A model for measuring disruption risks in the prefabrication supply chain

Somik Ghosh, University of Oklahoma, USA
Mustafa Hamad, McCarthy Building Companies, USA

sghosh@ou.edu

ABSTRACT

Use of prefabrication in construction projects is increasing due to the benefits in cost, time, quality, and safety. However, utilizing prefabrication introduces uncertainties inherent with the supply chain of the process. These uncertainties, if not managed, can disrupt the prefabrication process and result in schedule delays and cost overruns. This study proposes a model to measure disruption risks in the prefabrication process. The model was used in measuring the disruption risks of prefabrication of headwalls in patients' rooms for a healthcare project as a pilot study. The risk model could successfully identify the disruption risks originating anywhere in the supply chain based on input information such as required material quantity, batch sizes of material deliveries, production rates, and batch sizes of transporting the headwall units. Using the model, the project team identified two uncertainties that could lead to possible disruptions: the start of the prefabrication processes and the required production rate to meet the on-site schedule. This is a first step to developing a risk exposure model that can prove valuable to the risk managers to analyse and manage the impact of disruptions. This will help the risk managers in making informed decisions about where to focus their limited resources.

KEYWORDS: Disruption risk, Prefabrication, Supply chain management, Supply chain network

INTRODUCTION

In recent years, there is growing popularity of coupling prefabrication with on-site construction. Prefabrication can be classified into five categories: volumetric, panelised, sub-assemblies, components, and non-offsite manufactured (Ross, Cartwright, & Novakovic, 2006). Numerous benefits have been associated with the use of prefabrication; these benefits include reductions in cost, time, defect, waste, non-value-added activities, environmental impact, health, and safety risks. These benefits extend to improve the life cycle cost and whole life performance of the built facilities, thus increasing profitability (Zhai, Zhong, & Huang, 2015). However, these benefits come with added risks; utilizing prefabrication introduces risks and uncertainties in the process that cause complexity in the management of projects and their respective supply chains (Arashpour & Wakefield, 2015). In a typical construction project, the components that the project team decides to prefabricate are mostly assembled in an offsite facility. After assembly, the prefabricated components are stored in the offsite facility until they are delivered to the jobsite where they are temporarily stored before installation. The installation of the prefabricated components is dependent on the progress of the on-site construction process; in a sense, the process of assembly and delivery

Downloaded from SHAREOK. Persistent Handle URL: https://hdl.handle.net/11244/342474

of the prefabricated components converges with the on-site construction process as shown in Figure 1. The figure shows a simplified schematic of the offsite chain of activities for prefabrication converging with the on-site activities to accomplish the project objectives.

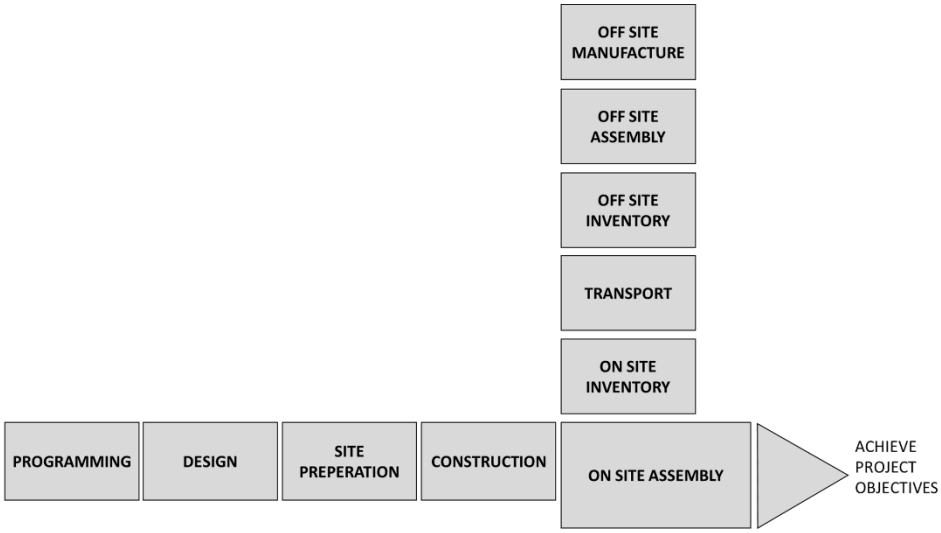


Figure 1: Offsite construction activities converging with on-site construction activities

Prefabrication refers to the activities that are completed offsite in support of the construction project. In this document, the authors have referred to the construction of the different components at offsite facilities along with their supply chains as prefabrication. The facilities used for assembly are part of an extended supply chain. The downstream of that supply chain is the activities that are executed at the construction job site. This arrangement results in multiple supply chain members with associated uncertainties that place unique challenges to the project team given the temporary nature of the construction projects. The problems arising due to the involvement of multiple supply chains affect more than their respective domains as they are the basis for many disruptions that occur during construction, resulting in high failure costs due to rework and time delays (Van Vught & Van Weele, 2015).

Ekeskär and Rudberg (2016) mentioned that supply chains exist whether they are managed or not. Thus, there is a distinction between supply chains as typical procedure of business and the management of the said supply chains. Supply Chain Management (SCM) is thus related with the prefabrication process. Uncertainties exist in the prefabrication supply chain as a result of which the on-site construction process has to stop and wait. It is a challenge for the risk managers to ascertain the potential uncertainties in the supply chain while finding appropriate methods to cope with them not to affect one or more of the project objectives: time, cost, quality, scope, or safety (Arashpour *et al.*, 2016). The construction industry is witnessing problems in managing the supply chain and the required integration in construction processes (Bankval *et al.*, 2010). With the increasing use of prefabrication in construction projects, managing the risks associated with the supply chains is critical to achieving the project objectives. Few studies have identified the uncertainties associated with using prefabrication in construction projects (Chopra & Sodhi, 2004; Arashpour *et al.*, 2016), but none so far has focused on measuring the disruptions occurring due to the uncertainties of the supply chain of the prefabrication process.

This paper aims to bridge the gap by offering a framework to manage operational disruption risk in the prefabrication supply chain of a construction project. The need to manage operational risk is addressed by proposing a conceptual framework to measure disruption risks based on risk exposure model that can evaluate the impact of a disruption originating anywhere in the supply chain. This approach allows identifying the effect of a disruption on the progress of a project before estimating the probability associated with that disruption helping risk managers in making informed decisions about where to focus their limited resources. The paper summarises the uncertainties associated with on-site construction and prefabrication and briefly describes the supply chain networks specific to construction projects. Subsequently, the paper presents the proposed framework based on the risk exposure model and a pilot case study conducted to test the model.

UNCERTAINTIES IN CONSTRUCTION SUPPLY CHAIN

During construction, various processes occur, such as material ordering, transportation, delivery, storage, staging, and moving around materials, which are part of the on-site logistics (Skjelbred *et al.*, 2015). The construction process is dynamic; expectations of having day-to-day changes in the processes are common (Zolfagharian & Irizarry, 2014), creating disruptions in the process flow. Ineffective management of these disruptions results in unnecessary costs, delays, and increased work errors (Sundquist, Gadde, & Hulthén, 2018).

