a new typology to investigate and classify the inventory models published so far. We examine the issues regarding the previous models. The results demonstrate the need for a conceptual framework to manage inventory and integrate SC members in the construction sector, given the recent BIM technology development.

We identified the present objective of decision-making in the construction SCM and the relationships between SC actors during the main construction phases study. We suggested potential SCM applications in the construction industry to meet new construction practices and technical requirements development. Therefore, based on the typology and the present decision focuses, we propose a new conceptual collaboration framework to integrate all the CSC members and enhance SC network performance.

A new mixed-integer linear programming model is proposed to reduce the total SC costs while collaboration between contractors is possible. The model was implemented using the IBM ILOG CPLEX Optimization Studio. The proposed model is analyzed through a numerical study to show the benefits of collaborative planning in construction project management. The decision model help also in finding efficient construction projects' sequences. The main objective is to achieve more coordination and, therefore, to reduce the total cost of the CSC.

Main findings

In chapter 1, we analyzed the progress of research on inventory systems in the construction sector, and we identify the gaps and factors that influence the inventory system in construction.

In chapter 2, a new typology is presented to classify inventory models in construction and identify which types of problems have been studied and what are the main achievements. We assessed this progress from the perspective of real-life systems of inventory in construction and their characteristics. The typology review showed that the researchers attempted to utilize different techniques and approaches to optimize inventory models in the construction sector.

In chapter 3 we noticed that the growth of SC integration was constrained and at a slower movement in the construction industry than the other industrial sectors based on the present decision-making. Therefore, it is recommended to enhance SC integration within the project phases to make CSC planning and operations significant. In particular, the combination of the General Contraction, the owner, and the planner leads to CSC network preparation and implementation performance through planning and design by creating decisions that seek to define CSC configuration. Therefore, for future SCM application movements in construction, this study proposes a new conceptual collaboration framework for the inventory system in construction projects. The proposed framework helps to avoid the congestion of materials on the construction site and reduce the inventory cost to reduce the impact of unseen risk factors that may affect any construction project's progress. It is essential to have tools to predict the influence of significant risk factors in advance identifying and understanding the risk events that affect CSC and developing models that automatically detect changes in the probability distributions of risk factors in the planning and the operation phases. The BIM provides a full range of construction project information (such as construction schedule, material quantity, and on-site inventory). The analysis layer then uses the provided data (e.g., cost analysis or network analysis) to support CSCM tasks.

Chapter 4 develops an integrated mathematical model for CSC that deals with the concurring problem of project scheduling and logistics planning. We consider a two-echelon CSC with one manufacturer, one warehouse, and different contractors working on different construction sites and various projects in this direction. The different SC network members collaborate to reduce the CSC's overall cost and avoid delays in project deliveries. The integrated mathematical model was developed to investigate ordering and production planning, transportation and inventory control, and project schedule, with a minimal SC total cost, comprised of the costs related to manufacturing costs, warehouse costs, and the project activities costs. The model validation with the case example shows that the proposed model performs better in total SC cost compared to CSC members without collaboration. Sensitivity analysis related to penalty and holding cost were implanted, the results show a reduction in total cost when we change the value of different levels of the CSC. This implies that the optimization model for the integrated CSC with collaboration can improve the construction logistics performance and deal with the practical requirements of the current issues in the construction industry.

Managerial implications

The typology in chapter 2 provided a classification of inventory models in CSC. It focused on the current problem facing implementing these approaches and techniques in real-life construction projects. Therefore, the typology presents a collaboration framework for inventory management in the construction sector in chapter 3. The proposed framework is designed to bridge the gap between the previous inventory models and the proposed model in chapter 4.

In the proposed model's direction, we have considered a multi-echelon CSC made of one manufacturer, one warehouse, and different contractors working on different construction sites with varying project activities. The critical implication of the proposed model presented in chapter 4 is to demonstrate the value of collaboration in the construction sector using SCM principles. The CSC participants can use the decision model to better coordinate activities sequencing and materials management, which contributes to cost reduction for all SC members. To succeed in using the collaborative model, SC members have to collaborate and share all the information needed to reduce the total CSC costs and prevent project delays.

Limitations and further researches

We are at the advent of a fourth industrial revolution, denoted as Industry 4.0. There is a lack of research concerning optimization inventory in construction beside the lack of proposed collaboration and integration models among SC members. However, some of the issues include weather conditions, labor shortage, machinery failure, and hazards at the construction sites, which are uncertain and harm inventory management. These factors could delay the delivery of the project and increase the cost and reduce the workforce's performance. Thus, effective planning to deal with these issues is essential for the construction projects managers while managing the inventory.

The availability of real-time information about the location and condition of items throughout the supply chain requires proposing new ways of modeling CSCs. It will generate a new wave of contributions from inventory systems under stochastic demand and understand how delays in project scheduling and uncertainty in demand impact supply chain performance.

