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Investigating the Factors Responsible for the Material Delivery Time Variance in the Construction Supply Chain of Prefabricated Products

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Abstract

Investing the factors responsible for the material delivery time variance in the construction supply chain management of prefabricated products

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The construction industry is a complex structure of various bodies that contributes in a unique way such that their proper workflow ensures project success. It is a known practice in the construction industry to change the scheduled material delivery date too often, asking how reliable is the material order variability? How does the system react to that variability? What are the reasons behind that order variability? This research investigates the material delivery order reliability in the construction supply chain for prefabricated products. Qualitative data will support statistical analysis, and the system dynamics model will show the connectivity between the variables. The system dynamics model will be used to understand the working of the order variability environment, which qualitative data will back. The quantitative data showed the

pattern that most of the material resulted in skewing right and with leptokurtic distribution denoting that the material was ordered earlier than scheduled, and the variability pattern was unstable and unpredictable. On the other hand, the qualitative data provided reasoning for material delivery variances noting 11 critical points.

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Chapter 1. INTRODUCTION

1.1 BACKGROUND

The construction industry is a complex structure of various bodies that contributes in a unique way such that their proper workflow ensures project success. Julian Lange defines construction as a sector than an industry. And he further explains it as follows (Rewriting),

Construction ... is often referred to as an industry but is more accurately described as a sector of the economy, such as manufacturing, transportation, or services. It is not a single activity but a group of loosely related activities by their products, technologies, and institutional settings. (Lange 1979)

The author of one of the papers wants to explain that the construction industry is way more different than any other industry, mainly the manufacturing industry. It is the difference in the working/production system of the two industries themselves. It is the final product in the construction industry, which is stationary, unlike manufacturing. (Marc Linder 1994)

Due to the participation of many stakeholders in this industry, the deliverables depend on each other, and good collaboration and communication are expected at each level. The more the system or processes are transparent, the more it is beneficial for the project's success.

The construction project's success depends on factors like time and costs specifically. Considering the construction industry's unique nature and the project-specific demand, this industry has many uncertainties and variabilities. Lean Construction is regarded as a revolutionary tool to streamline these factors in the present construction industry. (Esfahani 1999)

Even though Lean Construction has emerged from the manufacturing industry, its survival in the construction industry results in true collaboration, planning, and removal of unwanted process wastes.

The labor cost percentage is generally between 20 to 40%, and the rest will be material costs (Aaron Sullivan 2016). (J.W. 1985) Gives us the 60% figure for the cost of materials and equipment. This shows that the material cost is as vital as anything in the total construction cost. The supply chain addresses the delivery and coordination of that purchased material from the supplier/manufacturer to the contractor on site. The dependability of so many stakeholders challenges the coordination between them, and it is essential to manage every entity well to have desired results.

(Ireland and Bruce 2000) In his report, CPFR: the only beginning of the collaboration, he gives an excellent example of the thinking of the downstream and the upstream entity of the supply chain. The downstream party is only concerned with the demand forecast at the shelf, but the upstream party is involved with the demand estimates until the warehouse. Hence, the author says that it is always, "I win, now you figure out how to win" in a supply chain.

It is essential to study how the whole supply chain system works and how all stakeholders depend on each one. This research mainly identifies the reasons for the material order reliability for the prefabricated construction products. Emphasis will be given to understanding both sides, and all the relations will be analyzed with the help of system dynamics modeling, and a mental model will be plotted to get them.

1.2 RESEARCH AIM AND OBJECTIVE

The construction supply chain is mostly a made-to-order or engineered-to-order type supply chain. The uniqueness of projects makes the order and production of material strictly specific to the construction project. This research investigates the material delivery order reliability in the construction supply chain considering prefabricated materials. The study would identify the pattern of the material delivery order variability specific to prefabricated products, and it will allow an understanding of how suppliers and manufacturers handle their production system while dealing with this contractor's material order variability. This would help understand the collaboration and the integration amongst the construction supply chain participants towards order variability.

1.3 RESEARCH QUESTIONS

Considering the scope of the research, we will have to include several research questions, but here, an attempt has been made to cover all the content of this research in three research questions.

- 1) What are the reasons behind material delivery date shift or order variability from the contractor's side?
- 2) How is the production scheduling system structured with Suppliers and Manufacturers to manage contractor's material order variability?
- 3) Is there any pattern in the behavior of the material delivery variances of the prefabricated products? If yes, then what is the pattern?

1.4 RESEARCH METHODOLOGY

In this research, we are investigating the material delivery order reliability, addressing the construction supply chain management with prefabricated products in focus. To analyze this delivery order reliability, we need to study the significant participants from the construction supply chain: General Contractors/DB Sub-contractors and suppliers/manufacturers. This is because the supply chain is not one party's responsibility, but it should be focused on keeping the whole pipeline in the picture. Limiting the scope but considering the effect, we exclude SC participants like transporters, distributors, etc.

Both Quantitative and Qualitative data support the research. The quantitative data is secondary (someone else noted it, and I have utilized it), and the qualitative information is primary (I noted it and used it)

For the quantitative data, the research proposal was shared amongst industry professionals (presence across the USA), and they were made to understand the purpose of the research. The data was collected electronically (Email – Excel / PDF files) in the form of two variables: the scheduled delivery date and the actual delivery date for the corresponding prefabricated product. A total of three companies from across the nation provided the quantitative data mentioned above. The prefabricated materials considered were as follows,

- Metal framing for gypsum Board
- Mechanical, Electrical, plumbing distribution, and FF&FA Material
- Mass timber Beam and Column

For the qualitative data, Industry professionals employed as Production Managers from manufacturing companies, Business Development Managers, Project Managers, Project Engineers and Superintendents from the contractor and subcontractor side, Supply chain coordinators, and Company Researchers were contacted for an interview. A set of questions were set up separately for contractors and supplier/manufacturers and asked during the interviews. Platforms such as Zoom Video Conferencing and Microsoft Teams Meet were used to collect the data via audio and transcript recording.

The data collection was approached first through a professional social media platform, LinkedIn. By limiting the search to prefabricated companies, people from supply chain backgrounds, people from supplier and manufacturer sides who are handling production, and project managers. Project engineers and superintendents from the contractor side were contacted by sharing research proposals. By searching prefabricated construction events in the search bar of Google, participants were contacted and asked for the research input.

First, after receiving the data, the data cleaning process was implemented to analyze the quantitative data. The unwanted data was cleaned, and all the three-company data was brought on as a single formatted excel sheet for further calculations. Microsoft Excel's data analytical tool was used to perform statistical tasks. Descriptive statistics analysis was used to get the pattern of the order variability of the data received. Inferential statistics couldn't be used, as the sample collected was not enough to generalize or give a project of the whole system.

To analyze qualitative data, a coding method was utilized. Individual interview transcripts were coded line by line, and a theme or pattern was generated from that. Then, all the interviewee's interviews were sorted as per the theme, and they were utilized to support / back the quantitative data. Interviews as a method to collect the data were chosen as it provides modulation of questions and topic as per the answer received and hence can collect a lot of information pertinent to the research. Below is the demographic data of the interviewees given.

Sr. No.	Job Title	No. of Interviewee
1	Vice President Manufacturing Company	3
2	Project Manager - Contractor	2
3	Project Manager - Supplier	2
4	Superintendent - Contractor	1
5	Senior Project Engineer - Contractor	1
6	Project Engineer - Contractor	2

Table 1. 1 Job Titles of Interviewees

Sr. No.	Criteria of Years	No. of Interviewee
1	0-5 Years	2
2	6 – 10 Years	5

3	11 – 15 years	1
4	16 – 20 Years	2
5	More than 20 Years	1

Table 1.2 Experience in years of the Interviewees

System Dynamics Model

The system dynamics model was used to understand the pattern or behavior of the order reliability. The whole system process was understood by interviewing suppliers and manufacturers, and the causal loop diagram was drafted. Firstly, the critical variables in the supply chain environment considering the order reliability were observed, along with delays. VensimPLE software was used to draw the causal loop diagram. The delays and polarities help to understand how the system performs. It depicts the actual supply chain system with a focus on order reliability.

An attempt was not made to do any simulation study. The model's behavior depends on the modeler's capacity to draw the model and their competency to provide input to the model. Hence, theoretically, the model was drafted and utilized.

Data Collection Limitations and Obstacles

- 1) Much effort had to be provided for data collection. The data was either kept confidential, or they did not maintain any delivery order log sheet to know the scheduled and actual delivery dates.

- 2) The production schedule shows supplier and manufacturers' competency to handle the market well; Suppliers and manufacturers were reluctant to share such kind of confidential data.
- 3) The sample size of the data collected is small, on an average 15 material deliveries are received in the form of quantitative data. Hence predictive analysis could not be implemented.

Chapter 2. LITERATURE REVIEW

2.1 CONSTRUCTION AND ITS COMPLEXITY

Construction is a complex industry where there are many uncertainties involved. The value of the USA construction industry as a percentage of GDP is 4.3%, and the total number of new private construction in the USA by March 2022 was 1,140.91 bn USD. Looking at these figures, the industry has a considerable value, and it depicts itself as a developed industry. On the other hand, researchers are working on taking advantage of this industry's undiscovered/undeveloped parts. An article on the global edge webpage (Global Edge 2017) describes the construction industry as the driving force for all other industries. When the construction industry is doing well, it is assumed that all other industries are also doing well.

This industry has many project participants. Each construction project is one-of-a-kind and unique, demanding a particular deliverable, and to achieve it; there are many actors (Yeo and Ning 2001). The exciting thing about a construction project is that it is unique in nature. No two projects are shared, and hence the characteristics defer. The construction sector involves project participants like Architects, Designers, Engineers, Contractors, Subcontractors, Manufacturers, and Suppliers etc. These professionals come together depending on the project, and their coordination defines the project's success. The action required by all the actors in the construction project is short-lived. This is because the deliverable is to be achieved as a definite unique scope, and once it is done, the actors can concentrate on a different deliverable (Yeo and Ning 2001).

Here, analyzing your customer is essential for decision-making in this industry. A webpage article gives a systematic view of these project participants and their roles in the construction industry. ("Construction Project Team, Roles and Responsibilities" n.d.)

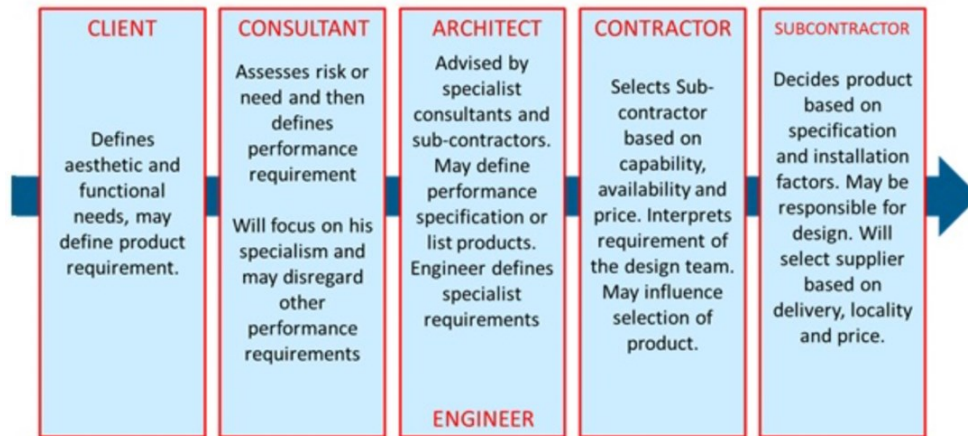


Figure 2. 1 Project Participants

The author (Jin et al. 2017) lists all those project participants involved and states that they are the drivers of the whole project because they have their capital invested. Hence, interest and risks are shared and consumed. The push and pull effects and their interrelationships can impact the construction sector.

Considering these many project participants and the nature of the work environment, since most of the participants are in different companies, there is a high chance they all are falling into a silo work culture. This leads to less collaboration and coordination, and hence poor communication leads to project failure. The involvement of trading partners in the decision-making enhanced the chain's value; instead, it occurred at more cost when the decision-making was done on individual goals (Ireland and Bruce 2000).

Since this research primarily focuses on supply chain management, it is crucial to know how the construction industry works as a production system.

2.2 CONSTRUCTION AS A PRODUCTION SYSTEM

It is essential to see construction from the production point of view (Bertelsen and Koskela 2004) mention the definition of construction from the production point of view as follows,

“Construction is a complex production of a one-of-a-kind product undertaken mainly at the delivery point by cooperation within a multi-skilled ad-hoc team.”

The research also enlists the four characteristics of construction: production, one-of-a-kind products, complexity, and an entity to be undertaken by cooperation.

(Jørgensen and Emmitt 2008) This paper, which reviews the transition of the lean production system from Manufacturing to the construction sector, argues that this transfer is slow, and there is much research done in the manufacturing world compared to the construction. The paper adds further that this slow progress can be that lean production principles in the manufacturing world are redundant for the construction sector. It is required to give much importance to the “Value” and “Waste” in construction. It is interesting to note that the concept of value is only valid if applied from the whole life perspective. This is because the value is related to the end-user. Since there are so many project participants in the construction world, several end-users and their needs are there. From that perspective, we cannot look for value from a single view, but it must be considered from the whole life perspective.

