EPiC Series in Built Environment
Volume 4, 2023, Pages 650–658
Proceedings of 59th Annual Associated Schools of Construction International Conference

Envisioning the Future of Supply Chain Management for Modular Construction through literature review

Qinghao Zeng, Ph.D. student and Pardis Pishdad-Bozorgi, Ph.D.
Georgia Institute of Technology
Atlanta, Georgia

Modular construction has been gaining momentum worldwide due to its potential in increasing project efficiency and reducing construction waste. It is centered around the utilization of prefabricated components and modules produced in off-site factories. Due to its unique features and close relationship with manufacturing industry, the supply chain management of modular construction requires more attention since transporting standardized modular parts with different completion levels is complicated to manage. What's more, the supply chain mapping and scheduling need to be improved due to the more specific requirements in terms of module components categories, building types, and labor availability and cost. In this research, the goal is to envision the future of modular construction supply chain management for more proactive adoption of modular construction. After conducting a systematic literature review, this research provides insights and recommendations for the current mapping design, scheduling, monitoring, and risk management. The contribution of this research involves the cost-benefit analysis of modular construction and a proposal for an enhanced supply chain system to increase logistics efficiency.

Key Words: Modular Construction, Supply Chain Management, Risk Management, Literature Review

Introduction

According to the definition of Construction Industry Institute (CII) (CII, 2011), modular construction (MC) includes all the work representing substantial offsite construction and assembly of components as well as finished projects onsite. It is based on the utilization of panelized components or full volumetric units which are produced in off-site factories and transported for assembly at the targeted areas (Ferdous, Bai, Ngo, Manalo, & Mendis, 2019), improving efficiency of the whole project delivery. Modular construction enhances productivity by dividing the complex onsite construction process into numerous stages within the off-site factories and assembly workhouses (Choi, Chen, & Kim, 2019; Council, 2009; Enshassi, Walbridge, West, & Haas, 2019).

T. Leathem, W. Collins and A. Perrenoud (eds.), ASC2023 (EPiC Series in Built Environment, vol. 4), pp. 650–658

Modular construction has been attracting numerous construction firms and practitioners for enhancing their project performance due to its advantages in budget and schedule predictability, assurance in quality as well as reduction in waste management and labor demand (Baldwin, Poon, Shen, Austin, & Wong, 2009; O'Connor, O'Brien, & Choi, 2014, 2016). What's more, based on the statistics from Markets (2020), the global construction is expected to become $12,031.1 billion with an annual growth rate of 5.7% by the end of 2024, in which modular construction is estimated as increasing at a 8.16% annual growth rate, demonstrating significance in market expansion within the construction industry. However, the potential of modularization of construction projects has not been fully capitalized due to their unique risks and uncertainties (O'Connor et al., 2014). One of the unique features for modular construction is that it's more sensitive to its supply chain since most of the prefabricated parts are constructed in the off-site factories or warehouses rather than assembled on site. Project modularization is "breaking up the whole process into discrete pieces", while supply chain management is considered as the network to integrate those "discrete pieces". Hence, this integration process requires the transportation of modules and module parts range from different completion levels, making it more complicated to manage. Besides, as type of modular construction differs, so does the required prefabrication components. Required building systems and materials varies among different types of buildings on the basis of building functions, special needs, and sustainable requirements. Therefore, supply chain mapping and scheduling should be improved due to the more specific requirements in terms of module components categories, building types, and labor situation including availability and cost.

In this research, the goal is to envision the future Modular Construction Supply Chain Management (MCSCM) for more proactive adoption of modular construction. Through literature review, this research provides insights and recommendations for the current mapping design, scheduling, monitoring, and risk management. The contribution of this research involves the cost-benefit analysis of modular construction and a proposal for an enhanced supply chain system to increase logistics efficiency.

Research Methodology

In order to understand how to improve the MCSCM, its features and process should be investigated and summarized first through a systematic literature review (see Figure 1). Furthermore, articles discussing about risk factors for determining the feasibility of modular construction in metropolitan areas should be studied as well. Last but not least, literatures focusing on classification of current modular construction supply chain should be analyzed to allocate resources more efficiently.