This research can be extended in different ways. First, numerical examples with more activities and projects should be subject to future work. Indeed, it is not difficult to see that the problem is NP-hard, and it is important to test some heuristics solution approaches for solving large instances. Second, the current model could be extended to include renewable resources and other objectives to evaluate CSC performance. Finally, we can extend this study for stochastic CSC in which the objective function is to minimize the expected total cost. Indeed, different parameters, such as demand, activities durations, and capacities, could be subject to uncertainty. Therefore, decomposition techniques combining MILP solvers and heuristics could be investigated to tackle real-world instances of construction projects.

APPENDIX I

MODELS DESCRIPTION

Table-A I-1 Models description and attributes

Author (s)	Research problem	Solution Method/ Algorithm	Key Model Attributes	Applied
(Fu, 2014)	Construction project scheduling & material batch ordering	Hybrid algorithm that combine Harmony search with Genetic algorithm	An integrated MIP model of project scheduling and batch ordering was developed. A hybrid algorithm, which combines harmony search and GA, was presented to solve the problem.	GC
(Hisham Said & El-Rayes, 2014)	Construction logistics planning	Genetic Algorithm	Automated multi-objective optimization designed to support the contractors in integrating and planning material supply and site decisions.	GC
(Qiurui Liu & Tao, 2015)	Material purchasing and inventory	Meta-heuristic PSO algorithm	Minimizing the total cost of each site. PSO algorithm is used to find the optimal order quantity, reorder point and lead-time.	Supplier, owner & contractor
(Tabrizi & Ghaderi, 2016)	Project Scheduling and material procurement	Meta-heuristics & exact method	A robust MIP used to minimize the corresponding costs & maximize the schedule robustness.	GC

Author (s)	Research problem	Solution Method/ Algorithm	Key Model Attributes	Applied
(Lu et al., 2016)	Construction material safety stock under non-stationary stochastic demand and random supply yield	Fixed point iteration method	A general approach is developed to determine safety stock of construction material under the base-stock replenishment policy.	Owner & GC
(Q. Liu et al., 2017)	Purchasing, production, and inventory integrated-operational problems in the CSC	A hybrid genetic algorithm with fuzzy random	Multi-objective optimization modelling with fuzzy theory & GA techniques developed to integrate purchasing and production for CSCO.	Supplier , GC & Owner
(Xu & Zhao, 2017)	Supplier selection and dynamic inventory (SSDI)	Meta-heuristic	BLPSO algorithm in this paper used to solve the conflicts of the SSDI problem.	Supplier & GC
(Hsu et al., 2017)	Logistics of modular construction (manufacturing, storage, and construction)	Computational	MILP proposed for the logistics of modular construction including three tires	Supplier & GC
(Meng et al., 2018)	Material Procurement	Exact method	Material-buy-in decision-making method (non-critical activities' flexible starting date is proposed. A ternary cycle algorithm is developed.	GC

Author (s)	Research problem	Solution Method/ Algorithm	Key Model Attributes	Applied
(C. Feng, Ma, Zhou, & Ni, 2018)	Integrated Production-distribution construction system (PDCS) in CSC	GA/PSO hybrid algorithm	Integrated the construction department into the material SC as a PDCS.	Supplier & GC
(Hsu et al., 2018)	Optimization of logistics' processes in modular construction (manufacturing, storage and assembly)	Computational	Mathematical model to establish the optimal production, transportation & inventory for the CSC.	Supplier, Warehouse & GC
(Jaśkowski et al., 2018)	Material quantities	Fuzzy linear programming	MILP model proposed for optimizing supplies of materials. The objective is to minimize the total inventory cost.	GC
(Deng et al., 2019)	Supplier selection material deliveries allocation of consolidation centers	Computational	Integrated framework based on BIM and GIS to support CSC decision-making.	GC
(Golkhoo & Moselhi, 2019)	Optimizing construction material delivery schedule and inventory	GA with Multi-layer perceptron method	GA-MLP method to generate optimized material delivery schedule. Multi-layer perceptron used to improve GA	GC
(Golpîra, 2020)	Integration of facility location problem into the CSC network design	Computational	MILP model proposed to support the operation of a multi (project - resource –supplier)	Supplier & GC

Table A I-2 Inventory models classification

Typology dimension	Value	Explanation	No of papers
The problem under investigation:			
Performance specification	Objective to be achieved as a result of selection of control policy & its parameters		
Performance indicator	E	Equilibrium	2
	S	Meeting operational service requirements	3
	C	Minimization of costs	14
	M	Multi-objective	8
Generic scientific aspects of the Paper:	Techniques applied to achieve the results		
Methodology	A	Approximative	15
	C	Computational experiments	3
	E	Exact	6
Research goal	Goal of the investigations		
	C	Comparison	8
	O	Optimization	22
	P	Performance evaluation	6