Much criticism has been pointed out by (Jørgensen and Emmitt 2008) that lean as a concept is much more valid in the manufacturing world due to the large production volume. It is highly standardized and repetitive, and it measures to achieve a constant decrease in lead time. It provides

limitations to the research done in the construction industry for this transition from manufacturing to the construction world in terms of lean as a topic.

Contrary to this, in the Lean Construction Journal 2005, a report proves that the lean construction principles from the manufacturing industry can be applied to the construction industry. This report was a concise form of the original information outlined in the CII report #191, authored by James E. Diekmann, Mark Krewedl, Joshua Balnick, Travis Stewart, and Spencer Wonis. It was proved with the help of 6 case studies done on the construction projects and with the use of lean tools like Value stream mapping, the delays and the bottlenecks were identified and solved. The report also provides an insight into how construction is still un-explored in areas like supply chain management and design in the building. Though it doesn't give evidence on how to solve these issues, it keeps an open question as more research needs to be done on these topics. The five major lean principles that the authors conclude are applicable in the construction industry are

- 1) Customer focus
- 2) Culture/People
- 3) Workplace Standardization
- 4) Waste Elimination
- 5) Continuous improvement / built-in quality

The paper published (Omar, Sam, and Julie, 2005) gives knowledge of lean as a production system application in the Manufacturing and construction sectors. It enlists the tools used in both industries with a bit of modification, as characteristics of the construction industry are that it has a unique set of projects, and the customer value is not limited to one customer but several stakeholders. (Koskela 1992) Identifies the construction industry's three characteristics that make

it unique to the manufacturing industry: site production, one-of-a-kind nature of projects, and complexity.

The following table gives knowledge of the lean production techniques (Omar, Sam, and Julie 2005)

Level	Lean construction technique	Goals	Related lean production techniques
I	Material Kanban Cards	Reducing inventories on site Pulling materials based on backward requests	Kanban system
II	Visual inspection Quality Management Tools Concurrent project engineering	Increase work flow by preventing defects Increase work flow by ensuring quality practices Minimize cycle time Optimize resources	Visual inspection (Poka-Yoke devices) Multi-functional layout Quality and Productivity Management System (TQM) Standard operations Single minute exchange of dies (SMED)
III	Last Planner Plan Conditions of Work Environment (PCMAT) Daily Huddle Meetings	Pull activities by reverse-phase scheduling Optimize resources in the long term Increase work flow by ensuring safety practices Optimize resource by adapting to variable conditions	Kanban system Production leveling Toyota Verification of Assembly Line (TVAL)

Table 2. 1 Lean Tools

Considering the sociotechnical design, the following figure explains how lean construction and the manufacturing system are related.

Scope: Design, Supply, Production			
Goals: Zero-waste, Flow and Pull			
Human subsystem	Problem-solving focus		
	Teamwork		
	Creative thinking		
Technical subsystem		Construction Project-based	Manufacturing Process-based
	Just-in-time	Material kanban cards Last Planner	Kanban system SMED Minimum batches
	Production smoothing	Concurrent engineering PCMAT Daily Huddle Meetings	Production leveling Multi-functional layout Standard operations TVAL Preventive maintenance
	Autonomation	Quality Management Tools Visual Inspection	Total Quality Management Autonomous control

Figure 2. 2 Sociotechnical Design

Hence, it concludes that lean production and manufacturing techniques can be applied to the poor construction world., The concurrent engineering last Planner and daily huddle meetings are a few.

Since the literature has proved in the lean construction domain that the lean production techniques can be used in it, despite its one-of-a-kind project system and uniqueness. Now we will focus on the supply chain management concepts.

2.3 SUPPLY CHAIN MANAGEMENT

Let's start exploring the area of supply chain management and how lean is related to this concept.

In the book, Successful Construction Supply Chain Management by (Stephen Pryke 2020), it is noted that Lean and the supply chain are related to each other. While introducing products in the supply chain, the production of the end product is related to the production waste. A linkage of the supply chain with lean is established by discussing "Just in Time" and "Toyota production system" principles.

(Vaidyanathan, Professor, and Rinker 2003) have investigated the critical differences between the manufacturing and construction supply chain. They are provided in the table below,

Characteristics	Manufacturing SCs	Construction SCs
Structure	Highly consolidated High barriers to entry Fixed locations High interdependency Predominantly global markets	Highly fragmented Low barriers to entry Transient locations Low interdependency Predominantly local markets
Information flow	Highly integrated Highly shared Fast SCM tools (factory planning and scheduling, procurement, SC planning)	Recreated several times between trades Lack of sharing across firms Slow Lack of IT tools to support SC (no real data and workflow integration)
Collaboration	Long-term relationships Shared benefits, incentives	Adversarial practices
Product demand	Very uncertain (seasonality, competition, innovation, etc.) Advanced forecasting methods	Less uncertain (the amount of material is known somewhat in advance)
Production variability	Highly automated environment (machines, robots), standardization, production routes are defined—lower variability	Labor availability and productivity, tools, open environment (weather), lack of standardization and tolerance management, space availability, material and trade flows are complex—higher variability
Buffering	Inventory models (EOQ, safety inventory, etc.)	No models Inventory on site to reduce risks Use of floats (scheduling)
Capacity planning	Aggregate planning Optimization models	Independent planning Infinite capacity assumptions Reactive approach (respond to unexpected situations, for example, overtime)

Table 2. 2 Comparison of Manufacturing and Construction Supply Chains

It is important to note here that the problems in the construction supply chain are much more similar to the manufacturing supply chain, with differences in projects being unique and hence lots of uncertainties and variabilities. In the above table, we can still see the fragmentation of the features in the construction supply chain, which needs to be addressed by collaboration and integration.

The concept of supply chain management has evolved from the traditional system first, which is known as Logistics. It is vital to know the definition and concepts of logistics before diving into supply chain management concepts. (Martin Christopher 2016) in his book, Logistics and Supply Chain Management defines Logistics term as (Re-writing),

” Logistics is the process of strategically managing the procurement, movement, and storage of materials, parts, and finished inventory (and the related information flows) through the organization and its marketing channels in such a way that current and future profitability are maximized through the cost-effective fulfillment of orders.”

The question is, the definition doesn't talk much about network integration, and from then, the supply chain concept has evolved.

He also adds that logistics management is a single plan system, where it is planned to create a single flow of goods and information throughout the business. He differentiates logistics from supply chain management by using words like the relationship between upstream and downstream suppliers and customers and the cost-effectiveness of the whole supply chain. The “whole chain can be greater than the sum of its parts with good cooperation and trust.”

(Coyle, Bardi, and Langley 1992) have mentioned in their book that supply chain management emerged from Logistics, which emerged from the distribution and production system concept. (Martin Christopher 2016), defines a supply chain as “the network of organizations involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate customer.”

According to (O'Brien 2008) from the Construction supply chain management handbook, the construction supply chain management is inspired by the manufacturing supply chain management. Still, it differs substantially from the fact that the manufacturing supply chain management emphasizes modeling volume production. In contrast, CSCM (construction supply chain management) focuses more on coordinating discrete quantities of material delivered to specific construction projects, which are unique in nature.

The CSCM depends upon the global sourcing of the materials and the transportation technologies available, along with the most important thing, the coordination between the owner, the construction team, and the supplier/manufacturer. Hence, (O'Brien 2008), in his CSCM handbook, states that, for all these reasons, effective construction project execution will mean effective CSCM.

Few authors like Koskela have provided much greater research on the construction supply chain and lean construction, connecting the construction supply chain with the Just-In-Time Delivery method's thin tool. The concept of supply chain management is molded by Just-in-Time Delivery and logistics management (Vrijhoef and Koskela, 2000.). The author argues that this supply chain management topic is large but still dominated by logistics.

The construction characteristics as a sector/industry, complex nature, and project uniqueness make the supply chain environment challenging. Some of them are challenges like self-interest, project delay, inventory space unavailability, made to order / engineered-to-order material are some of them. (Laitinen 1993) showed that every party in the supply chain adds a specific buffer for their excellent, allowing them to count for any uncertainties in the supply chain. This buffer can be in

terms of schedule time or inventory, ensuring the risk is mitigated in an uncertain situation. The research thought behind this is that there is some other thought by providing an extra buffer.

The construction supply chain is complex and temporary, as we have seen. The parties involved are there for their own business and profit. But one of the journals concluded that the professionals interviewed demanded the following things for the smoothening of the supply chain. They mention that all the supply chain participants must collaborate and engage in streamlining the supply chain flow. (Min et al. 2005)

- 1) Work together, implement and monitor all supply chain activities constantly.
- 2) Integrate cross-firm operations
- 3) Focus on common goals
- 4) Share data with all stakeholders
- 5) Need for a systematic course of action
- 6) Detail performance matrix to formalize collaboration arrangements

This shows how collaboration can make the supply chain more exciting and serve the same purpose for which it was formed but more systematically.

(Akintoye, McIntosh, and Fitzgerald 2000) concluded by taking a lesson from the success of supply chain collaboration in other industries. Contractors and suppliers who play a pivotal role in the construction supply chain should emphasize partnering and long-term relationships for greater productivity. Also, further to that, the contractors in the construction industry are more inclined toward the clients in a contractual way rather than suppliers. So, they suggest that contractors need to collaborate with suppliers and manufacturers for better supply chain management, which can bring effectiveness to the construction supply chain. The main objective of supply chain management is to create value for the whole supply chain network and not for one company.

(Martin Christopher 2016) Mentions that the simple goal of the supply chain is to match the market demand and supply, but this simple thought is made difficult in real life by the uncertainties and the volatilities.

Since the research is to determine factors responsible for the material delivery time variance and understand contractors' order variability trends, further literature would concentrate on supply chain coordination, its problems and solutions, material delivery time variance, and construction supply chain management uncertainties.

2.4 CONSTRUCTION SUPPLY CHAIN AS A COORDINATION SYSTEM

(Behera, Mohanty, and Prakash 2015) Mentions that the problems in the supply chain are relationship-based and are found right at the interface of the construction phases. They provide a diagrammatic representation of these issues. This shows how essential coordination is between the construction and the supply chain phases. Interchanging the information would make the problems vanish and mitigate the risk of any uncertainty. (Adebanjo, Teh, and Ahmed 2018) Analyzed that the supply chain relationship and integration are essential for the positive impact on the manufacturing performance of the material.

Following is the list of problems mentioned in by the author in his paper,

- 1) End-user/client interface: difficulties in finding out end user's wishes, changes of end user's wishes, lengthy procedures to discuss changes in feasibility, financing, and tendering.

- 2) Client/design interface: difficulties in finding out client's wishes, changes of client's wishes, lengthy procedures to discuss changes in concept and complete design.
- 3) Design/procurement interface: false documents, design changes, extended waiting for architect's approval.
- 4) Leading contractor/subcontractor's interface: inaccurate data, unmet information needs, adversarial bargaining, and other changes.
- 5) Leading contractor/indirect supplier's interface: deliveries not in conformance with planning, wrong and defective deliveries, long storage period, awkward packing, and large shipments.
- 6) Production/organizing interface: inaccurate data, subcontracted work not delivered according to the main design, contract, and planning.
- 7) Organizing/handing-over interface: inaccurate data, information needs not met, unresolved quality problems, delayed occupation due to late completion, adversarial bargaining, and other changes.

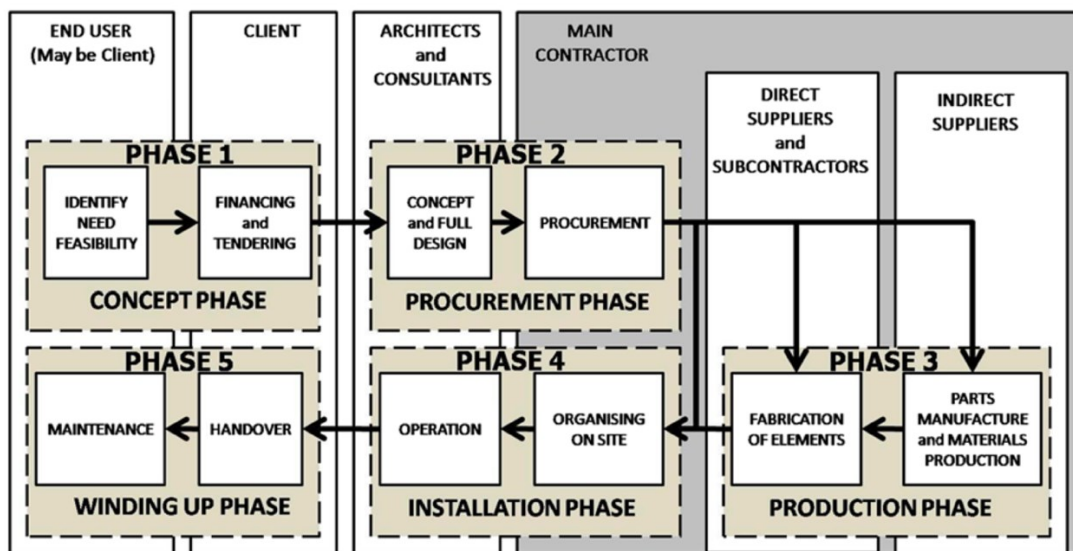


Figure 2.3 Supply Chain Interface (Behera, Mohanty, and Prakash 2015)

To mitigate the problems lying on the interface of the supply chain, we saw that better coordination and information sharing are essential. (Yu, Yan, and Cheng 2001) Notes that this information sharing provides more benefits like Vendor inventory management, Cross-docking, and quick response. With the supply chain partnership, information sharing can be streamlined better. When two parties get along, better forecasting can be done, reducing the variability in the construction supply chain. With the help of information sharing, we can also reduce the lead time since the operational efficiency increases and the whole production cycle works in a better sequence giving justice to the lead time (Min Ung and Bjornsson 2008).