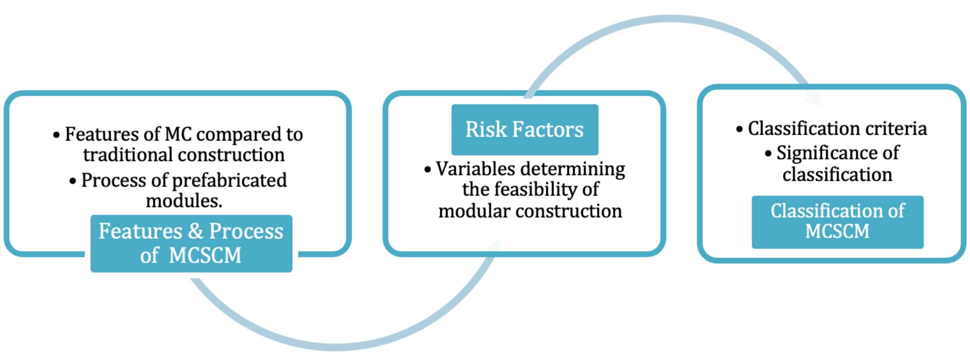

Figure 1 Literature review process and topics

Due to the academic influence of American Society of Civil Engineering (ASCE), numerous articles from journals of ASCE are under review. Here are the results of the article selection searching on Web of Science while the input keywords are "modular construction" and "supply chain" (see Table 1).

Table 1

Representative papers of the literature review

Source	Contribution	Research Methodology
(D. Lee & Lee, 2021)	Discuss about the implementation of digital twins to help predict potential logistics risks and accurate module delivery time.	Conducted a case study integrates BIM and GIS for real-time logistics simulation in modular construction to test the model performance.
(Doran & Giannakis, 2011)	Identify the application of supply chain practices of modular construction.	Conduct a case study to examine the construction supply chain from module manufacturer to module client.
(Hsu, Angeloudis, & Aurisicchio, 2018)	Provide insights about how to optimize logistics system of modular construction.	Conduct a case study adopting the stochastic supply chain network design.
(Hsu, Aurisicchio & Angeloudis, 2019)	Introduce a mathematical model for optimizing risk-averse logistics configurations for modular construction.	Conduct a case study demonstrating the performance of the model with multiple sources of uncertainty.
(Innella, Arashpour, & Bai, 2019)	Discuss the implementation of lean techniques in the modular building industry.	Conduct a comprehensive review of lean methodologies and tools connect lean with modular construction.
(Lee, Park, Lee & Hyun, 2019)	Propose a classification result of modular building construction projects based on schedule-driven.	Develop a simulation model and conduct a case study to test the reasonability of the classification.
(Liu & Lu, 2018)	Describes risk factors and impacts of the identified risk factors on project cost and duration for modular construction	Rank the risk factors with analytic hierarchy process (AHP).
(Ramaji & Memari, 2016)	Reviews the hierarchy of modular building components.	Review literature about interactions, functionality, and attributes of modular building's product architecture model.
(Sun, Wang & Zhao, 2020)	Provide reference for stakeholders adopting modular buildings with how to mitigate risks.	Review literature about constraints of modular buildings, conduct a questionnaire survey to determine domain constraints.
(Yang, Pan, Pan, & Zhang, 2021)	Identify and categorize uncertainties affecting the offsite logistics of high-rise modular	Literature review and questionnaire survey related to investigation of sources of uncertainties affecting offsite logistics.

	building projects in high-density cities.	

Literature Review

Features and Process of Modular Construction Supply Chain Management

Unlike the traditional supply chain structure, it's not the direct delivery of raw materials from suppliers to the construction sites that constructs the MCSCM, but a series of transportation among manufacturing facilities, warehouses of prefabrication components, and module distribution centers (Hsu, Angeloudis, & Aurisicchio, 2018). What's more, as supply chain is an integration of multiple dynamic systems interacting with each other, careful design and coordination are of great necessity to ensure the efficiency of logistics. Based on the evidence from literature, several features about MCSCM could be summarized (see Table 2).