Lange and Schilling (2015) identified the basic challenges of on-site logistics as the variability in production and supply systems. In a production system, the supply chain demonstrates variances from provisions as well as requirements. Disruptions in the on-site construction activities can be caused by, but not restricted to missing or delayed deliveries, inefficient storage space management, installation of wrong or damaged material, and insufficient separation of waste.

Uncertainties related to on-site construction logistics can be due to space allocation and material (Zolfagharian & Irizarry, 2014). These uncertainties can cause disruptions that negatively affect the productivity of a construction site as they occur due to insufficient planning. However, they can be eliminated or reduced by focusing on-site logistics planning at an early stage. Site logistics planning is primarily affected by the supply chain of the materials required for the project. There are different types of uncertainties under the space allocation category, including site layout planning, space allocation for construction activities, and spaces required for storage. Uncertainties related to material include required conditions of storage and materials delivered per specification (Sundquist, Gadde, & Hulthén, 2018).

Site layout planning is unique for each construction project as it depends on many variables. The challenge in optimising the site layout plan is to account for the various constraints such as the location of the project, accompanying facilities, and shape of the construction site. Site planners normally approach site facilities as rectangular blocks for easier positioning on a construction site. Such an approach creates an unequal area for construction within the site layout (Zolfagharian & Irizarry, 2014).

Construction activities require space allocation processes that consume funds and time. Conflicts regarding time-space allocation create problems such as constructability issues or delays in the construction process (Zolfagharian & Irizarry, 2014). Also, building materials require large storage space that is seldom available in construction sites. The storage conditions of materials often lead to damage due to access of water, movement of people, and

equipment. The delivered materials might not meet the required specifications and must be sent back or reordered, affecting the assembly flow. Furthermore, materials might be ordered late in the construction processes resulting in delays, while buying large quantities of materials might lead to waste (Sundquist, Gadde, & Hulthén, 2018).

Logistics affect the reliability of workflow as well as labour productivity; both are key metrics for labour performance (Seppänen & Peltokorpi, 2016). Inefficient supply and flow of construction material is stated to be a major cause for productivity and financial losses (Said & El-Rayes, 2010). Lack of material should never affect the flow in production processes. However, this does not imply that all material must be ordered early in the construction process and stored on site. Instead, the material should arrive just in time to the construction site (Skjelbred *et al.*, 2015).

Inventory buffer, whether it be on-site or offsite location, impact the workflow reliability. Inventory stored on-site reduces available space and might interfere with ongoing work tasks, thus impacting labour productivity. For instance, if the storage location is close to the area where work is being performed, it decreases material transfer and increases skilled labour productivity (Seppänen & Peltokorpi, 2016). Similarly, ordering small quantities of materials frequently reduces locked capital in material inventory. However, it increases material shortage chances leading to project delays. On the other hand, ordering large quantities of materials at once decreases material shortage possibility, but it increases the capital funds on material inventory (Said & El-Rayes, 2010). The balance between on-site material buffers and just in time deliveries can be achieved by evaluating conditions such as on-site storage capacity, distance to the supplier, lead time, and level of detail in the plans (Skjelbred *et al.*, 2015).

Supply Chain Disruptions

Problems in the supply chain can arise from various sources; some of these sources are labour disputes, supplier financial issues, natural disasters, and acts of war. These problems can disrupt or delay material, information, and cash flows affecting the project objectives. Supply chain risks are categorised into delays, disruptions, inaccurate forecast, system breakdown, procurement failure, inventory problems, and capacity issues, with each category having its drivers and mitigation strategies (Chopra & Sodhi, 2004).

Disruption risks can either be frequent or infrequent, short or long term, and will cause problems in the supply chain, ranging from minor to severe (Chopra & Sodhi, 2004). For instance, a transportation delay along the supply chain may create a temporary risk, while a sole supplier holding up material to force a price increase represents a long-term risk. A machine breakdown is not severe when there is excess inventory, but a war that disrupts transportation will significantly affect a project. Traditional methods for managing supply chain risks depend on knowing the likelihood of occurrence and the magnitude of impact for all scenarios that can materially disrupt the flow of operations (Simchi-Levi, Schmidt & Wei, 2014). Chopra and Sodhi (2004) mentioned that a company manages risks depending on the type of disruption and the level of preparedness. Probability-impact models are based on project size and the ability of the organisation to react to the risk and typically assign resources to high probability, high impact risks. The identified project risks are prioritised and rated for further analysis.

Disruptions arising from offsite uncertainties can be due to coordination between on-site and offsite activities. Offsite activities by themselves can also cause disruptions due to

uncertainties from delays, procurement, capacity, available resources, and equipment failure. Inaccurate demand forecasting is typically due to long lead times, seasonality, product variety, and a changing customer base size. Inaccurate forecasting leads to a mismatch between available resources and available work. Resources include services, material, and manpower. If the demand forecast is too low, available resources will be less than available work. In the same way, if demand forecast is too high, available resources will be more than available work (Chopra & Sodhi, 2004).

The start date for the prefabrication processes is dependent on the schedule of on-site activities. If the on-site activities are behind schedule, the prefabricated elements will not be installed based on the original schedule, and inventory will build up at the prefabrication site, creating congestion and disrupting the prefabrication process. In the same manner, if the on-site activities are ahead of schedule, they will have to stop and wait for the prefabricated elements to be installed to resume work (Arashpour *et al.*, 2016). The transportation of prefabricated elements at the right time is key for keeping the project on track and avoiding delays (Chopra & Sodhi, 2004). Prefabrication processes are carried out offsite in a controlled environment and are typically done in large quantities. Any dimensional and specification discrepancies in the prefabrication process will result in rework leading to delays. When the prefabrication processes are not compliant with on-site requirements, the products are sent back to be modified and, in some cases, scrapped (Arashpour *et al.*, 2016).

Delays in raw material flow will disrupt the prefabrication process. Raw material delays can happen for several reasons. Often delays are attributed to the raw material supplier and their ability to respond to change in demand or the quality of their output. Other reasons include amount of material handling, inspections required at border crossings or checkpoints, and changing transportation modes during shipping (Chopra & Sodhi, 2004). Procurement uncertainty is a result of an unanticipated increase in acquisition costs. If the raw material cost outweighs the savings and profit from prefabricating, the entire prefabrication processes will stop and look for alternatives resulting in delays (Chopra & Sodhi, 2004).

Capacity in the prefabrication process refers to available resources and space. Inventory can be increased in a single order; however, capacity can only be increased or decreased over a period of time. Increasing the capacity of the prefabrication process requires time and cost, if there is an excess capacity then there are unutilised resources leading to poor financial performance. On the other hand, if there is no more capacity for the prefabrication process, delays can be expected as the queue of processes increase (Chopra & Sodhi, 2004). Available resources are categorised into critical and dedicated resources. In any prefabrication process, equipment and material are considered critical resources; meanwhile, operators (manpower) are considered dedicated resources. If there is not enough dedicated resources, the prefabrication processes will suffer delays (Arashpour *et al.*, 2016). If a piece of equipment fails, there will not be enough dedicated resources resulting in delays and lost time (Arashpour *et al.*, 2016).