(Gosling, Naim, and Towill 2011) Talks about the uncertainties in the Engineering order type of construction supply chain and mentions 7 of the supply chain uncertainties focusing more on the supplier and subcontractor side. Re-writing the delays as a lousy performance from suppliers, subcontractors' capacity, suppliers' consistency, early or late deliveries, subcontractor bankruptcy, and timely & correct information from suppliers. This indicates that proper sharing of knowledge and proactiveness from the supplier or subcontractor side would make the supply chain less uncertain.

The author (Elfving 2003), in his research, mentions that the construction job site is unique from other projects; it is also the focal point of the construction supply chain. Unlike the manufacturing industry, the job site in the construction supply chain has no power to coordinate the SC. Here, the reliability of the site production system plays an important role. The site activities depend on each other, and the progress of these sequence activities has much impact on the SC. The demand from the job sites can be unstable, and hence it brings uncertainties to the construction SC. From the

supplier's side, those suppliers who give long lead times depending upon the material type and those who have limited capacity to handle the material production are prone to impacts from risks.

(Cachon and Fisher 2000) Their paper compares the traditional v/s supply chain using information technology and sharing tools in the supply chain. It shows that with the help of information sharing in the supply chain, we can reduce the supply chain cost by 2.2%, reduce the lead times by half, and its cost impact by 21% on average. They also mention that, instead of using information technology and information sharing to expand the business, they use it for smoothing the already going supply chain. That would be more beneficial.

By far, we have understood that collaboration and information sharing are essential for the success of the construction supply chain. But the decision making of which product requires how much collaboration and information sharing is a question. Lean encourages us to remove the overprocessing as a waste; hence the author summarizes the interdepartmental collaboration aspects in logistics and supply chain as follows; the four regions are described as (Kahn and Mentzer 1996)

- 1) **Low interaction, Low Collaboration:** Here, only department-specific activities are involved where only the logistic department is required to decide. Hence Interdepartmental collaboration and exchange are the lowest. The third-party logistics party can come into this section as the author mentions that they are not interdepartmental but intercompany.

- 2) **High Interaction, Low Collaboration:** The documentation requirement is more but not the teaming. The best example of this category is the manufacturer and the corresponding JIT supplier. The author mentions that JIT is more predictable and stable. Hence, collaboration can be less, but interaction must be more.

- 3) **Low Interaction, High Collaboration:** While the launching of a new product is considered to meet the customer demand, the collaboration should be high, but here, the document control that is the interaction can be less. As there is a limited scope of the reaction time. This can also include surprise orders, where putting the material onboard is essential; collaboration is more critical than interaction.

- 4) **High Interaction, High Collaboration:** These orders are significant, with stringent specifications, and are explicitly shipped for a particular job.

Hence by summarization, the construction orders can fall more in the fourth category with High interaction and High collaboration but can also be found in the third category, that is with low interaction and high collaboration (fewer chances)

(Minh, Naim, and R.Baker 1999) Talks about the mindset approach as a solution to the problem with collaboration and integration in the construction supply chain. They mention “Partnership” as the solution to this issue. While saying that, they sequentially explain how collaboration problems can lead to a lack of quality in the product, which can delay the project's progress. Instead of working for individual interests, working collaboratively, sharing as much information as possible, and bringing the smoothing effect to the supply chain is essential.

Collaboration and information sharing is understood, but how can we bring that into the picture? There is enough literature on implementing the CPFR (Collaborative Planning, Forecasting, and Replenishment) as a collaborative and smoothing tool in supply chain management. Here, key activities are very well planned such that the customer demand is met or satisfied, but it is essential from a research point of view to know the barriers to the application of CPFR.

Even though CPFR is an effective tool to bring collaboration and smoothing in the supply chain, The author (Barratt and Oliviera 2001) provides the barriers to the CPFR process, which are essential to note in the real world and provides limitations for its application, especially in the construction supply chain. The stock management failure in case of demand fluctuation, no proper planning, trust and sharing problems in the chain, and difficulty in managing the forecast are some of the barriers mentioned.

(Bray 2018) His report on the Turner and Townsend company website gives the construction sector opportunities to grab from the retail supply chain sector. Following is the summary of it.

- 1) **Embrace collaborative Forecasting:** If the construction sector can forecast the material demand and supply like the retail sector, it would stabilize the construction supply chain market. This would require better collaboration in the supply chain.
- 2) **By considering collaboration as the core part of the construction supply chain:** Collaborative behaviors is a partial success for the betterment of the supply chain; it needs to be embraced more often for full effectiveness.

While indicating the problem related to the construction supply chain, the author (Ala-Risku and Kärkkäinen 2006) provides a strong statement that to keep-up the project schedule on track along with the last planner system and to avoid the material delivery failure, the contractors keep the inventory at the site by ordering the material early and keep buffer in the schedule. Or he also mentioned that the material inventory risk is transferred to the supplier's or manufacturer's inventory, which is again not a good practice. The author clarifies that a better communication system between the site and supplier team is essential to avoid all these issues. But much literature suggests that construction projects are a unique and temporary entity; establishing such a communications system doesn't involve long-term planning. Hence, it is challenging for many information technologists to develop a solution.

2.5 CONSTRUCTION SUPPLY CHAIN: VARIABILITY

The core part of the research is the variability in the construction supply. Very little literature is available on tackling variability, for example, using the Last Planner System in the supply chain (Ballard 1999), the Integrated look ahead schedule (Chua, Jun, and Hwee 1999), material inventory, etc.

(Balakrishnan, Geunes, and Pangburn 2004) Mentions that order variability affects the inventory and the upstream service capacity cost. Also, to reduce the variability of the retailers, the suppliers use inventory as a tool to mitigate this risk of variable demand.

The paper also addresses the reasons for the cost components in the supply chain. They are as follows,

- Downstream inventory Cost: Retailer's effective demand

- Upstream Inventory Cost: Net orders by the suppliers
- Service Capacity cost: Total order Variability

They also provide a two-stage variability control mechanism as “order smoothing,” which addresses the upstream order variability. They identified the downstream component as “retailers” and upstream as “suppliers.” So, suppliers always must keep short-term demand ready by having inventory and long demand by having better transportation services. The only limitation of the research is that they have considered the retail market where repetitive demand and supply occur.

The demand variability is considered more on the upstream side than on the downstream side. Hence, the production variance exceeds the demand variance, known as the bullwhip effect (Yu, Yan, and Cheng 2001).

The variability in one firm can cause variability in another firm with different or enhanced magnitude even though the firms are not directly linked with channel flow; this is the definition of the “Bullwhip Effect.” (Germain, Claycomb, and Dröge 2008)

With the illustration of a dice game, the author provides insights into how the variability impacts the production system in the construction supply chain. With the simulation of the dice game, the author concludes that, with more significant variability, it is likely that the project may complete at the earliest and the latest. With more substantial variability, the production rates decrease, which means an increase in waste, and the intermediate buffers also increase. Hence it is essential to

analyze the factors responsible for the variability in the construction supply chain (Tommelein, Riley, and Howell 1999).

The author suggests that, in a predictable environment, the formal control in the supply chain is the driver of the variability. In an unpredictable environment, organizational integration plays a vital role.(Germain, Claycomb, and Dröge 2008)

(Balakrishnan, Geunes, and Pangburn 2004) Their paper addresses the upstream order variability issue and gives “order smoothing” as the solution for this issue. The limitation of this particular paper is that it is focused on the retail market and not on the construction market.

One of the papers presented by (Walsh et al. 2004) provides a view of an owner who took charge of the supply chain and kept on hold the materials at a particular stage in the construction supply chain, which allowed them to be agile against the design changes and could also reduce the lead time of the material by 75% and act well against the order variability.

The reduction of variability principle and the production management principles are related to each other (Santos and Powell 1999). The author mentions the two types of causes of the variability in construction, Random and Assignable causes namely. Further, they say that the accidental causes can be due to environmental factors that are not in the control of the operator and the assignable causes are easier to control. The book doesn't specifically mention the reasons for the material order and doesn't provide much knowledge about the specific causes. Also, the author has

specified variability in a broader sense. In our research, we are just discussing the order variability problem.

The paper published by (Chua, Jun, and Hwee 1999) gives the scheduling tool known as Integrated Look ahead planning, which helps minimize the uncertainties and variabilities in construction with the help of integrated information and resource sharing approach. Even though the paper could come up with this tool, it is the fact that no reason for these variabilities is mentioned. The new device is compared with the traditional look-ahead planning process. Hence research is required to know the variabilities in at least material delivery time variance so that a reliable production schedule can be drafted from the supplier and manufacturers' sides.

The demand variability shows exciting results in lead time. One of the papers published (Vidalakis, Tookey, and Sommerville 2013) resulted in a more increase in lead time with initial, small demand variability, i.e., the delivery from the supplier side may be delayed significant days than the demand variability of over 200%. The results show that the demand variability was between 100 to 200% there was a substantial increase in lead time. Again, the concentration was provided on the supplier/manufacturer side with the lead time variation, but the reasons for the demand variations were not studied.

There is a reasonable conclusion put forward by (Vrijhoef and Koskela, 2000.)that when there is no proper planning done at the start of the project, the operation team generally must come up with improvisation at their level, and that leads to demand variation, utilization of buffers and ordering

material with less lead time pressurizing suppliers and manufacturers. This touch bases on the research topic and gives an example of one of the reasons.

2.6 LITERATURE REVIEW SUMMARY

The full literature review is written with a perspective of understanding the tools and techniques in the construction supply chain management and to provide a background on how collaboration and integration happen in it. It is crucial to note that the variability reasons we are investigating are a core part of how supplier/manufacturer and contractor collaborate and share information. The lean Construction literature backs that the construction supply chain reduces lead time and integrates the stakeholders. The following table summarizes how the literature review is formatted in this research.

Sr.No.	Literature Review Heads	Summary of findings
1	Construction & it's Complexity	<ul style="list-style-type: none"> • The debate over construction as an industry or sector. • Involvement of stakeholders or project participants in view of the supply chain management. • Each construction project is a unique entity.
2	Construction: Production System	<ul style="list-style-type: none"> • Manufacturing production principles can be applied to construction and hence can be called a production system.
3	Supply Chain Management	<ul style="list-style-type: none"> • The construction supply chain is fragmented. • A lot of collaboration and integration are required for better output.

		<ul style="list-style-type: none"> • It is complex and temporary / Project specific. • CSCM focuses more on coordinating discrete quantities of material delivered to specific construction projects. • The whole chain can be greater than the sum of its parts.
4	Construction Supply Chain: Coordination System	<ul style="list-style-type: none"> • CSCM is a relationship-based entity and can be made successful. With partnership / long-term relationship. • Coordination issues lie at the interface of supply chain phases. • Reliability of the site production team plays a vital role in CSCM
5	Construction Supply Chain: Variability	<ul style="list-style-type: none"> • Literature available on tracking the variability by using tools like LPS but no literature available on reasons behind the variability. • To mitigate the risk of variability, suppliers and manufacturers use inventory as a solution. • Demand variability initiates from downstream but is considered more on upstream. • Variability impacts production system increases waste in processes and hence increase in lead time. • With demand variability, the result of lead time increase goes on reducing as the demand variability increases and becomes flattened for variability more than 200%

Table 2. 3 Literature Review Summary

Chapter 3. RESEARCH DATA ANALYSIS

To investigate the material order variability pattern, in the construction supply chain management, considering the prefabricated materials, the data analysis is done separately on quantitative and qualitative data. Using a system dynamic model (stock and flow diagram), the interrelationship between various variables are observed. For this scope of research, the model is not simulated but the relationship of the components governing the material delivery order variability is shown. Hence, this chapter contains the results obtained from the collected quantitative and qualitative data analysis. The descriptive method was used to analyze the quantitative data and the coding method was used to analyze qualitative data.

3.1 QUANTITATIVE DATA ANALYSIS:

Following are the material data received from the three companies across the USA. The data obtained was in the format of the scheduled and actual delivery date of materials. The difference between the actual delivery date and scheduled delivery date was calculated, and the descriptive statistical method was used to get the results.

Company A: Metal Framing for Gypsum Board

: Mechanical Material

: Electrical Material

: Plumbing Material

Company B: Fire Fighting and Fire Alarm Material

: Electrical Material

Company C: Mass Timber Beam and Column Material

We will first analyze individual data sets and then compare everything collectively to understand the pattern.

The set of 8 data sets of prefabricated materials was analyzed with the help of Microsoft excel.

The descriptive statistical experiments were done using an excel data analysis tool (inbuild) on the scheduled and actual delivery date variance.