APPENDIX II

MODEL IMPLEMENTATION

Spreadsheet A II-1 Model code

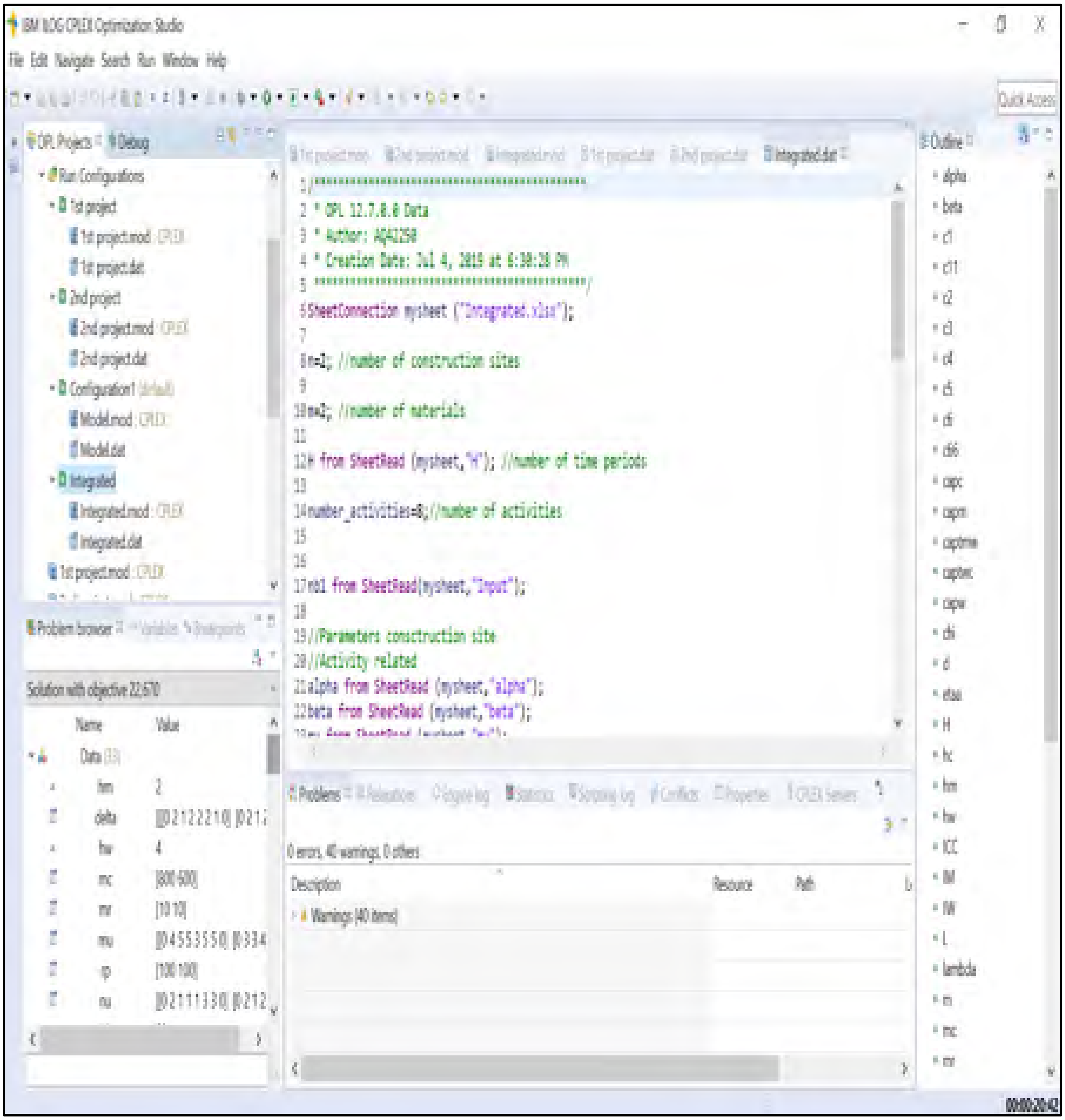

Table A II-1 Parameters related to construction project activities

Construction site	Activity	Preceding activity	Normal time	Crash time	Normal Cost	Crashing cost	Crashing cost per period
1	1	-	0	0	$ -	$ -	$ -
	2	1	4	2	$ 60.00	$100.00	$20.00
	3	2	5	1	$ 60.00	$200.00	$35.00
	4	2	5	1	$ 50.00	$150.00	$25.00
	5	3	3	1	$ 45.00	$ 65.00	$10.00
	6	4	5	3	$ 90.00	$200.00	$55.00
	7	6	5	3	$ 80.00	$300.00	$110.00
	8	7	0	0	$ -	$ -	$ -
2	1	-	0	0	$ -	$ -	$ -
	2	1	3	2	$ 50.00	$ 90.00	$40.00
	3	2	3	1	$ 50.00	$100.00	$50.00
	4	2	4	2	$ 40.00	$140.00	$200.00
	5	3	3	2	$ 35.00	$ 55.00	$25.00
	6	4	5	3	$ 80.00	$180.00	$50.00
	7	6	4	3	$ 70.00	$270.00	$20.00
	8	7	0	0	$ -	$ -	$ -

Table A II-2 Parameters related to modular products

Modular product	Volume in m3	Ordering cost	Maximum manufacturing capacity of modular product m per period	Manufacturing cost per unit of modular product m	Setup cost for producing of modular product m in each period
1	10.00	$ 45.00	4	$ 500.00	$ 50.00
2	5.00	$ 45.00	4	$ 300.00	$ 35.00