The interaction of uncertainties in construction projects that adopt prefabrication and its consequence on the project planning remains an overlooked area of research in the construction literature (Arashpour *et al.*, 2016). Therefore, a holistic analysis of uncertainty and an integrated risk management approach are required to increase the project plan reliability of such projects.

RESEARCH OBJECTIVE

The specific objective of the study was to identify the disruption risks in the prefabrication process and being able to measure it. This paper presents a conceptual disruption risk model based on risk exposure that will facilitate in measuring the disruption risk in the supply chain of prefabrication.

Project risk management is a methodical approach to identify, analyse, respond, and control risks, aiming to increase the likelihood and impact of positive results, and reduce the negative results (Arashpour *et al.*, 2016). Project risk identification uses various tools and techniques such as checklist analysis, documentation reviews, assumption analysis, diagramming techniques, and expert judgment (Arashpour *et al.*, 2017). Risks are rated and prioritised based on their occurrence probability and impact on project objectives. Probability-impact models are designed based on project size and the ability of the organisation to react to the risk, and typically assign resources to high probability, high impact risks. In terms of tools and techniques, additional dimensions have been added to the traditional probability–impact model of risk analysis. These dimensions include but are not limited to: the risk exposure extent (Jannadi & Almishari, 2003), risk manageability level (Aven, Vinnem, & Wiencke, 2007; Chan *et al.*, 2015), the influence of the surrounding environment and interdependencies among risks (Zeng, An, & Smith, 2007), and risk significance (Han *et al.*, 2008). These added dimensions aim to improve the traditional probability-impact model to better analyse the interacting risks in projects.

A disruption risk model evaluates the impact of a disruption originating anywhere in the supply chain, allowing the opportunity to know the effect of a disruption on the project progress before estimating the probability associated with that disruption. This approach helps risk managers make an informed decision about where to focus their limited resources by emphasising the impact of a disruption. This is because the impact of disruption depends on its duration rather than the cause. Also, the potential mitigation actions in response to a supply chain disruption are often the same regardless of the cause (Simchi-Levi *et al.*, 2015).

Analysis of the risk exposures of the supply chain nodes allows prioritising resource allocation; the analysis can be combined with the total spending at different nodes. This combination allows for developing different mitigation strategies for different nodes (Simchi-Levi *et al.*, 2015).

Disruption Risk Model

The disruption risk model is a novel risk exposure model that assesses the impact of a disruption originating anywhere in the supply chain of the prefabrication process. This model is unique to the construction industry as supply chains are temporary and project-based. The temporary nature of the construction supply chains makes them have limited demand and focus on accomplishing short-term goals (Behera *et al.*, 2015). In a typical construction project, the primary objective is to meet the final product demand with no regard to the time it takes to build up inventory levels to reach that final demand. The project-based approach for the supply chain that is conceptualised based on the project's temporary nature emphasises the final product demand. In most cases, the supply chain starts and ends with a specific project (*Behera et al.*, 2015). Thus, the uncertainties of these supply chains are difficult to identify. Uncertainties with low visibility can make supply chains vulnerable to unforeseen disruptions (Park, Min, & Min, 2016). The disruption risk model acts as a

tracking method of the time-period and product inventory accumulated to reach the final demand. The disruption risk is expressed as a ratio representing the impact of a disruption originating anywhere in the supply chain on the prefabrication operations. Therefore, project team members can analyse the impact of a disruption on the project objectives at any time yielding significant information for risk managers. Nodes with a low disruption risk value indicate that minimal impact on performance will occur in case of a disruption. Therefore, that node is not exposed to a risk that needs to be addressed.

In the same way, nodes with a high disruption risk value indicate that in case of a disruption, a significant impact on performance will occur, and that node is a risk that needs to be addressed. The disruption risk value can help recognise potential waste and excessive protection within the supply chain. Therefore, some common risk-mitigation strategies may lead to unnecessary resource allocation at low-exposure nodes and inadequate protection at high-exposure nodes.

Simchi-Levi *et al.* (2015) stated that any supply chain is exposed to a range of low-probability, high-impact risks that can disrupt their flow. This type of risks is difficult to manage as it is hard to predict and calculate (Cardoso *et al.*, 2014). It is difficult to identify these risks due to low visibility. Park *et al.* (2016) proposed that the occurrence of supply chain disruptions can be mitigated by inventory buffer and application of policies and procedures. While maintaining inventory buffer can be applicable to construction projects, development and application of policies to protect supply chain from disruptions are difficult due to the temporary nature of the construction supply chains. As a result, risk managers may employ countermeasures that leave their project or company exposed to significant risks while wasting resources to address other risks that cause minimal damage and disruption in the supply chain. In the event of a disruption, the construction production system might not immediately stop and display a negative impact on the project outcome(s).

RESEARCH APPROACH

A deductive approach was adopted for this study. It is advised by Stainton (2017) that with a deductive approach, a researcher begins with a theory and progresses onto research questions or a hypothesis, which is subsequently tested utilising data collection. In this study, the researchers developed a framework based on the disruption risk model explained previously. To develop the model, data was gathered from three sources: interviews with industry professionals, direct observation during site visits, and investigation of archival data of the participating firms. Eight industry professionals, from the authors' known circle, who had at least five years of experience working with prefabrication, were chosen for the interviews. The sample size selected for the semi-structured interview is determined through convenience sampling. Sincero (2015) advised that this non-probability sampling method is generally applied where the data is collected from a target population who are conveniently available to partake in the research. Although convenience sampling is often discouraged for research, in this situation there was convenient access to five construction professionals, who had previous experience of working with prefabrication, therefore convenience sampling to this element of research is justified. Five interviewees representing three different general contractors and three interviewees working for two different specialty trade contractors were interviewed. Further, information to develop the framework was collected by visiting offsite prefabrication facilities and construction jobsites of the participating contractors. Developing the framework was an iterative process of collecting data through interviews, visiting on-site and offsite prefabrication facilities, extracting and comparing information from archival data

of past projects, analysing the data to develop the framework, and getting the framework evaluated by the participants. To ensure consistency of the information, triangulation of data sources was used.

Semi-structured interviews included questions on the following items: (1) decision making process to adopt prefabrication, (2) impact of prefabrication on project's time, cost, and quality, and (3) process of prefabrication and details of the supply chain. From the interviews, it was evident that mostly the subcontractors were responsible for assembling the prefabricated components and delivering to the job site under the supervision of the general contractor. The interviewees were asked details of the supply chain, including the following: (1) number of material suppliers involved, (2) number and lead time of shipments, (3) location of manufacturing facilities, (4) crew members and production rate, (5) location of storage facilities, (6) quantities and frequency of shipments, and similar. On-site and offsite prefabrication facilities were visited to gather information on the composition of crews working on prefabricated components and their production rates. To verify consistency of the information collected through interviews and site visits, archival data from past projects where prefabrication was adopted, were examined. The information obtained from the three sources of data were used to develop the framework that represents the flow of information and processes required in the prefabrication process.