Material 1: Metal Framing for Gypsum Board: Company A

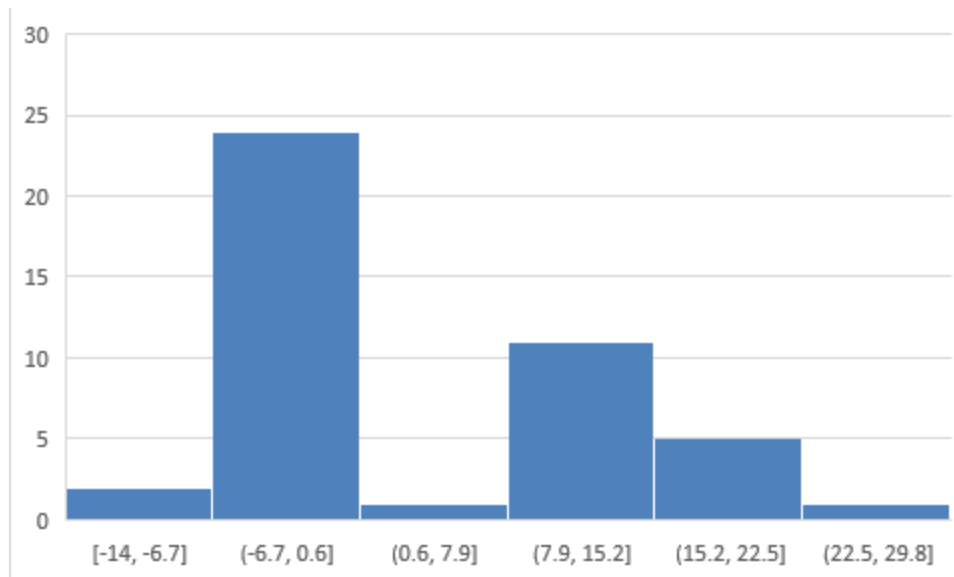


Figure 3. 1 Material 1 Distribution graph

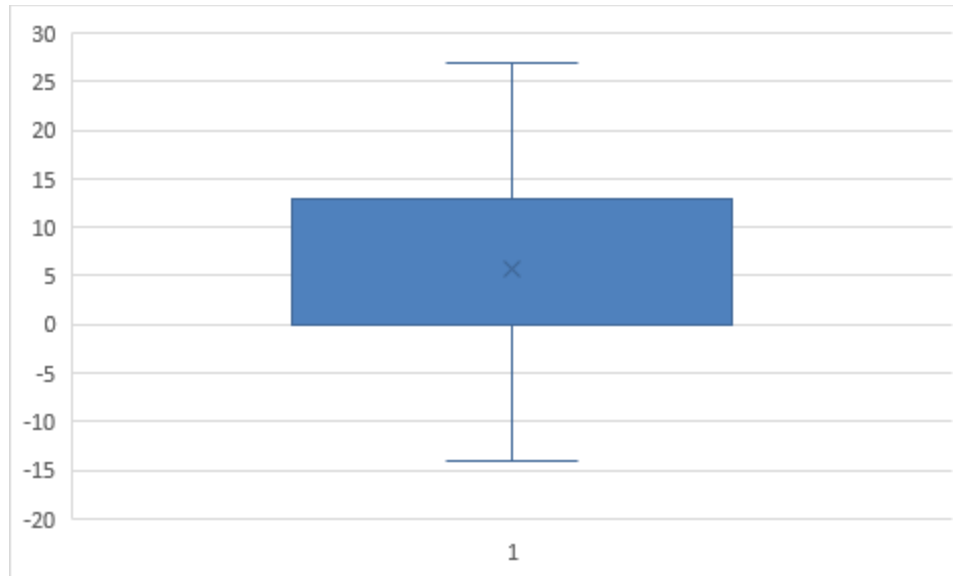


Figure 3. 2 Material 1 Box and Whisker Plot

The descriptive statistical data shows that the metal framing material distribution is nearly symmetrical. It has a slightly right-skewed pattern as the skewness lies between -0.5 and 0.5 with no outliers. The critical t-value < Actual t-value indicates the data is statistically significant. The count of the data sample is greater than 30; hence we can say that it was enough for us to decide the statistical significance of the data set. Since the data has fewer positive and negative extremes, we got Platykurtic distribution with a value of -0.4.

The following were the results obtained when compared with the normal distribution parameters.

Range	Predicted % Data	Actual % of Data
-1SD to 1SD	68%	82%
-2SD to 2SD	95%	98%
-3SD to 3SD	99.7%	100%

Table 3. 1 Material 1 Comparison of distribution parameters (Predicted v/s Actual)

The denser data from the above table is near the mean and makes the pattern thinner at the tail. Also, it is essential to note that 66% of the data out of 82% had no variance. The rest of the data from that range had more variance making it denser.

It was observed in the qualitative data that the maximum variance was obtained because of the owner's design changes for the level 1 material. The other variances were observed because of the global supply chain disruptions and material scarcity of the metal framing material.

Statistical Components	Metal Framing for Gypsum Board	Remarks
Mean	5.7	
Standard Error	1.4	
Median	0.0	
Mode	0.0	
Standard Deviation	9.0	
Sample Variance	81.2	
Kurtosis	-0.4	Platykurtic Distribution
Skewness	0.4	Right Skewed
Range	41.0	
Minimum	-14.0	
Maximum	27.0	
Sum	250.0	
Count	44.0	
Confidence Level (95.0%)	2.7	
Outliers	No Outliers	
Upper Confidence Level (95%)	8.4	
Lower Confidence Level (95%)	2.9	
Significantly Skewed	No	
Probability Assumption	5%	
Actual t- value	4.18	
Critical t-value	2.02	
Random or Significant	Significant	

Table 3. 2 Material 1 Statistical Components

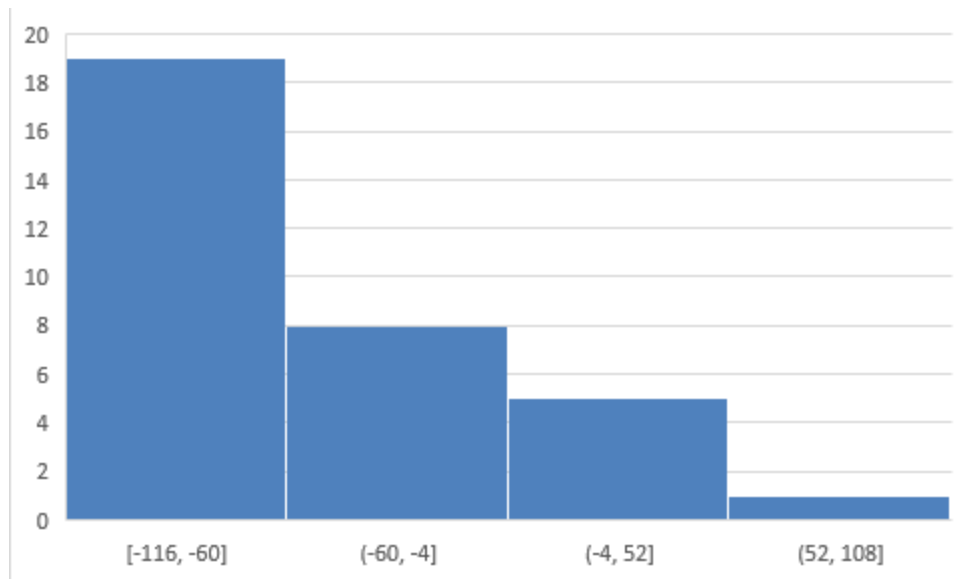
Material 2: Mechanical Material: Company A

Figure 3. 3 Material 2 Distribution Graph

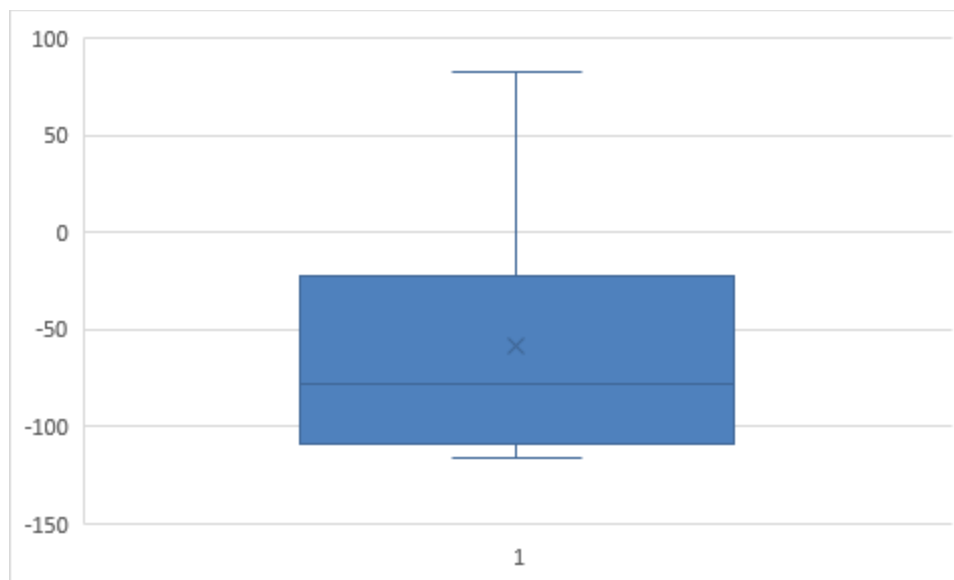


Figure 3. 4 Material 2 Box and Whisker Plot

Range	Predicted % Data	Actual % of Data
-1SD to 1SD	68%	79%
-2SD to 2SD	95%	97%
-3SD to 3SD	99.7%	100%

Table 3. 3 Material 2 Comparison of distribution parameters (Predicted v/s Actual)

Looking at the graph above, it is noted that the distribution is skewed right with more Kurtosis. The kurtosis calculated is 15.8, much more significant than three, and has more sharptails. The leptokurtic distribution indicates that the data has extreme outliers. Still, when the information is observed, it is noted that 79% of the data is between 1SD and it is negative, and the extreme data at the tail is positive, which contributes to around 20% of the data set., making it skewed. It is also important to note that, due to extreme variance, the sample resulted in non-significant but random; its actual t-value is less than that of the critical t-value.

The interview observed that the materials were delivered significantly early, about four months early, by considering the mechanical item supply chain disruptions and transport problems. Considering the mechanical items, we have pumps, condenser units, exhaust, pot feeders, tanks, etc., which are large items that need to be assembled with many spare parts, and hence precautions were taken looking at the global supply chain descriptions. It was noted that the schedule drafted had an extra buffer allocated to these materials such that, even though the material is delayed, the project progress should not be affected. Here, in this case, the material came on time, and the kept buffer did not get utilized, and we can see the unfavorable variance in the data received.

Statistical Components	Mechanical -1	Remarks
Mean	-58.2	
Standard Error	9.1	
Median	-78.0	
Mode	-109.0	
Standard Deviation	52.4	Greater Distribution Magnitude
Sample Variance	2750.1	
Kurtosis	-0.3	Platykurtic Distribution
Skewness	0.7	Right Skewed
Range	199.0	
Minimum	-116.0	
Maximum	83.0	
Sum	-1920.0	
Count	33.0	
Confidence Level (95.0%)	18.6	
Outliers	No Outliers	
Upper Confidence Level (95%)	-39.6	
Lower Confidence Level (95%)	-76.8	
Significantly Skewed	No	
Probability Assumption	5%	
Actual t- value	-6.37	
Critical t-value	2.04	
Random or Significant	Random	

Table 3. 4 Material 2 Statistical Components

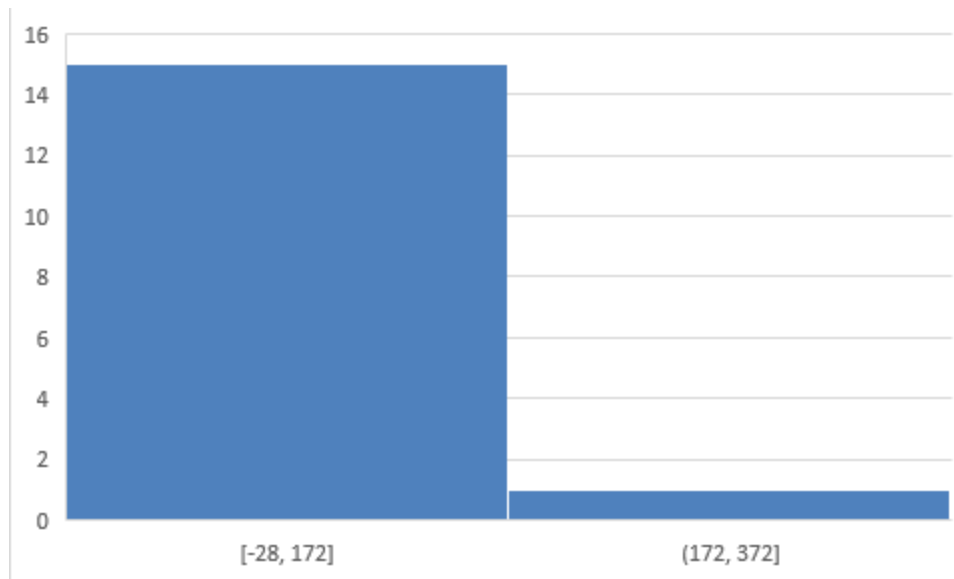
Material 3: Electrical Material: Company A