Table A II-3 Parameters related to storage, transportation and due dates of activities

Parameter	Value/ unit
Maximum capacity of each construction site i in m3	48 m3
Inventory cost per m3 for one period in each construction site i	$ 7.00
Maximum capacity of warehouse in m3	1600 m3
Inventory cost per m3 for one period in warehouse	$ 1.00
Maximum capacity of manufacturer in m3	60 m3
Inventory cost per m3 for one period in manufacturer	$ 3.00
Initial inventory at the manufacturer	4 products
Transportation cost of modular product from manufacturer to warehouse per truck	$ 2.00
Transportation cost of modular product from warehouse to each construction site i per truck	$ 2.00
Capacity of a truck running from manufacturer to warehouse in m3	6 m3
Capacity of a truck running from warehouse to construction sites in m3	3 m3
Due date of the project of construction site 1 and 2 respectively after which a delay penalty cost is paid	Period 19/ 16

Spreadsheet A II-2 Product flow tracking, m=1

T		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Theta(m,t)= One if a unit of material m manufactured in period t, zero otherwise		0	0	0	0	1	1	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0
Chi(m,t)= Manufacturing quantity of material m in period t		0	0	0	0	3	3	0	0	0	4	4	0	0	0	0	2	0	0	0	0	0
ximw(m,t)= Quantity of material m shipped from factory to warehouse at period t		0	4	0	0	3	3	0	0	0	4	4	0	0	0	0	2	0	0	0	0	0
IM(m,t)= Inventory level of material type m at manufacturer by the end of period t		4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
xiwc(m,i,t) = Quantity of material m shipped from warehouse to construction sites at period t	Varphi(m,i,t)	0	1	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0
	i=1	0	2	0	0	0	3	0	0	0	0	4	0	0	0	0	1	0	0	0	0	0
	Varphi(m,i,t)	0	1	0	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0
	i=2	0	2	0	0	3	0	0	0	0	4	0	0	0	0	0	1	0	0	0	0	0
IW(m,t)= Inventory level of material type m at the warehouse by the end of period t		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
IC(m,i,t) =Inventory level of material type m at construction site i by the end of period t	i=1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	i=2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Spreadsheet A II-3 Product flow tracking, m=2

T		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Theta(m,t)= One if a unit of material m manufactured in period t, zero otherwise		0	0	0	0	1	1	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0
Chi(m,t)= Manufacturing quantity of material m in period t		0	0	0	0	4	4	0	0	0	4	0	0	0	0	0	2	0	0	0	0	0
ximw(m,t)= Quantity of material m shipped from factory to warehouse at period t		0	4	0	0	4	4	0	0	0	4	0	0	0	0	0	2	0	0	0	0	0
IM(m,t)= Inventory level of material type m at manufacturer by the end of period t		4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
xiwc(m,i,t) = Quantity of material m shipped from warehouse to construction sites at period t	Varphi(m,i,t)	0	1	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0
	i=1	0	2	0	0	0	4	0	0	0	0	2	0	0	0	0	1	0	0	0	0	0
	Varphi(m,i,t)	0	1	0	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0
	i=2	0	2	0	0	4	0	0	0	0	2	0	0	0	0	0	1	0	0	0	0	0
IW(m,t)= Inventory level of material type m at the warehouse by the end of period t		0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
IC(m,i,t) =Inventory level of material type m at construction site i by the end of period t	i=1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	i=2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