The Framework of the Model

The supply chain of a prefabricated component in its most generic form is shown below in figure 2; the links between the general contractor and the first-tier subcontractors have been shown. As these subcontractors are contractually obligated to the general contractor, the general contractor closely manages the links. The linked subcontractors can go past the first tier; however, in most cases, the general contractor has contractual relationships with only the first-tier subcontractors. Also, the suppliers to the first-tier subcontractors have no direct contractual obligations towards the general contractor. Thus, the links between the suppliers and the subcontractors are shown as non-managed links in Figure 3. The interviews revealed that most of the raw materials required for the assembly of commonly prefabricated components are directly delivered to the assembly point (offsite prefabrication facility) from the supply houses or manufacturers.

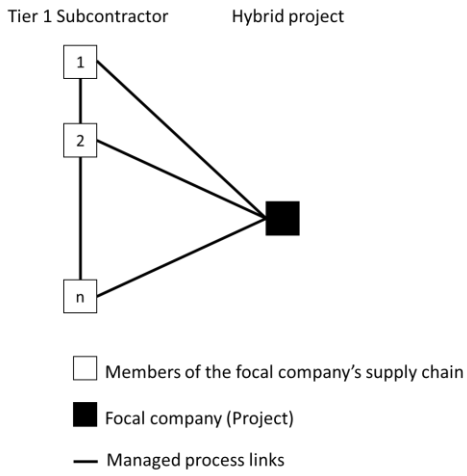


Figure 2: Supply chain of typical prefabricated component

The model shows the SCN as the sequence of activities required for the prefabrication process, which consisted of three phases. The first phase is contacting the material suppliers and delivering the materials to the point of assembly. The second phase is assembling and the third phase is transporting the finished products to the job site. Each phase consists of inputs, processes, outputs and time constraints. The primary challenge faced in developing the model was to account for the time constraints between processes and phases. This challenge was addressed by establishing a time unit of one week and adding a time loop for each phase to capture the elapsed time accurately.

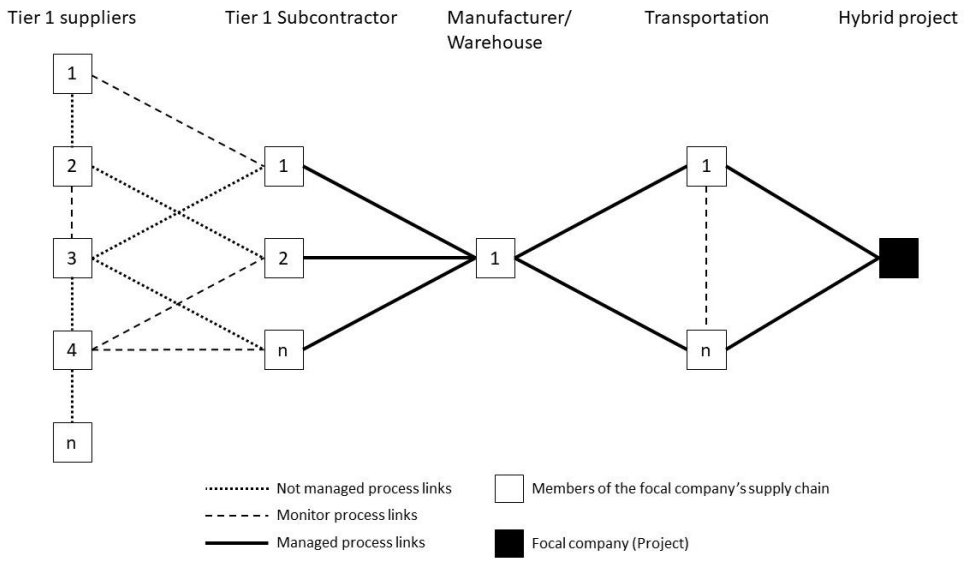


Figure 3: Supply chain of typical prefabricated component

For the first phase, the model requires three inputs: material lead time, material quantity take-off, and the delivery quantity each time. As for the processes, two processes take place. The first is a count for the delivered material each time unit, as shown in Equation 1. The second process calculates the material disruption risk value each time, as shown in Equation 2.

$$\sum_i Delivered\ quantity = \sum_i Delivered\ quantity + Delivery\ quantity_i \quad (1)$$

$$Material\ disruption\ risk\ factor = \frac{(Quantity\ takeoff_i - \sum_i Delivered\ quantity)}{Quantity\ takeoff_i}\ \% \quad (2)$$

A decision variable shown in Equation 3 controls the time loop for the first phase. If the decision variable is not met, the time loop is activated, and another time unit is added to the time count. If the decision variable is met, then the model continues to the second phase.

$$\sum_i Delivered\ quantity \geq Quantity\ takeoff_i \quad (3)$$

The outputs of the first phase are the material disruption risk value each time and the total time required to reach the material take-off. It is important to note that phase two does not require the decision variable in phase one to be satisfied before starting the activities in phase

two. The decision variable is set to ensure that material quantity take-off is met and the time to reach the take-off is accounted for.

As for the second phase, two inputs are required for the model, the number of finished products required by the project and the desired production rate. The production rate is assumed to be constant throughout the prefabrication process. Prefabrication processes are assumed to begin after the first delivery of material. Two processes are included in this phase. The first process calculates the number of finished products at a specific time according to Equation 4. The second process calculates the production disruption risk each time, as shown in Equation 5.

$$Finished\ product = Production\ rate\ \times time\ units \tag{4}$$

$$Production\ disruption\ risk\ factor = \frac{(Quantity\ of\ finished\ product - Finished\ product)}{Quantity\ of\ finished\ product}\ \% \tag{5}$$

A decision variable shown in Equation 6 controls the time loop for the second phase. If the decision variable is not met, the time loop is activated, and another time unit is added to the time count. If the decision variable is met, then the model continues to the third phase.

$$Finished\ product\ \geq Quantity\ of\ finished\ product \tag{6}$$

The outputs of the second phase are the production disruption risk value each time and the total time required to reach the number of finished products. It is important to note that the production rate is a variable that can be manipulated to adjust the time required for production. Also, phase three requires the decision variable in phase two to be satisfied before starting the activities in phase three. The decision variable is set to ensure that quantity of finished product is satisfied, and the time it took to reach that quantity is accounted for.