Figure 3. 5 Material 3 Distribution Graph

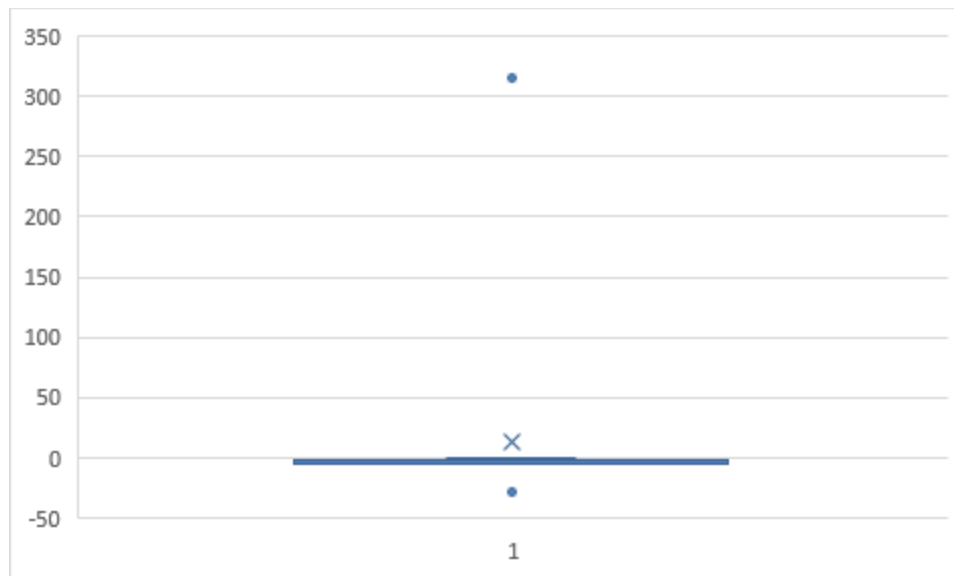


Figure 3. 6 Material 3 Box and Whisker Plot

Range	Predicted % Data	Actual % of Data
-1SD to 1SD	68%	94%
-2SD to 2SD	95%	94%
-3SD to 3SD	99.7%	100%

Table 3. 5 Material 3 Comparison of distribution parameters (Predicted v/s Actual)

This material data set had a few delivery dates. Since the sample size was tiny, the results obtained by doing descriptive statistical analysis were random and not significant. Getting a leptokurtic distribution graph with kurtosis 15.8 indicates that the extremes have greater magnitude and outliers. There is only one delivery that got delayed (315 days). The rest were delivered early (-6 days). The above Box and Whisker diagram provide a detailed description. The data will not be considered for the research purpose as it has genuine outliers. The actual % data was the same for 1SD and 2SD, 94%.

Statistical Components	Electrical -1	Remarks
Mean	13.8	
Standard Error	20.1	
Median	-6.0	
Mode	-6.0	
Standard Deviation	80.6	Greater Distribution Magnitude
Sample Variance	6490.2	
Kurtosis	15.8	Leptokurtic Distribution
Skewness	4.0	Right Skewed
Range	343.0	
Minimum	-28.0	
Maximum	315.0	
Sum	221.0	
Count	16.0	
Confidence Level (95.0%)	42.9	
Outliers	Yes	
Upper Confidence Level (95%)	56.7	
Lower Confidence Level (95%)	-29.1	
Significantly Skewed	Yes	
Probability Assumption	5%	
Actual t- value	0.69	
Critical t-value	2.13	
Random or Significant	Random	

Table 3. 6 Material 3 Statistical Components

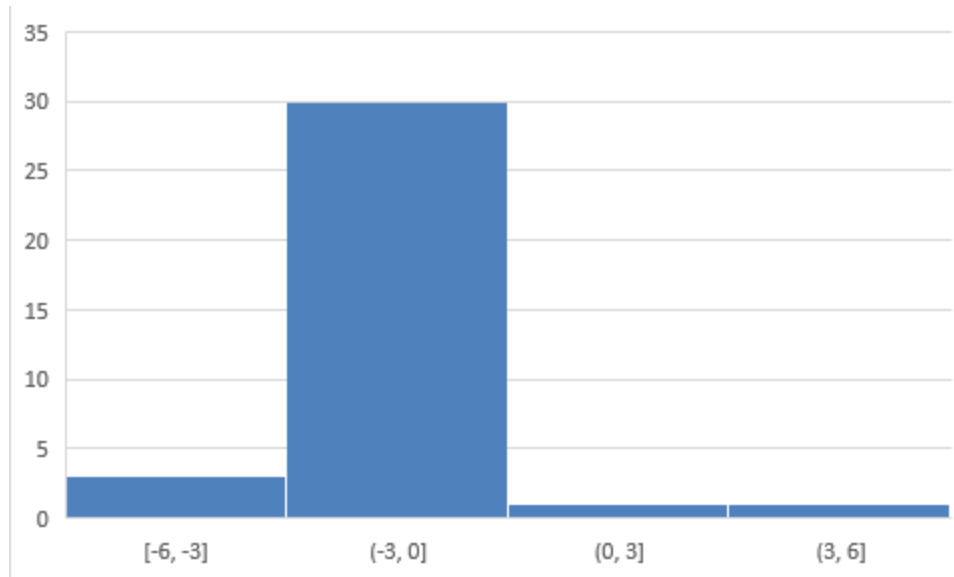
Material 4: Electrical Material 2: Company A

Figure 3. 7 Material 4 Distribution Graph

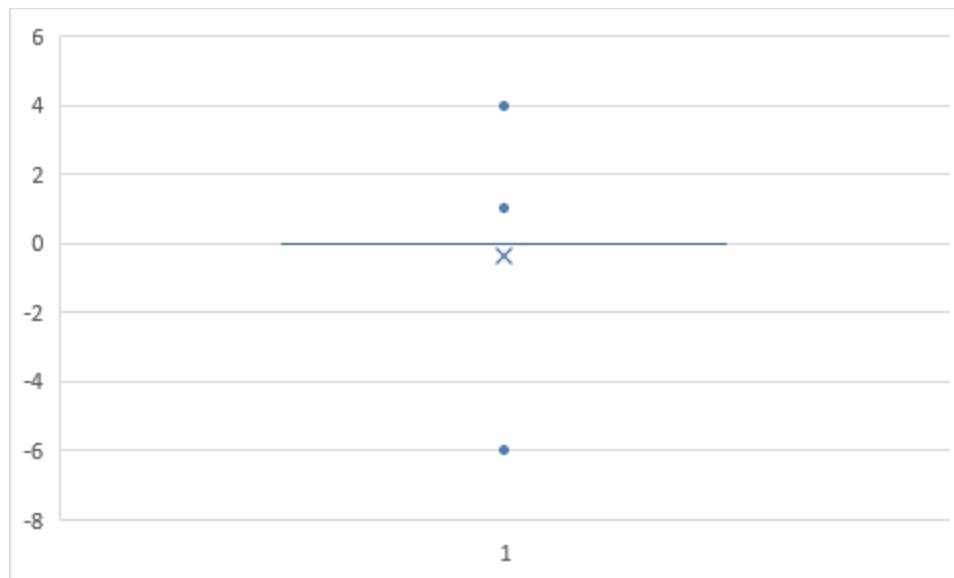


Figure 3. 8 Material 4 Box and Whisker Plot

Range	Predicted % Data	Actual % of Data
-1SD to 1SD	68%	89%
-2SD to 2SD	95%	89%
-3SD to 3SD	99.7%	100%

Table 3. 7 Material 4 Comparison of distribution parameters (Predicted v/s Actual)

Out of 35 deliveries received on-site, 31 of this material were on time, giving zero variance. The distribution of this data set resulted in left-skewed with skewness -2.1. The kurtosis was large, noted at 6.2 with Leptokurtic distribution. Again, the SD and 2SD ranges were reported at 89%, concluding that most of the data is near the mean, but the rest of the 11% data is varied with greater magnitude taking it to the left of the axis, making it left-skewed.

The qualitative analysis observed that this data, divided into two levels only, had level 1 delivered on time and just had variances in the level 2 deliveries. The sequential trade progress was observed, making the shift of a week for the material delivery at level 2 of the project.

Statistical Components	Electrical -2	Remarks
Mean	-0.4	
Standard Error	0.3	
Median	0.0	
Mode	0.0	
Standard Deviation	1.9	
Sample Variance	3.5	
Kurtosis	6.2	Leptokurtic Distribution
Skewness	-2.1	Left skewed
Range	10.0	
Minimum	-6.0	
Maximum	4.0	
Sum	-13.0	
Count	35.0	
Confidence Level (95.0%)	0.6	
Outliers	Yes	
Upper Confidence Level (95%)	0.3	
Lower Confidence Level (95%)	-1.0	
Significantly Skewed	No	
Probability Assumption	5%	
Actual t- value	-1.17	
Critical t-value	2.03	
Random or Significant	Random	

Table 3. 8 Material 4 Statistical Components

Material 5: Plumbing Material 1: Company A

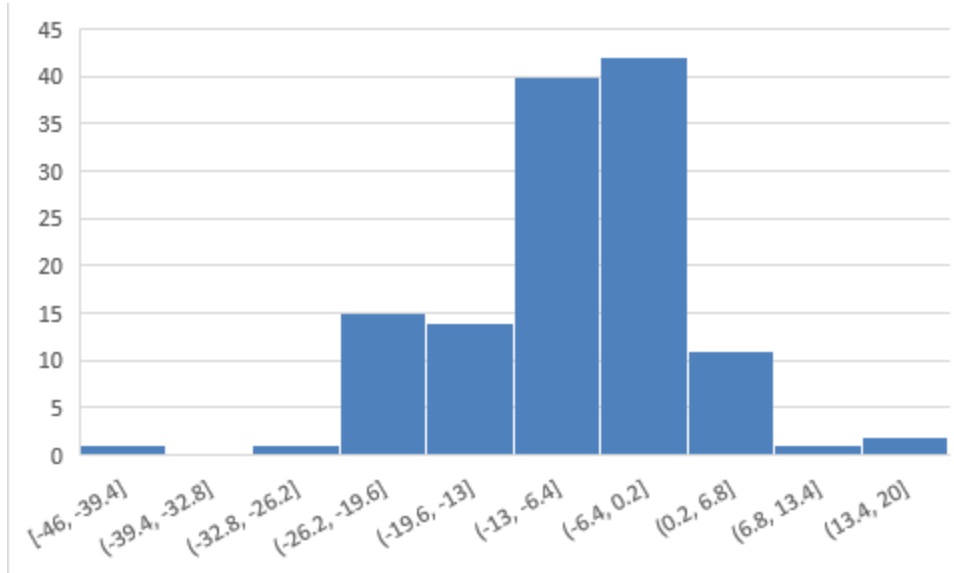


Figure 3.9 Material 5 Distribution Graph

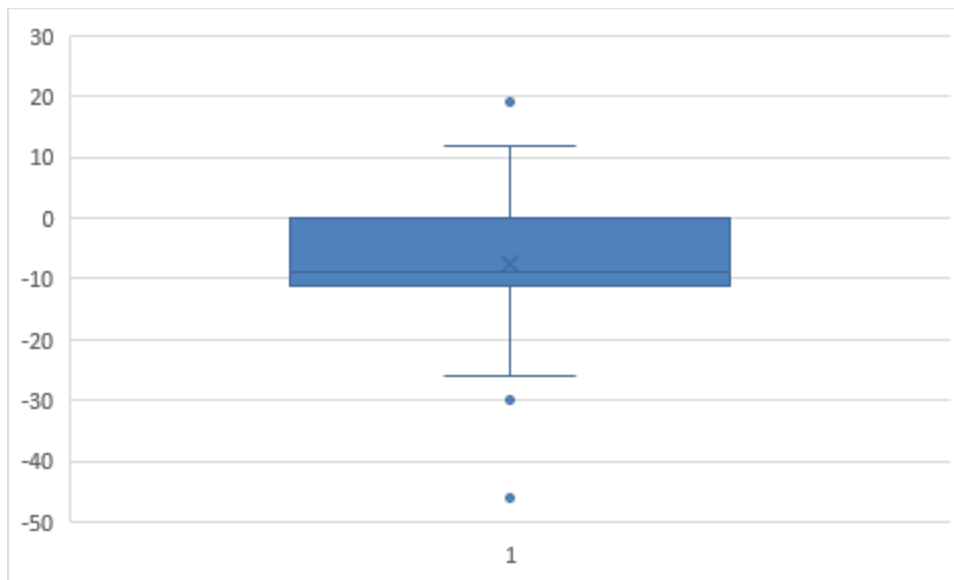


Figure 3.10 Material 5 Box and Whisker Plot (With Outliers)

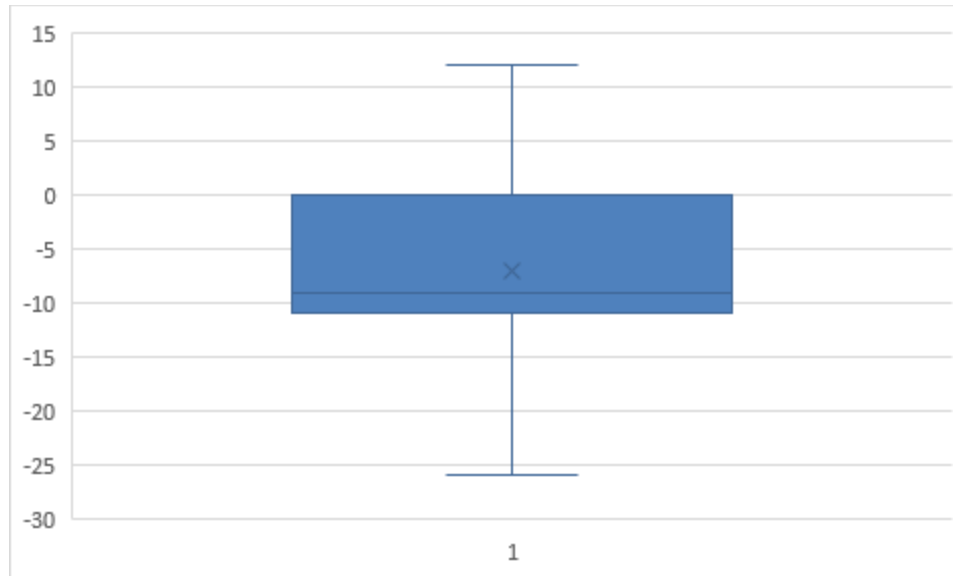


Figure 3. 11 Material 5 Box and Whisker Plot (W/o Outliers)

Range	Predicted % Data	Actual % of Data
-1SD to 1SD	68%	76%
-2SD to 2SD	95%	96%
-3SD to 3SD	99.7%	100%

Table 3. 9 Material 5 Comparison of distribution parameters (Predicted v/s Actual)

When rectified with the outliers, material 5 showed a nearly symmetrical distribution with Kurtosis -0.79 and skewness -0.2. The mean before and after removing the outliers changed by 0.00749 units which is significantly less and denote that the extreme outliers had little effect on the central zone. The actual data had 76% of values in the 1SD area and 96% in 2SD, which is much closer to the predicted data. Here, about 87% of the material received was delivered on time or early; hence, the mean is harmful.