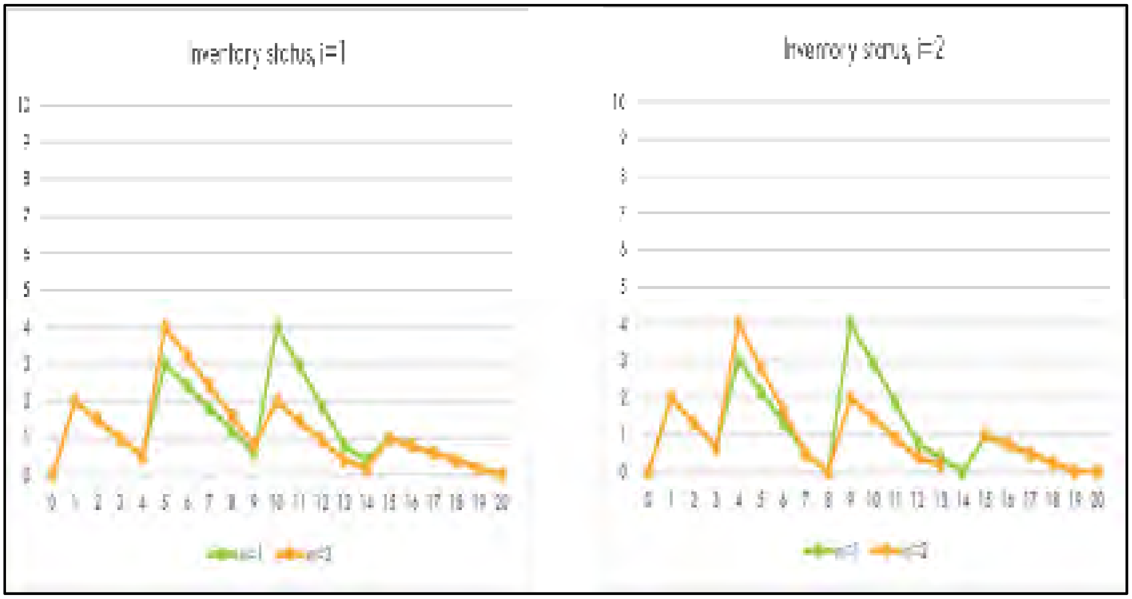

Figure A II-1 Inventory status at each construction site

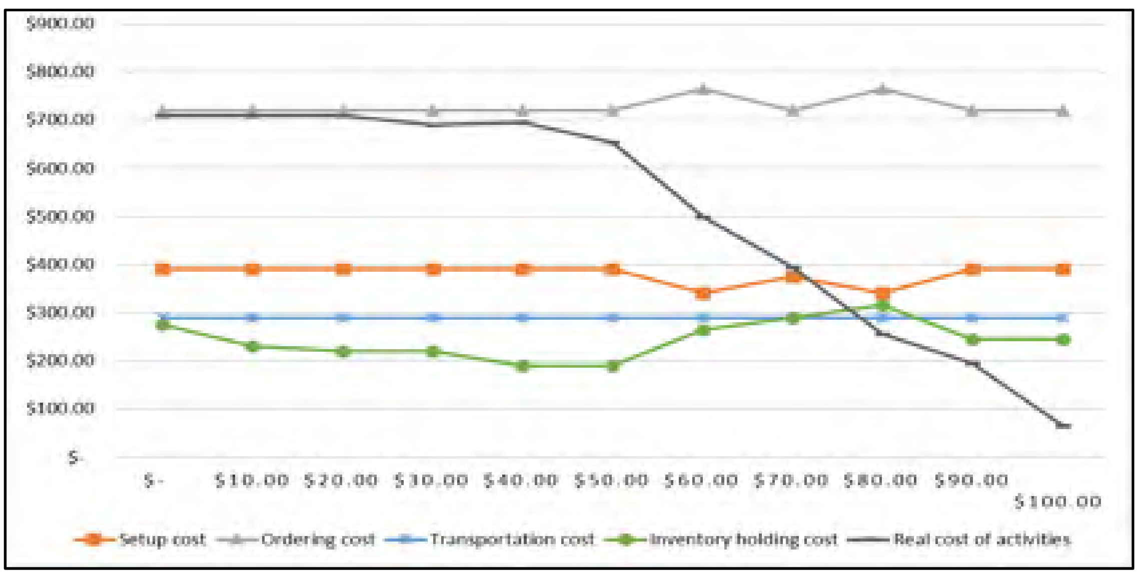

Figure A II-2 Impact of the reward on the costs of the integrated model

LIST OF BIBLIOGRAPHICAL REFERENCES

Albaloushi, H., & Skitmore, M. (2008). Supply chain management in the UAE construction industry. *International Journal of Construction Management, 8*(1), 53-71.

Aloini, D., Dulmin, R., Mininno, V., & Ponticelli, S. (2012). Supply chain management: a review of implementation risks in the construction industry. *Business Process Management Journal*.

Amornsawadwatana, S. (2011). *Effective design of the construction supply chain: A case of small buildings in Thailand.* Paper presented at the Industrial Engineering and Engineering Management (IEEM), 2011 IEEE International Conference on.

Aquilano, N. J., & Smith, D. E. (1980). A formal set of algorithms for project scheduling with critical path scheduling/material requirements planning. *Journal of Operations Management, 1*(2), 57-67.

Azambuja, M., & O'Brien, W. (2009). Construction supply chain modeling: issues and perspectives. *Construction Supply Chain Management Handbook, 1*.

Azhar, S., Nadeem, A., Mok, J. Y., & Leung, B. H. (2008). *Building Information Modeling (BIM): A new paradigm for visual interactive modeling and simulation for construction projects.* Paper presented at the Proc., First International Conference on Construction in Developing Countries.

Azhar, S., Khalfan, M., & Maqsood, T. (2012). Building information modelling (BIM): now and beyond. *Construction Economics and Building, 12*(4), 15-28.

Behera, P., Mohanty, R., & Prakash, A. (2015). Understanding construction supply chain management. *Production Planning & Control, 26*(16), 1332-1350.

Briscoe, G., Dainty, A. R., & Millett, S. (2001). Construction supply chain partnerships: skills, knowledge and attitudinal requirements. *European journal of purchasing & supply management, 7*(4), 243-255.

Bryde, D., Broquetas, M., & Volm, J. M. (2013). The project benefits of building information modelling (BIM). *International Journal of project management, 31*(7), 971-980.

Chen, J.-H., & Lin, J.-Z. (2010). Developing an SVM based risk hedging prediction model for construction material suppliers. *Automation in construction, 19*(6), 702-708.