As for the third phase, the total quantity is taken from the quantity of finished product in phase two. One input is required for the model, which is the transportation quantity each time. The transportation is done according to the installation rate assumed by the project team. As for the processes, two processes are considered. The first is a count for the delivered products each time, as shown in Equation 7. The second process computes the transportation disruption risk value each time, as shown in Equation 8.

$$\sum_k Delivered\ product = \sum_k Delivered\ product + transportation\ quantity_k \tag{7}$$

$$Transportation\ disruption\ risk\ factor = \frac{(Quantity\ of\ finished\ product - \sum_k Delivered\ product)}{Quantity\ of\ finished\ product}\ \% \tag{8}$$

A decision variable shown in Equation 9 controls the time loop for the third phase. If the decision variable is not met, the time loop is activated, and another time unit is added to the time count. If the decision variable is met, the model ends.

$$\sum_k Delivered\ product = Quantity\ of\ finished\ product \tag{9}$$

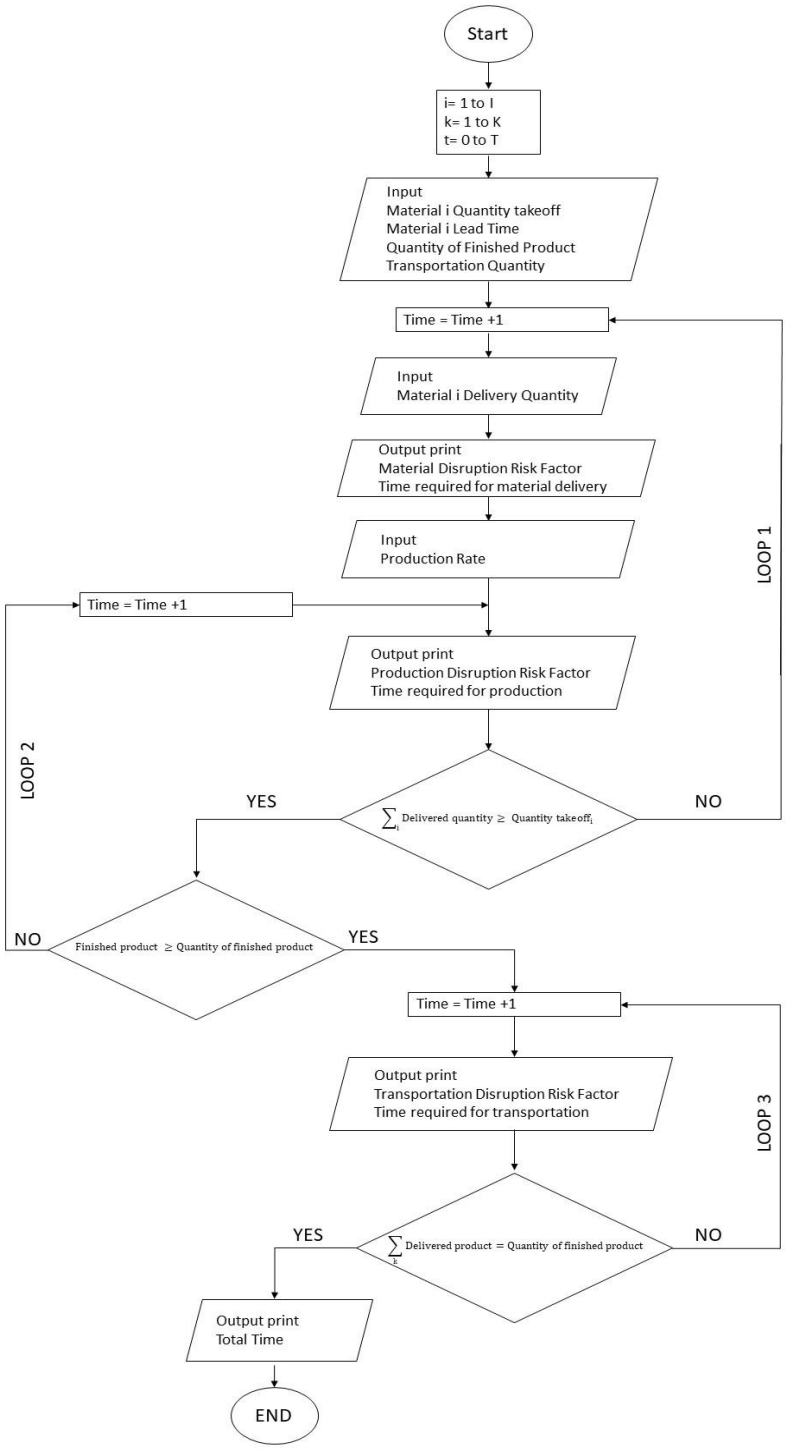


Figure 4: Conceptual model of the prefabrication supply chain

The outputs of the third phase are the transportation disruption risk value each time and the total time required to transport the number of finished products. An output of the whole model is a graph of the project disruption risk value, and the total time required from the start of the model to the end; this is calculated by Equation 10. Figure 7 illustrates the developed model.

$$Total\ time = Material\ lead\ time + Production\ time + Transportation\ time \quad (10)$$

Pilot Case Study

A pilot case study was conducted to evaluate the efficacy of the proposed model. A healthcare project that involved the addition of a new five-story building, totaling 168,000 square-feet with an estimated cost of $71 million and an estimated duration of 20 months was selected for the pilot case study. The project team decided to prefabricate the headwalls of patients' rooms in an offsite facility. The prefabricated headwalls were to have all the electrical and mechanical rough-ins required for the installation of medical equipment. The team took three months to finalise the mock-ups that involved coordination of multiple subcontractors, including the carpenter, framer, mechanical, and electrical contractors.

The electrical subcontractor's facility was used for the purpose of assembling as well as storing the prefabricated headwalls. The offsite prefabrication facility was located 10 miles away from the job site with an approximate floor area of 1000 square-feet. There were four types of headwalls as shown in Figures 5a-5d with a total count of 85 units needed for the pilot project. The scope of work consisted of framing using pre-cut metal studs, installing medical gas piping and connections, installing electrical and low voltage piping and connections, and installing wood blocking. All the required materials were delivered to the assembling facility. Each of the subcontractors had a crew assigned to the assembling facility; crew sizes were two framers, two pipefitters, four electricians, and one carpenter. From the mock-ups, the headwall production rate was found to be four completed units per week.

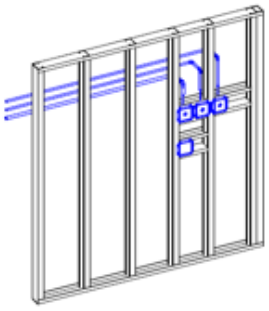


Figure 5a – Prefabricated headwall Type A

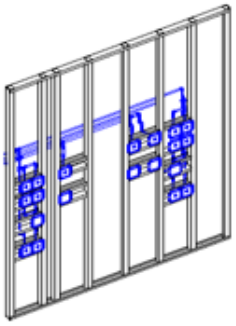


Figure 5b – Prefabricated headwall Type B

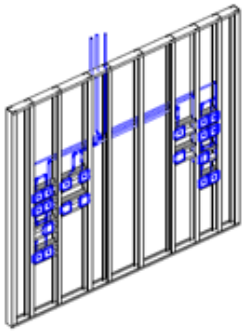


Figure 5c – Prefabricated headwall Type C

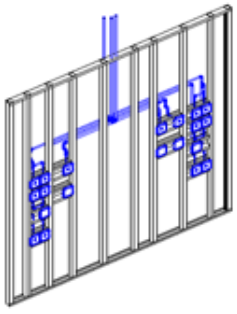


Figure 5d – Prefabricated headwall Type D

Applying the Model to the Pilot Project

The pilot project consisted of a forward supply chain with limited demand from the project. The supply chain was comprised of four levels: 1) raw-material suppliers, 2) facility where assembling and storing took place, 3) transportation, and 4) the job site installation. The quantitative data inputs required for the model were acquired from the project team. The inputs consisted of 1) material lead time, 2) material quantity take-off, 3) material delivery quantity, 4) headwall take-off, 5) production rate, 6) transportation quantity. The next section shows the screens in which these inputs are used to run the model.