Again, the delay for this material was noted because of the global supply chain description due to the pandemic.

Statistical Components	Plumbing -1	Remarks
Mean	-7.4	
Standard Error	0.9	
Median	-9.0	
Mode	0.0	
Standard Deviation	9.6	
Sample Variance	93.0	
Kurtosis	1.4	Leptokurtic Distribution
Skewness	-0.4	Left skewed
Range	65.0	
Minimum	-46.0	
Maximum	19.0	
Sum	-942.0	
Count	127.0	
Confidence Level (95.0%)	1.7	
Outliers	Yes	
Upper Confidence Level (95%)	-5.7	
Lower Confidence Level (95%)	-9.1	
Significantly Skewed	No	
Probability Assumption	5%	
Actual t- value	-8.67	
Critical t-value	1.98	
Random or Significant	Random	

Table 3. 10 Material 5 Statistical Components

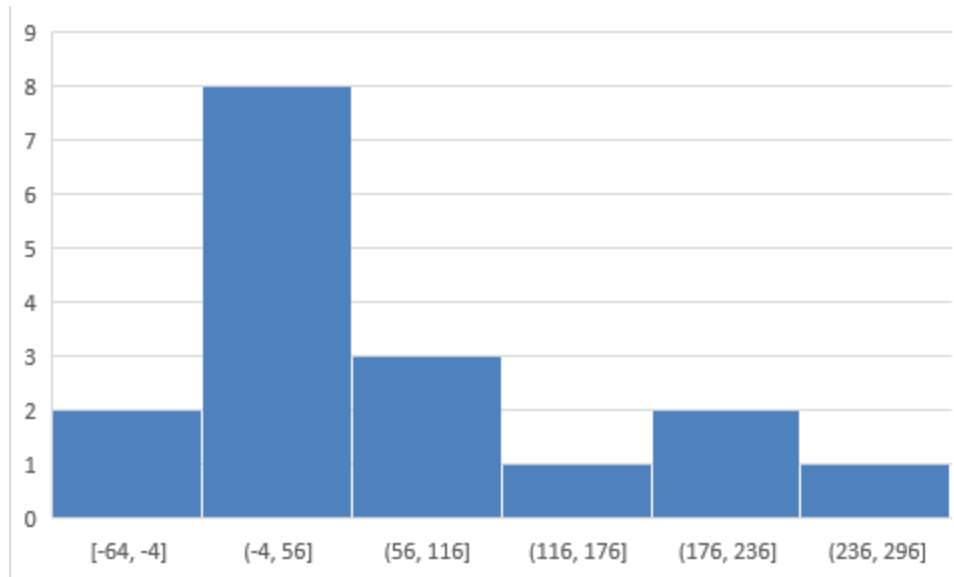
Material 6: Fire Fighting and Fire Alarm Material: Company B

Figure 3. 12 Material 6 Distribution Graph

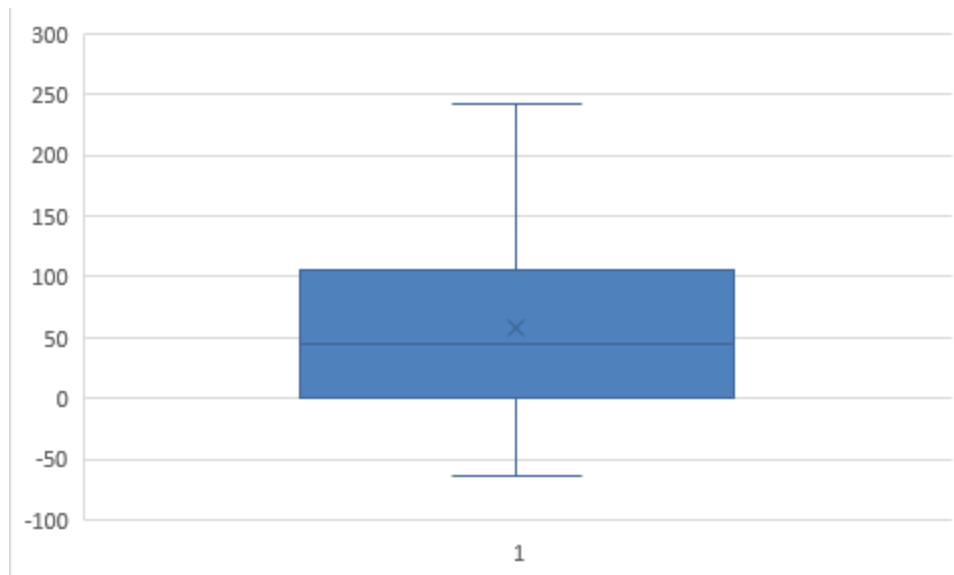


Figure 3. 13 Material 6 Box and Whisker Plot

Range	Predicted % Data	Actual % of Data
-1SD to 1SD	68%	74%
-2SD to 2SD	95%	94%
-3SD to 3SD	99.7%	100%

Table 3. 11 Material 6 Comparison of distribution parameters (Predicted v/s Actual)

The statistical analysis shows that the data is moderately right skewed. The actual data got much closer to the predicted one; the data distributed in 1SD was 76%. The order variability seen with this material was heavy. The reasons couldn't be drawn as the company just provided the quantitative data, and the interview couldn't be taken for unknown reasons.

By doing the t-value analysis, the data proved to be significant.

Statistical Components	FF&FA -1	Remarks
Mean	58.8	
Standard Error	20.0	
Median	45.0	
Mode	0.0	
Standard Deviation	82.3	Greater Distribution Magnitude
Sample Variance	6780.3	
Kurtosis	0.2	Leptokurtic Distribution
Skewness	0.9	Right Skewed
Range	306.0	
Minimum	-64.0	
Maximum	242.0	
Sum	999.0	
Count	17.0	
Confidence Level (95.0%)	42.3	
Outliers	No Outliers	
Upper Confidence Level (95%)	101.1	
Lower Confidence Level (95%)	16.4	
Significantly Skewed	No	
Probability Assumption	5%	
Actual t- value	2.94	
Critical t-value	2.12	
Random or Significant	Significant	

Table 3. 12 Material 6 Statistical Components

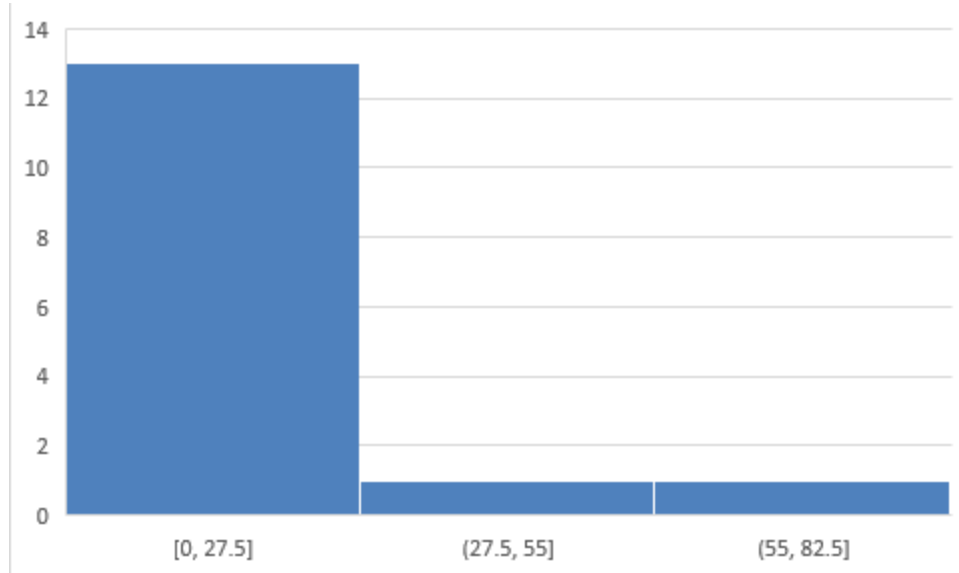
Material 7: Mass Timber Material: Company C

Figure 3. 14 Material 7 Distribution Graph

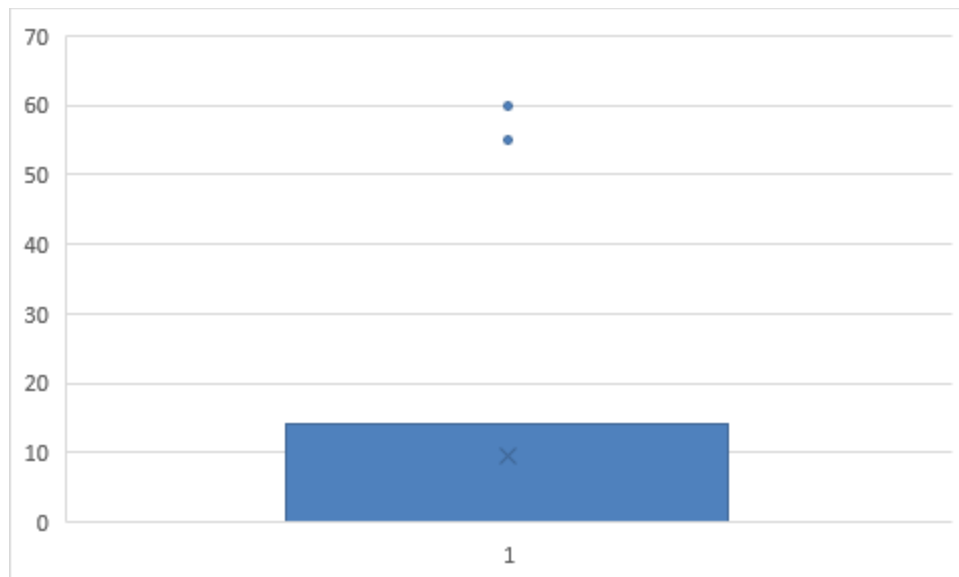


Figure 3. 15 Material 7 Box and Whisker Plot

Range	Predicted % Data	Actual % of Data
-1SD to 1SD	68%	87%
-2SD to 2SD	95%	87%
-3SD to 3SD	99.7%	100%

Table 3. 13 Material 7 Comparison of distribution parameters (Predicted v/s Actual)

The above observation clearly shows that the data set is exceptionally right skewed. The supplying company went out of business even though the material delivery schedule was handled perfectly throughout the job. Hence, the supply chain description happened. Therefore, at the end of the project, the deliveries for the material went off by around 50 days, turning the normally customarily distributed pattern into rightly skewed. We have both SD and 2SD % as the same for the actual data,

Statistical Components	Mass Timber	Remarks
Mean	9.6	
Standard Error	5.2	
Median	0.0	
Mode	0.0	
Standard Deviation	20.1	Greater Distribution Magnitude
Sample Variance	402.5	
Kurtosis	3.5	Leptokurtic Distribution
Skewness	2.2	Right Skewed
Range	60.0	
Minimum	0.0	
Maximum	60.0	
Sum	144.0	
Count	15.0	
Confidence Level (95.0%)	11.1	
Outliers	Yes	
Upper Confidence Level (95%)	20.7	
Lower Confidence Level (95%)	-1.5	
Significantly Skewed	Yes	
Probability Assumption	5%	
Actual t- value	1.85	
Critical t-value	2.14	
Random or Significant	Random	