Chen, J.-h., & Ma, S.-h. (2008). *A dynamic reputation incentive model in construction supply chain.* Paper presented at the 2008 International Conference on Management Science and Engineering 15th Annual Conference Proceedings.

Chen, P.-H., & Nguyen, T. C. (2019). A BIM-WMS integrated decision support tool for supply chain management in construction. *Automation in construction, 98*, 289-301.

Cheng, J. C., & Kumar, S. (2015). *A BIM-based framework for material logistics planning.* Paper presented at the 23rd Annual Conference of the International Group for Lean Construction.

Dainty, A. R., Millett, S. J., & Briscoe, G. H. (2001). New perspectives on construction supply chain integration. *Supply chain management: An international journal, 6*(4), 163-173.

Dallasega, P., Rauch, E., & Linder, C. (2018). Industry 4.0 as an enabler of proximity for construction supply chains: A systematic literature review. *Computers in Industry, 99*, 205-225.

Dave, B., Kubler, S., Främling, K., & Koskela, L. (2016). Opportunities for enhanced lean construction management using Internet of Things standards. *Automation in construction, 61*, 86-97.

Deng, Y., Gan, V. J., Das, M., Cheng, J. C., & Anumba, C. (2019). Integrating 4D BIM and GIS for construction supply chain management. *Journal of Construction Engineering and Management, 145*(4), 04019016.

Ding, L., Zhou, Y., & Akinci, B. (2014). Building Information Modeling (BIM) application framework: The process of expanding from 3D to computable nD. *Automation in construction, 46*, 82-93.

Dodin, B., & Elimam, A. (2001). Integrated project scheduling and material planning with variable activity duration and rewards. *Iie Transactions, 33*(11), 1005-1018.

ECLLP, H. (2013). Supply chain analysis into the construction industry-a report for the construction industrial strategy. *BIS Research Paper, 145*.

Feng, C., Ma, Y., Zhou, G., & Ni, T. (2018). Stackelberg game optimization for integrated production-distribution-construction system in construction supply chain. *Knowledge-Based Systems, 157*, 52-67.

Feng, X., & Zhang, H. (2010). Study of Inventory Control Based on the Supply Chain Management in Construction Enterprises *ICLEM 2010: Logistics For Sustained Economic Development: Infrastructure, Information, Integration* (pp. 4512-4517).

Fang, Y., & Ng, S. T. (2011). Applying activity-based costing approach for construction logistics cost analysis. *Construction Innovation*.

Fernie, S., & Tennant, S. (2013). The non-adoption of supply chain management. *Construction Management and Economics, 31*(10), 1038-1058.

Fu, F. (2014). Integrated scheduling and batch ordering for construction project. *Applied Mathematical Modelling, 38*(2), 784-797.

Gan, V. J., & Cheng, J. C. (2015). Formulation and analysis of dynamic supply chain of backfill in construction waste management using agent-based modeling. *Advanced Engineering Informatics, 29*(4), 878-888.

Ganbold, O., & Matsui, Y. (2017). Impact of environmental uncertainty on supply chain integration. *The Journal of Japanese Operations Management and Strategy, 7*(1), 37-56.

Golkhoo, F., & Moselhi, O. (2019). Optimized material management in construction using multi-layer perceptron. *Canadian Journal of Civil Engineering, 46*(10), 909-923.

Golpîra, H. (2020). Optimal integration of the facility location problem into the multi-project multi-supplier multi-resource Construction Supply Chain network design under the vendor managed inventory strategy. *Expert Systems with Applications, 139*, 112841.

Gould, F. E., & Joyce, N. E. (2009). *Construction project management*: Prentice Hall.

Govindan, K., Azevedo, S., Carvalho, H., & Cruz-Machado, V. (2015). Lean, green and resilient practices influence on supply chain performance: interpretive structural modeling approach. *International Journal of Environmental Science and Technology, 12*(1), 15-34.

Guerlain, C., Renault, S., & Ferrero, F. (2019). Understanding Construction Logistics in Urban Areas and Lowering Its Environmental Impact: A Focus on Construction Consolidation Centres. *Sustainability, 11*(21), 6118.

Habibi, F., Barzinpour, F., & Sadjadi, S. J. (2019). A mathematical model for project scheduling and material ordering problem with sustainability considerations: A case study in Iran. *Computers & Industrial Engineering, 128*, 690-710.

Hamdan, S. B., Barkokebas, B., Manrique, J. D., & Al-Hussein, M. (2015). *A BIM-based simulation model for inventory management in panelized construction.* Paper presented at the ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction.

Horman, M. J., & Thomas, H. R. (2005). Role of inventory buffers in construction labor performance. *Journal of Construction Engineering and Management, 131*(7), 834-843.

Hsu, P.-Y., Angeloudis, P., & Aurisicchio, M. (2018). Optimal logistics planning for modular construction using two-stage stochastic programming. *Automation in construction, 94*, 47-61.

Hsu, P.-Y., Aurisicchio, M., & Angeloudis, P. (2017). *Supply chain design for modular construction projects*.

Jung, Y., & Joo, M. (2011). Building information modelling (BIM) framework for practical implementation. *Automation in construction, 20*(2), 126-133.