For the model to calculate the material disruption risk value associated with each period, the user is required to input the material lead time, material quantity take-off, and material order quantity. Figure 6 shows an example of information for metal studs the user needed to provide. For the pilot project, material lead time was two weeks, material quantity take-off was 6000 LF of metal studs, and the first order was going to be for the entire quantity of 6000 LF. In this example, the material was going to be delivered at once; the disruption risk value was zero indicating there was no disruption risk. Once the information for all the required materials for the prefabricated headwalls was populated, the model computed the disruption risk for that period.

Material Supply

Material 1		Metal studs	
Material Lead Time	=	2	Week
Material Quantity Takeoff	=	6000	LF

Material Orders		
Material Order1	=	6000
Done	=	
Supply Time	=	1

Disruption Risk factor
0%

Figure 6: Information related to materials provided by the users

After providing information on required materials, the user is required to input the production quantity and the production rates. Once the required fields are populated, the model calculates the production disruption risk value associated with each period as shown in Figure 7. The figure shows that 85 headwalls could be prefabricated at an expected production rate of four completed units per week. In this case, there were 22 time periods (weeks) for the entire production process. The disruption risk value decreased each time until it reached a value of zero. The model requires the user to input the desired batch size per delivery. Subsequently, the model calculated the transportation disruption risk value associated with each period. Figure 7 shows the total number of headwalls to be delivered over five weeks.

Production				
Production Quantity Takeoff		=	85	unit
Production Rate		=	4	Week
Production Batch				Disruption Risk factor
1	=	4		95%
2	=	8		91%
3	=	12		86%
4	=	16		81%
5	=	20		76%
6	=	24		72%
7	=	28		67%
8	=	32		62%
9	=	36		58%
10	=	40		53%
11	=	44		48%
12	=	48		44%
13	=	52		39%
14	=	56		34%
15	=	60		29%
16	=	64		25%
17	=	68		20%
18	=	72		15%
19	=	76		11%
20	=	80		6%
21	=	84		1%
22	=	85		0%
Done	=			

Transportation			
Transportation Quantity Needed	=	85	unit
Transported quantinty			Disruption Risk factor
Transportation 1	=	20	76%
Transportation2	=	20	53%
Transportation3	=	20	29%
Transportation4	=	20	6%
Transportation5	=	5	0%
Transportation Time	=	5	

Figure 7: Information related to production rates and batch sizes provided by the users

After all the input fields are populated, the model presented a graph of the project disruption risk, as illustrated in Figure 8. Additionally, the model computed the total time required for the entire prefabrication process from ordering materials to receiving the prefabricated headwalls at the job site.

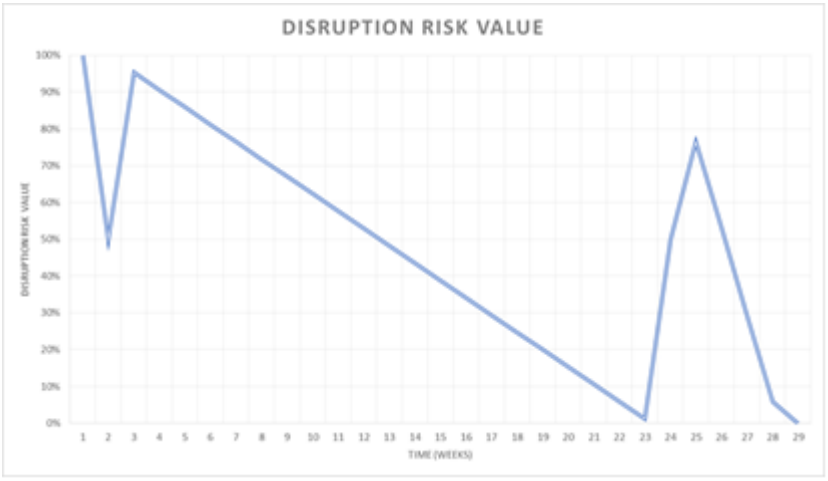


Figure 8: Disruption risks of the prefabrication process for the pilot project

For the pilot project, the disruption risk was 100% in week one, which decreased to 50% during week two. The disruption risk value increased from week two to four from 50% to 95%. After that, the disruption risk value decreased from week four to week 23 from 95% to 1%. The risk increased again from week 23 to 25 to reach a value of 80%. Finally, the disruption risk value decreased from week 25 to 29, reaching zero. The fluctuation in disruption risk value was a result of risk transfer between tasks. The first increase was at week two, where the material supply activity was finished, making the disruption risk value zero.

Meanwhile, the production tasks started at week two with a disruption risk value of 95%, resulting in a disruption risk value of 50%. At week three, the only disruption risk was from the production activity with a value of 91%. The same was applicable for the time period from week 23 through 26, where the production tasks were completed and the transportation tasks started.

DISCUSSION

The current study proposed a framework to identify the effect of disruptions in the supply chain of prefabricated components used in construction projects. Prefabrication is adopted in construction projects to reduce the variabilities of on-site production. As temporary supply chains characterise construction projects, it is crucial to manage the supply chains. Existing studies have identified uncertainties in the prefabrication supply chain. The proposed framework conceptualised the prefabrication supply chain as a network of nodes and links, and an algortim to compute the disruptions. As the prefabrication process converges with the on-site production during the installation of the prefabricated components, inaccurate forecast can lead to mismatch between on-site production and prefabricated logistics (Chopra & Sodhi, 2004). Based on the production rate of the crews and the time taken to transport the prefabricated components, the proposed model enables calculation of the overall duration of the process with possible disruptions at each phase. In the pilot project, based on the model's output, the project team could allocate 37 weeks for the entire process, broken into two weeks for material lead time, 30 weeks for the prefabrication processes, and five weeks for the transportation. This information was important for planning purposes as the prefabrication processes' start dates were interdependent with on-site activities.

After providing the required inputs, the model could compute the disruption risks in the process. A linear relationship was found between the disruption risk values of the process and the time to finish that process, attesting to the temporary nature of the construction supply chains. The disruption risk values decreased as the activities approached completion. However, at the same time an activity was completed, a new activity started with a high disruption risk value resulting in a sudden increase in the disruption risk of the project; the increase was a result of risk transfer between activities.