Table 2

Features of MCSCM

Features	Reasons	Source
Cost effective	Reduced raw material transportation. No need for on-site assembly. Reduced vulnerability to weather extremes.	(CII, 2011) (Sun et al., 2020) (Hsu, Aurisicchio, & Angeloudis, 2019)
Lean concept applicable	Good affinity with manufacturing industry. Standardized with certain level of customization.	(Winch, 2003) (Innella et al., 2019)
Hierarchical	Different levels of completion exist among prefabricated components.	(Ramaji & Memari, 2016)
Resource predictable	Raw Materials are prefabricated into modules, easier to estimate. Labor's working performance is insensitive to single project demands, easier to estimate labor cost. Reduced on-site materials waste due to manufacturing accuracy as well as controlled environment Scheduling is simply based on assembly of modules, less complex than assembling building systems directly.	(Hsu et al., 2019) (Sun et al., 2020) (J. Lee, Park, Lee, & Hyun, 2019)

In the process of traditional supply chain of a construction project, a total of five stakeholders are usually involved: raw material supplier, equipment manufacturer, material and equipment receiver, on-site assembler, project manager (Vrijhoef & Koskela, 2000). Tracking and managing the supply chain is project-based, leading to schedule delay and resource waste caused by uncertainty of material quantity and complexity of resource distribution. Occasional change orders are also considered as one of the threats to the stability and efficiency of the supply chain management. On the contrary, considered as the combination of prefabrication, standardization, and dimensional coordination, modular construction supply chain is more dynamic and flexible (Innella et al., 2019). Since most of the modules and components are standardized and prepared in the prefabrication factories, some on-site assembly time could be saved, allowing for greater tolerance in scheduling. Although modules are standardized, high level of customization is also accessible in terms of building types, locational, and economic situations. Therefore, the whole system of MCSCM should be divided into clusters and categorized into different groups for better customization to meet the requirements of different building owners.

Risk Factors of Modular Construction

Generally, while considering factors that determine the success and suitability of adopting modular construction projects, many researchers agree that local social, legal, and environmental conditions are to be considered (Abdul Nabi & El-adaway, 2020; Sing, Chan, Liu, & Ngai, 2021; Wuni, Shen, & Osei-Kyei, 2019). As Azhar, Lukkad, and Ahmad (2012) categorizes 13 groups of factors that could contribute to the success of modular construction, among which “owner’s willingness” and “early and effective project management” are stated to be the top 2 factors. Besides, Wuni et al. (2019) also conducted a comprehensive literature review stating that the availability of skilled labor force and management teams are of great significance, and Choi et al. (2019) summarizes the most recognized barriers for modular constructions in modern areas are conditional site access, limited on-site space, transportation convenience and labor availability. Also, based on the research by Yang, Pan, Pan, and Zhang (2021), source of uncertainties for MCSCM could be categorized into four groups: manufacturing process uncertainties (MPU), demand for module uncertainties (DMU), module supply uncertainties (MSU), and planning and controlling uncertainties (PCU). MPU refers to the detailed internal process within the offsite logistics, DMU includes the owner’s, designer’s and contractor’s requirement for modules, MSU covers the supply of raw materials for building modules and components, and PCU focuses more on the coordination and scheduling of logistics (Yang et al., 2021). Here is a table summarizing the specific risk and contributing factors of each group (see Table 3).

Table 3

Specific risks and contributing factors of each MCSCM group

Group	Specific Risks	Quantitative Risk Factors	Sources
MPU	Lack of skilled workforce, ineffective manufacturing design, long-distance transportation, machine problems.	Number of labors, machine inspection times, distance between factories, warehouses, and sites.	(Yu, Al-Hussein, Al-Jibouri, & Telyas, 2013)
DMU	Late design changes, speed of module installation.	Number of change orders, time for preparing modules.	(Rahman, 2014; Zhai, Fu, Xu, & Huang, 2019)
MSU	Accuracy of material quantity, timely delivery of the materials	Percentage of accurate material supply, delay time of materials.	(Li, Al-Hussein, Lei, & Ajweh, 2013)
PCU	Incorrect control actions, inadequate quality control systems, poor stakeholder communication, inadequate technology failures.	Data loss, waste caused by lack of communication	(Sun et al., 2020; Vrijhoef & Koskela, 2000)

Importance of Classifying Modular Construction Supply Chain

The classification of supply chain based on project features is both theoretically and practically significant (Frohlich & Dixon, 2001), so does MCSC. As Rosenfeld (1996) proposes two kinds of networks for supply chain management. One is called “hard networks” where different firms and organizations join forces and collaborate for better producing, purchasing and operating the whole system. The other one is called "soft networks", where firms form to groups to solve common problems, share information and obtain new abilities and skills. So, to achieve the best efficiency of SCM, the whole system should be stratified and classified based on land cost, labor cost, component type, and other criterion, in order to manage different types of "buyer-supplier" relationship and organize the products and materials in a better way.