Irizarry, J., Karan, E. P., & Jalaei, F. (2013). Integrating BIM and GIS to improve the visual monitoring of construction supply chain management. *Automation in construction, 31*, 241-254.

Jaśkowski, P., Sobotka, A., & Czarnigowska, A. (2018). Decision model for planning material supply channels in construction. *Automation in construction, 90*, 235-242.

Kanimozhi, G., & Latha, P. (2014). Material Management in Construction Industry. *Indian Journal of Applied research, 4*(4), 6-9.

Ko, C. H. (2010). An integrated framework for reducing precast fabrication inventory. *Journal of civil engineering and management, 16*(3), 418-427.

Kumar, S. S., & Cheng, J. C. (2015). A BIM-based automated site layout planning framework for congested construction sites. *Automation in construction, 59*, 24-37.

Le, P. L., Elmughrabi, W., Dao, T.-M., & Chaabane, A. (2020). Present focuses and future directions of decision-making in construction supply chain management: a systematic review. *International Journal of Construction Management, 20*(5), 490-509.

Lin, Y., & Tserng, H. (2001). *A model of supply chain management for construction using information technology.* Paper presented at the Proceedings of the XVIII Symposium of Automation and Robotics in Construction.

Lin, X., Ho, C. M., & Shen, G. Q. (2018). Research on corporate social responsibility in the construction context: A critical review and future directions. *International Journal of Construction Management, 18*(5), 394-404.

Liu, Q., & Tao, Z. (2015). *A multi-objective optimization model for the purchasing and inventory in a three-echelon construction supply chain.* Paper presented at the Proceedings of the Ninth International Conference on Management Science and Engineering Management.

Liu, Q., Xu, J., & Qin, F. (2017). Optimization for the integrated operations in an uncertain construction supply chain. *IEEE Transactions on Engineering Management, 64*(3), 400-414.

Lu, H., Wang, H., Xie, Y., & Li, H. (2016). Construction material safety-stock determination under nonstationary stochastic demand and random supply yield. *IEEE Transactions on Engineering Management, 63*(2), 201-212.

Lundesjo, G. (2011). Using Construction Consolidation Centres to reduce construction waste and carbon emissions. *Banbury, Oxon, Great Britain: Waste & Resources Action Programme*.

Madhavi, T. P., Mathew, S. V., & Sasidharan, R. (2013). Material management in construction–a case study. *International journal of research in engineering and technology, 2*(13), 400-403.

Maghrebi, M., Waller, T., & Sammut, C. (2013). Integrated Building Information Modelling (BIM) with supply chain and Feed-Forward control. *YBL Journal of Built Environment, 1*(2), 25-34.

Manavazhi, M. R., & Adhikari, D. K. (2002). Material and equipment procurement delays in highway projects in Nepal. *International Journal of project management, 20*(8), 627-632.

Meng, J., Yan, J., Xue, B., Fu, J., & He, N. (2018). Reducing construction material cost by optimizing buy-in decision that accounts the flexibility of non-critical activities. *Engineering, Construction and Architectural Management*.

Okuda, A., Ishigaki, A., Yamada, T., & Gupta, S. M. (2018). Inventory management in a manufacturing-remanufacturing system with cannibalization and stochastic returns. *LogForum, 14*.

Patil, A. R., & Pataskar, S. V. (2013). Analyzing material management techniques on construction project. *International Journal of Engineering and Innovative Technology, 3*(4), 96-100.

Papadonikolaki, E., Vrijhoef, R., & Wamelink, H. (2015). Supply chain integration with BIM: a graph-based model. *Structural Survey, 33*(3), 257-277.

Papadopoulos, G. A., Zamer, N., Gayialis, S. P., & Tatsiopoulos, I. P. (2016). Supply Chain Improvement in Construction Industry.

Polat, G., Arditi, D., & Mungen, U. (2007). Simulation-based decision support system for economical supply chain management of rebar. *Journal of Construction Engineering and Management, 133*(1), 29-39.

Porwal, A., & Hewage, K. N. (2013). Building Information Modeling (BIM) partnering framework for public construction projects. *Automation in construction, 31*, 204-214.

Qu, T., Nie, D., Chen, X., Chen, X., Dai, Q., & Huang, G. Q. (2015). Optimal configuration of cluster supply chains with augmented Lagrange coordination. *Computers & Industrial Engineering, 84*, 43-55.

Robles, G., Stifi, A., Ponz-Tienda, J. L., & Gentes, S. (2014). Labor productivity in the construction industry-factors influencing the Spanish construction labor productivity. *International Journal of Civil and Environmental Engineering, 8*(10), 1061-1070.

Russell, M. M., Howell, G., Hsiang, S. M., & Liu, M. (2013). Application of time buffers to construction project task durations. *Journal of Construction Engineering and Management, 139*(10), 04013008.

Saad, M., Jones, M., & James, P. (2002). A review of the progress towards the adoption of supply chain management (SCM) relationships in construction. *European journal of purchasing & supply management, 8*(3), 173-183.