Schedule changes of on-site activities can demand adjustment of the prefabrication supply (Arashpour *et al.*, 2016), which can be modelled in the proposed model. Based on the real time information, the model could inform the project team about probable disruptions due to any modification in the process. In the case of the pilot project, the prefabricated headwalls were stored at the offsite facility for an additional eight weeks before they could be installed at the job site. The project team could have saved the extra cost of storing the headwalls and used that time for modifications or mock-ups by better planning. The project team’s best

chance to modify the total time for the prefabrication process was by controlling the production rate in the process. The production process times could be shortened by increasing the production rate.

CONCLUSION

The study aimed to develop a model to identify and measure the disruption risks in the prefabrication process by investigating the risk exposure inherited from uncertainties in the supply chain. Developing the framework of the model was an iterative process of collecting data through interviews, visits to on-site and offsite prefabrication facilities, extracting and comparing information from archival data of past projects, analysing the data to develop part of the framework and getting it evaluated by the participants. The framework of the model has been presented in Figures 2 through 4. While Figures 2 and 3 present the components of the typical supply chains, Figure 4 shows the detailed framework with the nodes and links. The proposed model was evaluated by conducting a pilot case study. The pilot project was a healthcare project budgeted around $71 million where the project team decided to prefabricate the headwalls of patients' rooms.

Based on the findings, the model offered a better opportunity for the project team to identify disruption risks and expose uncertainties that might have affected the project objectives or construction schedule. The model uncovered two significant uncertainties. The first is when to start the prefabrication processes, and the second is the required production rate to meet the schedule. The model identified the optimal time for starting the prefabrication process by identifying the time required for each activity in the entire prefabrication process. Moreover, the model enabled the tracking of progress for the prefabrication process by comparing the planned period to the actual time spent on that activity or by comparing the planned production rate to the actual production rate. Additionally, the model facilitated information coordination across disciplines more effectively, aiding in decision-making and problem-solving processes.

Traditionally, supply chain risks in the construction industry are managed by first identifying the likelihood of occurrence and the magnitude of impact, followed by preparing to reduce or eliminate the cause of disruption based on the type of disruption and the level of preparedness. Probability-impact models are based on project size and the ability of the organisation to react to the risk and typically assign resources to high probability, high impact risks. However, this approach may overlook the risks with low probability and high impact disruptions. The model contributes to current construction practices by accurately capturing the prefabrication supply chain, including its members, structural configuration, and process links among members. The model assesses the impact of a disruption originating anywhere in the supply chain. The model also identifies potential disruption risks that can significantly affect project performance, helping risk managers allocate resources more judiciously. Based on the findings, the model provides information on supply chain disruptions by computing the disruption risk value for all activities involved in the prefabrication process throughout the prefabrication process. This information identifies a project's exposure to a disruption risk at any given time.

There were a few limitations in the pilot case study conducted to evaluate the efficacy of the proposed disruption risk model. The deductive research method used for this study requires

subsequent testing of the model by data collection. The proposed model could only be evaluated on one pilot project. Findings from one pilot project is not enough to validate the efficacy of the proposed model. Moreover, the supply chain of the pilot project was limited to the headwall prefabrication supply chain. Limitations of headwall prefabrication supply chain consisted of a short supply chain with a small number of tiers and key members. The supply chain products were general commodities that can be found from multiple sources. This reduced the vulnerability of the supply chain. The supply chain influenced the study results as different supply chains have different practices, configurations, and products. Finally, the lack of historical data on this kind of investigation could be considered a study limitation.

ACKNOWLEDGEMENTS

We would like to thank the project team of McCarthy Building Companies who worked on the Oklahoma Heart Hospital, Super West Expansion to allow us to conduct the pilot study. We thank the project team for all the useful suggestions that helped us modify and improve the model.

REFERENCES

Arashpour, M., Abbasi, B., Arashpour, M., Hosseini, M.R., & Yang, R. (2017). Integrated management of on-site, coordination and offsite uncertainty: Theorizing risk analysis within a hybrid project setting. *International Journal of Project Management*, *35*(4), 647-655. https://doi.org/10.1016/j.ijproman.2017.02.016

Arashpour, M., Wakefield, R., Lee, E.W.M., Chan, R., & Hosseini, M.R. (2016). Analysis of interacting uncertainties in on-site and offsite activities: Implications for hybrid construction. *International Journal of Project Management, 34*(7), 1393-1402. https://doi.org/10.1016/j.ijproman.2016.02.004

Arashpour, M., & Wakefield, R. (2015). Developing an uncertainty analysis model for offsite building production. In: ISEC-08: Implementing Innovative Ideas in Structural Engineering and Project Management (pp. 1121-1125). ISEC Press. https://doi.org/10.14455/ISEC.res.2015.7

Arashpour, M., Wakefield, R., Blismas, N., & Minas, J. (2015). Optimization of process integration and multi-skilled resource utilization in offsite construction. *Automation in Construction, 50*, 72-80. https://doi.org/10.1016/j.autcon.2014.12.002

Almohsen, A. & Ruwanpura, J. (2011). Logistics management in construction industry. Proceeding of the International Council for research and Innovation in Building and construction (CIB), p.10.

Aven, T., Vinnem, J.E., & Wiencke, H.S. (2007). A decision model for risk management, with application to the offshore oil and gas industry. *Reliability Engineering & System Safety, 92*(4), 433-448. https://doi.org/10.1016/j.ress.2005.12.009

Bankvall, L., Bygballe, L.E., Dubois, A., & Jahre, M. (2010). Interdependence in supply chains and projects in construction. *Supply Chain Management: An International Journal*, *15*(5), 385-393. https://doi.org/10.1108/13598541011068314

Behera, P., Mohanty, R.P., & Prakash, A. (2015). Understanding construction supply chain management. *Production Planning and Control*, *26*(16), 1332-1350. https://doi.org/10.1080/09537287.2015.1045953

Cardoso, S. R., Barbosa-Póvoas, A.P.F., Relvas, S., & Novais, A.Q. (2014). Resilience assessment of supply chains under different types of disruption. *Computer Aided Chemical Engineering*, *34*, 759-764. https://doi.org/10.1016/B978-0-444-63433-7.50111-5

Carvalho, H., Barroso, A.P., Machado, V.H., Azevedo, S., & Cruz-Machado, V. (2012). Supply chain redesign for resilience using simulation. *Computers and Industrial Engineering*, *62*(1), 329-341. https://doi.org/10.1016/j.cie.2011.10.003

Construction, M. H. (2011). Prefabrication and modularization: Increasing productivity in the construction industry. Smart Market Report.

Chan, R. W., Yuen, J. K., Lee, E. W., & Arashpour, M. (2015). Application of Nonlinear-Autoregressive-Exogenous model to predict the hysteretic behaviour of passive control systems. *Engineering Structures*, *85*, 1-10. https://doi.org/10.1016/j.engstruct.2014.12.007

Chopra, S., & Meindl, P. (2007). Supply chain management. Strategy, planning & operation. In Das summa summarum des management (pp. 265-275). Gabler. https://doi.org/10.1007/978-3-8349-9320-5_22

Chopra, S., & Sodhi, M. S. (2004). Managing risk to avoid supply-chain breakdown. *MIT Sloan Management Review*, *46*(1), 53.