Different from traditional supply chain in which materials are directly transported to the construction site, MCSCM simplifies the work on site but challenges the project managers with organizing the transportation and storing of prefabricated components and modules (Ahmed, Kristal, Pagell, & Gattiker, 2017). Normally, most of the prefabricated components for modular construction are linear members (beams, lintels, columns), rigid structural frames, roofing and flooring components, doors and windows, and wall panels because these components are standardized easy for transportation, dismantling and assembling (Admin, 2021). Additionally, a great number of Mechanical, Electrical and Pumping (MEP) components are also prefabricated and preinstalled for transportation.

According to the survey from Jones (2020), the most frequent building types for prefabrication and modular construction are healthcare facilities, hotels and motels, college building and dormitories, high-rise offices and schools. All of those building types are usually located in the dense population area where land price and labor cost are higher, especially in metropolitan areas. Therefore, in order to reduce the unnecessary cost for on-site assembly and transportation of materials, warehouses and factories for modular construction are constructed and distributed in the rural area, and the design of warehouse locations and clustering of warehouses to minimize the transportation time and cost is the goal for classifying MCSCM.

Discussion – Future improvements of Modular Construction Supply Chain

Due to continuous flow of globalization and product specialization, a new term, "supply chain management 2.0", has emerged to demonstrate both the changes in the supply chain management itself but also the changes in the processes, technologies and tools. Based on the literature review, potential solutions for mitigating the impacts of risk factors could be summarized as: reasonable allocation of workforce based on labor availability and cost, better supply chain mapping based on project types, flexible scheduling strategy based on supply and demand, and monitoring of transported products and modules based on real-time data transmission and response.

Workforce Allocation

Workforce planning and distribution in terms of skills and wages is directly affecting the budget of the project (Arashpour, Wakefield, Blismas, & Minas, 2015). As Nasirian, Abbasi, Cheng, and Arashpour (2022) assert that we should think about workforce distribution from both managerial perspective and technical perspective. Since modular supply chain could be divided into three stages as: materials to prefabrication manufacturing, prefabricated components to module assembly, assembled modules to the construction site, each stage requires workforce with different skills and expertise. In the previous supply chain, workers are supposed to collaborate together on the field to finish necessary jobs, leading to increase in labor cost and project duration since work sequence exist and the project schedule is process-based. On the comparison, the workforce for future supply chain is distributed into multiple locations including factories, warehouses, and distribution points based on the local labor costs and land cost in order to lower the budget. Research by Nasirian, Arashpour, and Abbasi (2019) also conduct an investigation about construction workforce planning and asserts that skilled-based workforce planning is the matured approach for allocating labor resources between construction and manufacturing industry.

Supply Chain Mapping

Because supply chain mapping is defined as a methodology to increase the transportation efficiency, provide visibility and reduce disruption, it's responsible for the duration of module transportation and distribution to various construction sites. Normally, in previous MCSCM, several lines are established directly between manufacturing factories and construction sites to ease the transportation process and reduce potential risks. However, as construction sites are located in different areas with different traffic conditions, population density, and freight shipping fees, it's reasonable to make some alternations to the mapping design considering these factors.

Scheduling Strategy

As mentioned before, current project scheduling is process-based, meaning that the workflow could progress only when previous steps are finished. However, for future modular construction, the project workflow will be project-based. In other words, the arrangement of module transportation and distribution is based on project needs rather than assembling process, allowing for more flexibility of the scheduling and also reduce the time wasted by waiting for previous work to be done.