Said, H., & El-Rayes, K. (2011). Optimizing material procurement and storage on construction sites. *Journal of Construction Engineering and Management, 137*(6), 421-431.

Said, H., & El-Rayes, K. (2014). Automated multi-objective construction logistics optimization system. *Automation in construction, 43*, 110-122.

Serpell, A., & Heredia, B. (2004). Supply chain management in construction: Diagnosis and application issues. *Globalisation and Construction, 455*.

SHEYKH, S. M., Shadrokh, S., & HASANZADEH, F. (2009). Concurrent project scheduling and material planning: A genetic algorithm approach.

Simatupang, T. M., & Sridharan, R. (2016). A critical analysis of supply chain issues in construction heavy equipment. *International Journal of Construction Management, 16*(4), 326-338.

Soltani, A., & Fernando, T. (2004). A fuzzy based multi-objective path planning of construction sites. *Automation in construction, 13*(6), 717-734.

Spiliotopoulou, E., Donohue, K., Gürbüz, M. Ç., & Heese, H. S. (2018). Managing and reallocating inventory across two markets with local information. *European journal of operational research, 266*(2), 531-542.

Srivastava, S. K. (2007). Green supply-chain management: a state-of-the-art literature review. *International journal of management reviews, 9*(1), 53-80.

Stadtler, H. (2008). Supply chain management—an overview *Supply chain management and advanced planning* (pp. 9-36): Springer.

Stevens, G. C., & Johnson, M. (2016). Integrating the supply chain… 25 years on. *International Journal of Physical Distribution & Logistics Management*.

Tabrizi, B. H., & Ghaderi, S. F. (2016). A robust bi-objective model for concurrent planning of project scheduling and material procurement. *Computers & Industrial Engineering, 98*, 11-29.

Tabrizi, B. H. (2018). Integrated planning of project scheduling and material procurement considering the environmental impacts. *Computers & Industrial Engineering, 120*, 103-115.

Taleizadeh, A. A., & Noori-daryan, M. (2016). Pricing, manufacturing and inventory policies for raw material in a three-level supply chain. *International Journal of Systems Science, 47*(4), 919-931.

Tserng, H. P., Yin, S. Y., & Li, S. (2006). Developing a resource supply chain planning system for construction projects. *Journal of Construction Engineering and Management, 132*(4), 393-407.

Vaidyanathan, K. (2009). Overview of IT applications in the construction supply chain. *Construction Supply Chain Management Handbook*, 15-11.

Vaidyanathan, K., & Howell, G. (2007). *Construction supply chain maturity model–conceptual framework.* Paper presented at the Proceedings IGLC.

Vidalakis, C., Tookey, J. E., & Sommerville, J. (2011). The logistics of construction supply chains: the builders' merchant perspective. *Engineering, Construction and Architectural Management, 18*(1), 66-81.

Vrijhoef, R., & Koskela, L. (2000). The four roles of supply chain management in construction. *European journal of purchasing & supply management, 6*(3), 169-178.

Walsh, K. D., Hershauer, J. C., Tommelein, I. D., & Walsh, T. A. (2004). Strategic positioning of inventory to match demand in a capital projects supply chain. *Journal of Construction Engineering and Management, 130*(6), 818-826.

Walsh, M., & Watson, L. (2011). Part 1A: Market analysis towards the further development of seaweed aquaculture in Ireland. *Bord Iascaigh Mhara (BIM). 49p. Available online at:< http://www. bim. ie/media/bim/content/publications/corporate-otherpublications/A% 20Market% 20Analysis% 20towards% 20the% 20Further% 20Development, 20*.

Winch, G. M. (2009). *Managing construction projects*: John Wiley & Sons.

Wong, J., Wang, X., Li, H., & Chan, G. (2014). A review of cloud-based BIM technology in the construction sector. *Journal of Information Technology in Construction, 19*, 281-291.

Xie, B. Y. (2013). *Optimal Scheme of Solving the Problem of Construction Enterprise Formwork Inventory with Storage Theory.* Paper presented at the Applied Mechanics and Materials.

Xu, J., & Zhao, S. (2017). Noncooperative game-based equilibrium strategy to address the conflict between a construction company and selected suppliers. *Journal of Construction Engineering and Management, 143*(8), 04017051.

Xue, X., Li, X., Shen, Q., & Wang, Y. (2005). An agent-based framework for supply chain coordination in construction. *Automation in construction, 14*(3), 413-430.

Xue, X., Shen, Q., Tan, Y., Zhang, Y., & Fan, H. (2011). Comparing the value of information sharing under different inventory policies in construction supply chain. *International Journal of project management, 29*(7), 867-876.

Zeb, A., Khan, D., Sajid, M., & Khattak, S. B. INVENTORY ANALYSIS OF CONSTRUCTION PROJECT.

Zeng, Y., & Xiao, R. (2014). Modelling of cluster supply network with cascading failure spread and its vulnerability analysis. *International Journal of Production Research, 52*(23), 6938-6953.

Zou, A. J. (2012). *Optimization Research of Construction Inventory Management on Site Based on Inventory Theory.* Paper presented at the Applied Mechanics and Materials.