CSCMP (2013), Supply chain management definitions and glossary [Online], Council of Supply Chain Management Professionals (CSCMP), Available: http://bit.ly/1sYBIlP [Accessed: 26th of February 2016].

Ekeskär, A., & Rudberg, M. (2016). Third-party logistics in construction: The case of a large hospital project. *Construction Management and Economics*, *34*(3), 174-191. https://doi.org/10.1080/01446193.2016.1186809

Elleuch, H., Dafaoui, E., Elmhamedi, A., & Chabchoub, H. (2016). Resilience and vulnerability in supply chain: Literature review. *IFAC-PapersOnLine*, *49*(12), 1448-1453. https://doi.org/10.1016/j.ifacol.2016.07.775

Govindan, K., Fattahi, M., & Keyvanshokooh, E. (2017). Supply chain network design under uncertainty: A comprehensive review and future research directions. *European Journal of Operational Research*, *263*(1), 108-141. https://doi.org/10.1016/j.ejor.2017.04.009

Hamzeh, F.R., Tommelein, I.D., Ballard, G., & Kaminsky, P. (2007, July). Logistics centers to support project-based production in the construction industry. In Proceedings of the 15th Annual Conference of the International Group for Lean Construction (IGLC 15) (pp. 181-191).

Han, S.H., Kim, D.Y., Kim, H., & Jang, W.S. (2008). A web-based integrated system for international project risk management. *Automation in construction*, *17*(3), 342-356. https://doi.org/10.1016/j.autcon.2007.05.012

Hosseini, S., Barker, K., & Ramirez-Marquez, J.E. (2016). A review of definitions and measures of system resilience. *Reliability Engineering and System Safety, 145*, 47-61. https://doi.org/10.1016/j.ress.2015.08.006

Jannadi, O.A., & Almishari, S. (2003). Risk assessment in construction. *Journal of Construction Engineering and Management, 129*(5), 492-500. https://doi.org/10.1061/(ASCE)0733-9364(2003)129:5(492)

Lambert, D.M., & Cooper, M.C. (2000). Issues in supply chain management. *Industrial Marketing Management, 29*(1), 65-83. https://doi.org/10.1016/S0019-8501(99)00113-3

Lange, S., & Schilling, D. (2015). Reasons for an optimized construction logistics. In Proceedings of the 23rd Annual Conference of the International Group for Lean Construction (pp. 733-742).

Mossman, A. (2007). Lean Logistics: Helping to create value by bringing people, information, plan and equipment and materials together at the workface. International Group for Lean Construction. Michigan, EE. UU.

Pan, W., Gibb, A.G., & Dainty, A.R. (2012). Strategies for integrating the use of offsite production technologies in house building. *Journal of Construction Engineering and Management, 138*(11), 1331-1340. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000544

Park, K., Min, H., & Min, S. (2016). Inter-relationship among risk taking propensity, supply chain security practices, and supply chain disruption occurrence. *Journal of Purchasing and Supply Management, 22*(2), 120-130. https://doi.org/10.1016/j.pursup.2015.12.001

Ross, K., Cartwright, P., & Novakovic, O. (2006). A guide to modern methods of construction. IHS BRE Press.

Said, H., & El-Rayes, K. (2010). Optimizing material procurement and storage on construction sites. *Journal of Construction Engineering and Management, 137*(6), 421-431. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000307

Sanei, M., Mahmoodirad, A., & Niroomand, S. (2016). Two-stage supply chain network design problem with interval data. *International Journal of e-Navigation and Maritime Economy, 5*, 74-84. https://doi.org/10.1016/j.enavi.2016.12.006

Seppänen, O., & Peltokorpi, A. (2016). A new model for construction material logistics: From local optimization of logistics towards global optimization of on-site production system. In 24th Annual Conference of the International Group for Lean Construction.

Simchi-Levi, D., Schmidt, W., & Wei, Y. (2014). From superstorms to factory fires: Managing unpredictable supply chain disruptions. *Harvard Business Review, 92*(1-2), 96-101.

Simchi-Levi, D., William, S., Wei, Y., Zhang, P.Y., Combs, K., Ge, Y., Gusikhin, O., Sander, M., & Zhang, D. (2015). Identifying risks and mitigating disruptions in the automotive supply chain. *INFORMS Journal on Applied Analytics 45*(5), 375-390. https://doi.org/10.1287/inte.2015.0804

Sincero, S. (2015). Methods of Survey Sampling. Washington: Survey Guide.

Skjelbred, S., Fossheim, M. E., & Drevland, F. (2015). Comparing Different Approaches to Site Organization and Logistics: Multiple Case Studies. In Proc. 23rd Ann. Conf. of the Int'l. Group for Lean Construction (pp. 13-22).

Stainton, H. (2017). Saunders Research Onion - Guide To Structuring Research Methodology. Austin: Tourism Teacher.

Sundquist, V., Gadde, L. E., & Hulthén, K. (2018). Reorganizing construction logistics for improved performance. *Construction Management and Economics, 36*(1) 49-65. https://doi.org/10.1080/01446193.2017.1356931

Tennant, S., McCarney, M., & Tong, M. (2012, September). Re-engineering the Construction Supply Chain: Transferring on-site activity, offsite. In 28th Annual ARCOM conference (Vol. 2, pp. 739-749). Edinburgh: ARCOM.

Van Vught, R.P.A.C., & Van Weele, A.J. (2015). Managing supply chain relationships in construction industry: compete or collaborate. In conference IPSERA; 2015-03-29; 2015-04-01. Vrije Universiteit Amsterdam.

Vrijhoef, R., & Koskela, L. (2000). The four roles of supply chain management in construction. *European Journal of Purchasing and Supply Management, 6*(3), 169-178. https://doi.org/10.1016/S0969-7012(00)00013-7

Vugrin, E.D., Warren, D.E., & Ehlen, M.A. (2011). A resilience assessment model for infrastructure and economic systems: Quantitative and qualitative resilience analysis of petrochemical supply chains to a hurricane. *Process Safety Progress, 30*(3), 280-290. https://doi.org/10.1002/prs.10437

Zeng, J., An, M., & Smith, N. J. (2007). Application of a fuzzy based decision-making methodology to construction project risk assessment. *International Journal of Project Management, 25*(6), 589-600. https://doi.org/10.1016/j.ijproman.2007.02.006

Zhai, Y., Zhong, R.Y., & Huang, G.Q. (2015). Towards Operational Hedging for Logistics Uncertainty Management in Prefabrication Construction. *IFAC-PapersOnLine, 48*(3), 1128-1133. https://doi.org/10.1016/j.ifacol.2015.06.235

Zolfagharian, S., & Irizarry, J. (2014). Current trends in construction site layout planning. In Construction Research Congress 2014: Construction in a Global Network (pp. 1723-1732). https://doi.org/10.1061/9780784413517.176