Transportation Monitoring

One of the most significant issues for all the supply chain management is quality control of the product during the transportation process, especially for modular construction since components are supposed to be assembled separately in different factories. Thus, digital twin assistance could be applied to monitor real-time logistics and simulate the whole process for determining potential risks, since digital twin means a virtual replica of the physical module in the real world (D. Lee & Lee, 2021). Within the digital twin, Building Information Modeling (BIM) are applied to store all the data concerning details of the logistics process, warehouse, module assembly places, and the construction sites; Internet of Things (IoT) sensors can be utilized in factories, warehouses, trucks, and module components to mark and locate the real-time location and condition of each component. Additionally, with the aid of Geographic Information System, the marked locations could be connected with the global mapping system, enabling the optimization process of the supply chain routes.

Conclusion and Future Research

In this paper, a literature review concerning modular construction and its supply chain management is conducted, demonstrating the features and basic process of MCSCM, risk factors along the supply chain, as well as the classification of MCSCM in terms of project types and component categories. Later in the discussion part, four types of suggestions corresponding to each risk are proposed to improve the current supply chain system from the perspective of workforce, scheduling, routes mapping and process monitoring for MCSCM. Future research can focus on conducting experiments by applying the suggested recommendations in the four categories in real modular projects and conducting case study analysis to demonstrate and quantify the benefits in terms of reduction in project duration and cost. Also, the estimation of modular construction market in the next 15 years based on the increasing population and different building types of demand is considered as another meaningful topic for proactive approach to emerging MCSCM.

References

Abdul Nabi, M., & El-adaway, I. H. (2020). Modular construction: Determining decision-making factors and future research needs. *Journal of Management in Engineering, 36*(6), 04020085. [DOI: 10.1061/(ASCE)ME.1943-5479.0000859]

Azhar, S., Lukkad, M., & Ahmad, I. (2012). *Modular v. stick-built construction: Identification of critical decision-making factors.* Paper presented at the 48th Annual Conference of Associated Schools of Construction.

Baldwin, A., Poon, C.-S., Shen, L.-Y., Austin, S., & Wong, I. (2009). Designing out waste in high-rise residential buildings: Analysis of precasting methods and traditional construction. *Renewable Energy, 34*(9), 2067-2073. [DOI: 10.1016/j.renene.2009.02.008]

Choi, J. O., Chen, X. B., & Kim, T. W. (2019). Opportunities and challenges of modular methods in dense urban environment. *International journal of construction management, 19*(2), 93-105. [DOI: 10.1080/15623599.2017.1382093]

CII. (2011). Transforming modular construction for the competitive advantage through the adaptation of shipbuilding production processes to construction. In: Construction Industry Institute, Univ. of Texas at Austin Austin, TX.

Council, N. R. (2009). *Advancing the competitiveness and efficiency of the US construction industry*: National Academies Press.

Doran, D., & Giannakis, M. (2011). An examination of a modular supply chain: a construction sector perspective. *Supply Chain Management: An International Journal, 16*(4), 260-270. [DOI: 10.1108/13598541111139071]

Enshassi, M. S., Walbridge, S., West, J. S., & Haas, C. T. (2019). Integrated risk management framework for tolerance-based mitigation strategy decision support in modular construction projects. *Journal of Management in Engineering, 35*(4), 05019004. [DOI: 10.1061/(ASCE)ME.1943-5479.0000698]

Ferdous, W., Bai, Y., Ngo, T. D., Manalo, A., & Mendis, P. (2019). New advancements, challenges and opportunities of multi-storey modular buildings–A state-of-the-art review. *Engineering Structures, 183*, 883-893. [DOI: 10.1016/j.engstruct.2019.01.061]

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. [DOI: 10.1016/j.autcon.2018.05.029]

Hsu, P.-Y., Aurisicchio, M., & Angeloudis, P. (2019). Risk-averse supply chain for modular construction projects. *Automation in Construction, 106*, 102898. [DOI: 10.1016/j.autcon.2019.102898]

Innella, F., Arashpour, M., & Bai, Y. (2019). Lean methodologies and techniques for modular construction: chronological and critical review. *Journal of Construction Engineering and Management, 145*(12), 04019076. [DOI: 10.1061/(ASCE)CO.1943-7862.0001712]

Lee, D., & Lee, S. (2021). Digital twin for supply chain coordination in modular construction. *Applied Sciences, 11*(13), 5909. [DOI: 10.3390/app11135909]