Table 3. 14 Material 7 Statistical Components

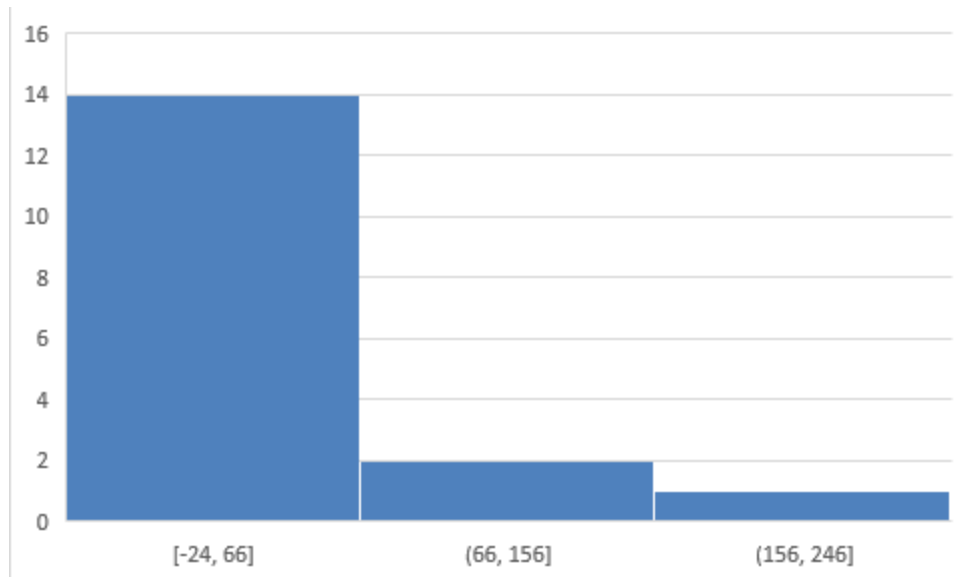
Material 8: Mechanical Material: Company A

Figure 3. 16 Material 8 Distribution Graph

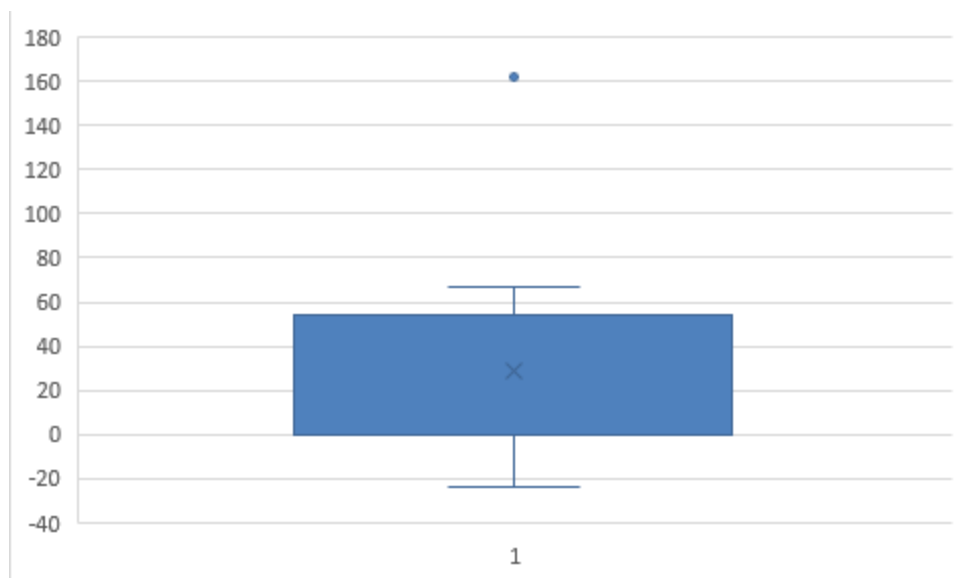


Figure 3. 17 Material 8 Box and Whisker Plot

Range	Predicted % Data	Actual % of Data
-1SD to 1SD	68%	87%
-2SD to 2SD	95%	87%
-3SD to 3SD	99.7%	100%

Table 3. 15 Material 8 Comparison of distribution parameters (Predicted v/s Actual)

From the calculated data, the distribution graph for this material is right-skewed distribution graph right-skewed. There is just one early delivery, eight deliveries were on time, and the rest eight were delayed widely. This is reflected in table 3.15 that about 94% of the results fall between 2 standard deviations. From the box and whisker plot. It is just one outlier that can be noted, which doesn't affect the skewness of the graph when removed.

Statistical Components	Mechanical-2	Remarks
Mean	28.9	
Standard Error	10.8	
Median	0.0	
Mode	0.0	
Standard Deviation	44.5	Greater Distribution Magnitude
Sample Variance	1982.3	
Kurtosis	4.0	Leptokurtic Distribution
Skewness	1.7	Right Skewed
Range	186.0	
Minimum	-24.0	
Maximum	162.0	
Sum	492.0	
Count	17.0	
Confidence Level (95.0%)	22.9	
Outliers	No	
Upper Confidence Level (95%)	51.8	
Lower Confidence Level (95%)	6.0	
Significantly Skewed	Yes	
Probability Assumption	5%	
Actual t- value	2.68	
Critical t-value	2.12	
Random or Significant	Significant	

Table 3. 16 Material 8 Statistical Components

Findings of Quantitative Data Analysis:

Sr. No.	Material Code	Material Name	Observation	Reason for Variance
1	Material-1	Metal Frame	It is slightly skewed right. The mean of the sample is positive without any outlier.	Design Change from the owner's side which forced the contractor to shift the delivery days by 2 weeks. It also has an effect of global supply chain management.
2	Material-2	Mechanical	It is skewed right, but 82% of the data is delivered early here, and 3% of each is either on time or delivered late on site. Hence the mean of the distribution has a negative value, and there is no outlier; because of the 82% of data being delivered early, the distribution has a right-skewed pattern.	Here, due to a global supply chain issue, the schedule was made by keeping a significant buffer but in the actual case, the material got delivered early. The material which got delayed is just 3% in the sample.
3	Material-3	Electrical	This can be considered as a special case. The material delivery count is 15, There is a positive and wide spreader outlier which causes the data to skew right and left. The data is skewed right while considering the right (Mean positive) and turns skewed left if the outlier is removed (Mean negative). Rest all the deliveries are either early or on time.	This is the example of contractor giving preference to early delivery of the material on site considering global supply chain issue.
4	Material-4	Electrical	It has skewed left due to the presence of the outlier. Without outlier it is a straight line without any variance since all other deliveries are on time.	It has most of on-time deliveries. The material being electrical material, which requires precision, and a delayed delivery is

			Interesting thing is, here 3 readings are coming outliers which are the only deviated data or else all others are delivered on time. It's quartile 1 and 2 both are zero.	generally not favorable from a project point of view.
5	Material-5	Plumbing	The distribution is left skewed (With or without outliers both). It has combination of all the possible deliveries and mean is negative.	Interview could not be arranged for this material and company.
6	Material-6	FF&FA	It is skewed right, with no outliers. The data has large, delayed variance.	The reason provided was the global supply chain issue.
7	Material-7	Mass Timber	Right skewed with outliers. The outliers are those which are delayed deliveries received. Rest all are on time.	The supplier shutting down the business is the reason for the delayed deliveries or else, the team was working in integrated delivery method, and all the processes were well coordinated resulting in on time delivery of the material even in Covid time.
8	Material-8	Mechanical	It is right skewed with just 1 outlier.	The reason for delay noted was, the parts of the mechanical products to be assembled at single shop, came with delay and hence the assembly did not work out well. It was also affected by the global supply chain issue.

Table 3. 17 Summary of Quantitative Observations

Hence, by observing the above data, the suppliers and manufacturers can simulate their production schedule and predict the order reliability pattern.

3.2 SYSTEM DYNAMICS MODELING

A system dynamic modeling technique was used to study the behavior of order reliability. With the help of interview data, the whole supply chain system was analyzed, and the variables were drawn out of it. For the sake of simplicity and to avoid the conflicts, the model is not simulated, as the simulation needs functions in the variables and adding the functions; preparing the model is a competency-based thing, which is highly dependent on how the modeler models the system and provides input while assuming few things.

Following are the causal loops formed,

Loop 1: Project Team Competency ➤ Design Accuracy ➤ Material QTO ➤ Material Order Accuracy ➤ Lead Time. ➤ Uncertainties ➤ Project Progress.

Loop 2: Lead Time ➤ Uncertainties ➤ Material Demand ➤ Production

Loop 3: Order Variability ➤ Permit ➤ Project Progress ➤ Material Demand
Production ➤ Lead Time

Loop 4: Order Variability ➤ Information Sharing ➤ Project Progress

Loop 5: Project team Competency ➤ Lean Implementation ➤ Project Progress
Information Sharing

For defining purpose and since the simulation is not performed, the variables used were forms of process and not nouns. The polarity and their relationships were provided with the help of knowledge received after interviewing supply chain participants. There were two stocks considered, Project progress and Order Variability. First, by creating Project progress as a stock, we can very well accumulate the data in that stock and use it in the order variability directly. It was concluded that the project progress is one of the most important reasons for the contractor's order variability.

The interviews noted that the variable parameters like Permit, Schedule accuracy, Inventory capacity, Lead Time, and collaboration/transparency are the essential factors that define the order reliability in the construction supply chain market.

If we study the prepared model, it is clearly shown that many such variables are interlinked with each other and impact the order variability.

For example, the lead time is not just governed by a single entity. Still, there are several entities on which it is dependent, such as Transportation availability, Raw material availability, and production dependent on material demand.

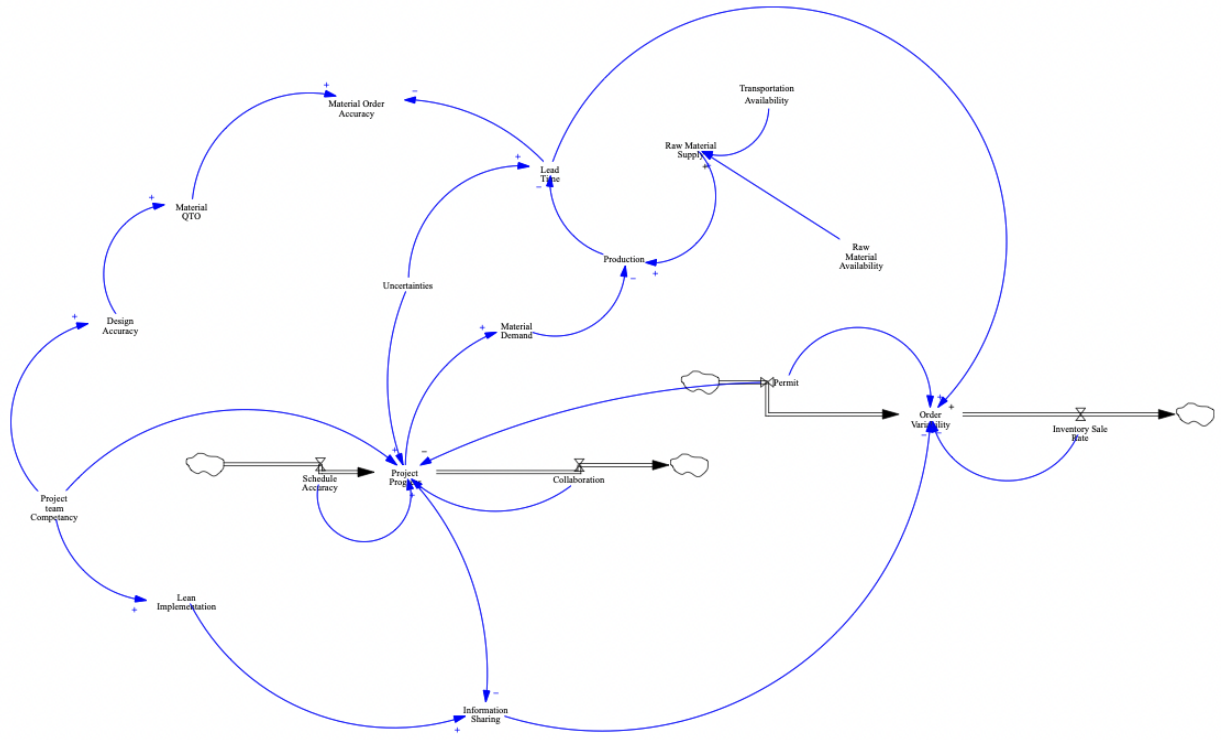


Figure 3. 18 System Dynamic Model

Chapter 4. DISCUSSION

The observations drawn from both supplier/manufacture/ contractor interviews and the quantitative data are discussed below. For the qualitative data purpose, interviews were also conducted with those construction professionals who have not contributed to quantitative data. The qualitative data received was rich in content and had great insights into the material order reliability of the prefabricated products.

- 1) From the contractors' point of view, the early involvement of suppliers and manufacturers in the project schedules provides excellent value to the supply chain. Interestingly, it was noted that suppliers and manufacturers often take advantage of contractors' project delay routine and mislead the contractors by providing the wrong lead times of the materials. Was mentioned by one of the suppliers, *"I got five guys on a job when it's supposed to be seven or eight, and we take a little bit of heat from the general contractor that we don't have the appropriate, my guys, on-site, But again, they didn't start when they were supposed to, so we have a little leeway, and you know, it's just a lot of communication."* It is in their self-interest to keep less crew size in front of the contractor and utilize the actual crew size in accomplishing several other jobs. This is done under the assumption that the project is anyway going to get delayed.
- 2) On the other hand, contractors keep at least a 3-week buffer in the schedule shared by the suppliers and manufacturers or the lead time to account for construction uncertainties and supply chain problems. One of the GCs stated, *"By asking subcontractors the lead times of the materials, they then ask the suppliers what the lead times are. After receiving those, we usually add 3-4 weeks of buffer in our scheduling depending upon the schedule needs"*.