Lee, J., Park, M., Lee, H.-S., & Hyun, H. (2019). Classification of modular building construction projects based on schedule-driven approach. *Journal of Construction Engineering and Management, 145*(5), 04019031. [DOI: 10.1061/(ASCE)CO.1943-7862.0001656]

Li, H. X., Al-Hussein, M., Lei, Z., & Ajweh, Z. (2013). Risk identification and assessment of modular construction utilizing fuzzy analytic hierarchy process (AHP) and simulation. *Canadian Journal of Civil Engineering, 40*(12), 1184-1195. [DOI: 10.1139/cjce-2013-0013]

Liu, J., & Lu, M. (2018). Constraint programming approach to optimizing project schedules under material logistics and crew availability constraints. *Journal of construction engineering and management, 144*(7), 04018049. [DOI: 10.1061/(ASCE)CO.1943-7862.0001507]

Markets, R. a. (2020). Modular construction market—Growth, trends, and forecast (2020-2025). Retrieved from https://www.researchandmarkets.com/reports/4515000/modular-construction-market-growth-trends

O'Connor, J. T., O'Brien, W. J., & Choi, J. O. (2014). Critical success factors and enablers for optimum and maximum industrial modularization. *Journal of Construction Engineering and Management, 140*(6), 04014012. [DOI: 10.1061/(ASCE)CO.1943-7862.0000842]

O'Connor, J. T., O'Brien, W. J., & Choi, J. O. (2016). Industrial project execution planning: Modularization versus stick-built. *Practice periodical on structural design and construction, 21*(1), 04015014. [DOI: 10.1061/(ASCE)SC.1943-5576.0000270]

Rahman, M. M. (2014). Barriers of implementing modern methods of construction. *Journal of Management in Engineering, 30*(1), 69-77. [DOI: 10.1061/(ASCE)ME.1943-5479.0000173]

Ramaji, I. J., & Memari, A. M. (2016). Product architecture model for multistory modular buildings. *Journal of Construction Engineering and Management, 142*(10), 04016047. [DOI: 10.1061/(ASCE)CO.1943-7862.0001159]

Sing, M., Chan, J., Liu, H., & Ngai, N. N. (2021). Developing an analytic hierarchy process-based decision model for modular construction in urban areas. *Journal of Engineering, Design and Technology*(ahead-of-print). [DOI: 10.1108/JEDT-05-2021-0242]

Sun, Y., Wang, J., Wu, J., Shi, W., Ji, D., Wang, X., & Zhao, X. (2020). Constraints hindering the development of high-rise modular buildings. *Applied Sciences, 10*(20), 7159. [DOI: 10.3390/app10207159]

Vrijhoef, R., & Koskela, L. (2000). The four roles of supply chain management in construction. *European journal of purchasing & supply management, 6*(3-4), 169-178. [DOI: 10.1016/S0969-7012(00)00013-7]

Winch, G. (2003). Models of manufacturing and the construction process: the genesis of re-engineering construction. *Building Research & Information, 31*(2), 107-118. [DOI: 10.1080/09613210301995]

Wuni, I. Y., Shen, G. Q., & Osei-Kyei, R. (2019). Scientometric review of global research trends on green buildings in construction journals from 1992 to 2018. *Energy and buildings, 190*, 69-85. [DOI: 10.1016/j.enbuild.2019.02.010]

Yang, Y., Pan, M., Pan, W., & Zhang, Z. (2021). Sources of uncertainties in offsite logistics of modular construction for high-rise building projects. *Journal of Management in Engineering, 37*(3), 04021011. [DOI: 10.1061/(ASCE)ME.1943-5479.0000905]

Yu, H., Al-Hussein, M., Al-Jibouri, S., & Telyas, A. (2013). Lean transformation in a modular building company: A case for implementation. *Journal of Management in Engineering, 29*(1), 103-111. [DOI: 10.1061/(ASCE)ME.1943-5479.0000115]

Zhai, Y., Fu, Y., Xu, G., & Huang, G. (2019). Multi-period hedging and coordination in a prefabricated construction supply chain. *International Journal of Production Research, 57*(7), 1949-1971. [DOI: 10.1080/00207543.2018.1512765]