Considering both sides, it is noted that transparency is an essential factor in keeping the supply chain as close as possible to the project material procurement pipeline. Because there is a false demand held in front of the suppliers and manufacturers, it affects their production schedule and initiates the bullwhip [effect in the construction supply chain. Also, since the involvement of buffer creates a false assumption, it is noted that the project is getting accelerated from the contractors' side. Hence, the materials have to be ordered much ahead of the time provided to the suppliers and manufacturers. This phenomenon was observed in the Company A materials, where we observed that the negative variance obtained was throughout the deliveries and not just for a few material deliveries. It is the limitation of the research where it is essential to analyze the other side of the supply chain for the same material here; just the contractor side was considered (This was due to a lack of participation from the suppliers and manufacturers side)

- 3) The example of the bullwhip effect plays a vital role in order reliability. Following is the chain of effect taking place in today's construction market. The bullwhip effect can reduce the agility of the supply chain, amplify the variability of the orders, reduce efficiency, and add more cost to the supply chain. Because of the Bullwhip effect, the material orders received by the suppliers or manufacturers are more variabilities and uncertain than that of retailers. One of the authors concludes an exciting result of his research by completing that the suppliers or manufacturers only should react when the market consumption changes and not when the customer has a short lead-time requirement. This is possible when the customer provides information on the order, i.e., why the order is coming and why there is so much demand. This would help dampen the bullwhip effect and impact the supply chain (Moyaux and Chaib-draa 2007).

- 4) Hence in these uncertain times, where the market has a demand for materials and labor, and contrary to that, there is labor and material shortage, so to avoid this effect, it was noted that the contractors should share the demand information with the suppliers and manufacturers and not allow them to forecast the demand. It is supplier and manufacturers' competency to predict the demand accurately by looking at the market condition and not at the unknown factors. The Mechanical and the quantitative electrical data received were delayed because of the great demand but shorter supply, labor shortage in the manufacturing shops, and the USA transport crisis. One of the project managers from the contractor's side mentioned that *"The phrase "sitting on a ship outside of LA" was heard many times over the past few years. This comes into play when we think about the material that isn't scarce but cannot get to where it needs to be physical. We have seen construction an uptick despite all of the other challenges. This increases labor demand, making it more difficult to secure resources. We have seen construction on an uptick despite all of the other challenges. This increases labor demand, making it more difficult to secure resources."*

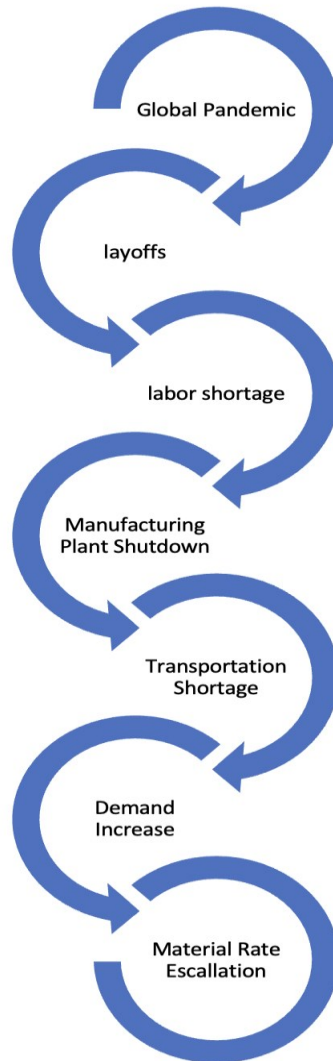


Figure 4. 1 Chain of Issues

- 5) Lean practices are also an essential factor in order variability. Lean in the supply chain reduces the lead time and removes the waste from the processes. But if it is not

implemented from the start of the project and implemented midway, it can hamper its progress and hence the supply chain. The best example given was the delivery of the prefabricated panels for one of the projects by the superintendent on site, stating that, “*we might implement it just when the delivery date is nearby and instead of double handling the material we plan now to go with JIT. This happens because lean practices were not part of this before, but during the construction, the team starts implementing it*”. On that project, the lean JIT was implemented midway. Due to that, the quality control management got disrupted and led to either material delivery delay or material delivery rejection only. In the case of JIT, the quality control part is either done at the shop beforehand or through submittals, which is very important.

- 6) Many contractors concluded that they prefer ordering the material early on-site when looking at the global supply chain problems. One of the interviewees stated that when asked about early delivery or on-time delivery; the answer received was, “*If you ask me the same question, two years ago, I will say in time deliberate by if you ask me right now, which is what you're doing right now, I will say order as soon as possible.*” Also, another interviewee from the contractor's side mentioned that “*it is OK to spend a couple of thousand bucks behind getting the material early on-site in comparison with the project cost and incurring more cost by having material late at the site.*” When asked about the inventory space, 3 out of 5 contractors said they have enough room at the site to keep inventory ahead of time. But the rest of them said it is either held at the supplier or manufacturer's yard, or we provide them some off-site inventory space and pay for it. Also, the contractors in contractual privity with owners directly tend always to order the material early, saying it is better to pay for the inventory than waiting for the material and

deaccelerating the project progress and incurring costs likewise. That is the reason for keeping a buffer and ordering the material early. They also contain material early to lock the price and mitigate the risk of price escalation. One contractor also noted that they call fabric early even though the project progress is going well; that way, they might incur some cost for the supplier and manufacturer, but it is always preferable and practiced.

- 7) Against the coordination and involvement in the supply chain, construction project participants interviewed were aggregating that constant coordination with supplier/manufacturer and sub-contractor is essential for a reliable supply chain,” *We work hand in hand with our installation team to let them know when the materials will appear. We get a crane rental or a crane or a lift.*” It was noted that the contractors also use software to keep track of the materials with suppliers and manufacturers. As the activity approaches on schedule, involving suppliers and manufacturers in the weekly review meetings is as important as anything. Implementation of LPS is vital. One of the contractors, when asked about involving suppliers and manufacturers in the project schedule, one of the contractors came up with an interesting fact that GC shares every piece of information with the sub-contractors. Still, they don’t know whether that information is shared with the subcontractor’s supplier/manufacturer, “ *We do share the schedule with our subcontractors, but it is subcontractors' responsibility to share the schedule with their suppliers and manufacturers; we don’t track that thing, as what level of adjustment needs to be done in the schedule is subs responsibility.*” The information chain link is weak, and hence, even though proper care has been taken at the downstream end, mid-way between the pipeline, it can create a problem, and thus, the reliability reduces.

- 8) Keeping transparency is agreed upon by everyone but never kept in the proper sense. One of the questions in the interview asked the contractors whether they provide a reason to the supplier and manufacturer for order variability ((early or delay)? All the contractors mentioned that it is not essential or needed to provide them the reason. Just sending an email or a call is sufficient to let them know that the scheduled delivery date has been changed. This affects the suppliers and manufacturers to get a faulty demand or decline in market condition. It is observed that, from the supplier/manufacturer side, they forecast against the wrong set of figures. And most importantly, the trust factor plays an important role, as taking advantage of one another's mistakes leads to supply chain management breakdown.
- 9) Suppliers and manufacturers gave an essential point for keeping information transparency at its peak. One of the interviews mentioned that upstream entities' responsibility is to demand high performance from downstream entities. If they are not sharing any information, it is their responsibility to ask for it and keep themselves updated. One of the suppliers mentioned that they plan to set up a process in the coming days to coordinate well with the GCs. All GCs from the region will be called, and together, they will solve the issue of lead time and production control.
- 10) When asked about the inventory space, all the suppliers and manufacturers said that they not have got much inventory space. Some part of the inventory space is kept for the partial inventory comprising standardized items / spare parts, and some are held against the delay. But when asked about handling the contractor's order variability, the roofing fabricator stated that if the order date change is received, they simply contact another contractor and ask if they want the material early, *“What happens often is that we will let you know that if*

you don't take it now, it might go back in the queue and I will transfer the material to the next person up who's waiting on materials, and your materials now get shipped to that person to somebody else, and you're back in line again waiting for your materials.” The contractor who changed the order delivery date must wait in the queue again. This strict behavior is noted right after Covid, as the lead time for raw material has shifted from 7 days to 8 months. Many suppliers and manufacturers have found keeping the material at some other offsite place on contractors’ risk, where contractors pay for the inventory, *“The GC is the client who has to take it; they have to find a place.”* The inclusion of a contracting clause against the inventory management is also kept in Front of the contractors.

The quantitative and qualitative analysis gives an overall idea of how the pattern of the order delivery variability is for the prefabricated materials and the reasons behind that pattern. Six out of eight material results are right-skewed, excluding material-4 and material-5. The array of data is towards the left tail of the distribution. The mean being positive indicates that the materials are ordered later than the scheduled delivery date ($\text{Difference} = \text{Actual Delivery date} - \text{Scheduled Delivery Date}$). The qualitative data supports this statement because it was stated in interviews that, due to pandemics, global supply chain disruptions, and specific transport problems, the material is preferred to be ordered earlier. Also, contractor tries to safeguard themselves by including buffering the schedule sent to vendors; now, if the buffer is not getting consumed, it is evident that the site has an early requirement of the material, which is informed to the vendors in the form of the date change order. It is important to note that the positivity of the mean is since some of the materials from the sample require assembly in the shop, and the parts and pieces are brought to one shop first. So, suppose the delivery of a single element is delayed. In that case, the

whole material gets delayed, and that is what happened with the materials with the right-skewed pattern but have a positive mean.

Further, by studying the combined effects of tails, it is understood that only material one and material 2 have Platykurtic distribution, and the rest of the material has Leptokurtic distribution. That being observed, it can be concluded that the sample variability of material one and material 2 is stable and predictable because there is no effect of outliers in them. But on the other hand, in the rest of the materials, the distribution being Leptokurtic, the distribution of variability order is volatile and unpredictable, with the presence of outliers. Since the sample data is small for this study, the outliers were not removed, and the results were analyzed. From the interviews, it was understood that the prefabricated material is concerned with assembling the material at the shop. There are high chances that one single product being ordered is formed by combining many different parts collected from many other locations as per the design requirements (Engineered to order); hence current supply chain environment doesn't support the ideal assembly, and thus, for a single project, a couple of materials deliveries shows outliers.

Getting back to the literature, (Laitinen 1993) mentioned that one of the options to deal with the uncertainties in the supply chain management is to keep a buffer in schedule and inventory in the shop. This research supports this option, and it came as a result that contractors keep a buffer in their schedule, and on the other hand, vendors keep inventory (small and in the form of partial inventory). Another finding from this research was that the vendors take advantage of the contractor's considering buffer. Also, it is assumed that the project will get delayed and thus, try to show false information to the contractors (production crew size) and buy different jobs meanwhile.

On the other hand, some positive findings on how to streamline the supply chain were welcoming, and it's being practiced in the real world. As mentioned by (Min et al. 2005) following were the points kept Infront for getting the supply chain streamlining.

- 1) Work together, implement and monitor all supply chain activities constantly.
- 2) Integrate cross-firm operations
- 3) Focus on common goals
- 4) Share data with all stakeholders
- 5) Need for a systematic course of action
- 6) Detail performance matrix to formalize collaboration arrangements

The long-term relationship (Akintoye, McIntosh, and Fitzgerald 2000) criteria for better collaboration was also implemented by one of the suppliers stating that they try to adjust with the contractor's order variability as, for them, long term relationship and business are essential.

All the interviews constantly restated that collaboration, information sharing, and integration of all the supply chain participants are necessary for the construction supply chain. As mentioned by (Behera, Mohanty, and Prakash 2015), the problems lying at the interface motivate the purpose of this supply chain coordination.

While the literature says that to address the order variability, the supplier or manufacturer must keep inventory in their shop. Still, considering the unique conditions where this research is done, these suppliers and manufacturers have started including contract clauses against change in material delivery order date. This is because even they are in the same environment of increased lead time and many uncertainties for having raw material. So instead of consuming that risk, the contract clause mitigates it.

While we discuss the supportive findings of this literature from this paper, it is essential to know that there is a significant impact of unusual uncertainties in this data. Considering the prefabricated material, the assembly of a single mechanical product can take way too long a lead time because of the global supply chain issue, forming an outlier. Hence strategically, the contractors have implemented a practice of ordering material earlier. If there is no laydown area for that, these contractors are ready to put this material at a different storage location at their own cost.

Looking at the data collection hurdles, it is proposed that both supplier/manufacturer and contractor maintain a procurement log and note these delivery dates for each material. Following is the sample format in which this data can be stored. The company can use this data for risk assessment and plan the order delivery accordingly for the following projects.

Since this research uses a system dynamics model but doesn't simulate it, it would be encouraging for further research to simulate the model and check the behavioral pattern of the order variability concerning different variables taken at a time or collectively. Here, the difference between ideal cases and actual cases can be studied, and each variable's effect and whether it affects it can be known. This would help suppliers/manufacturers and contractors make better decisions and allow them to concentrate to a greater extent on certain variables.

Chapter 5. CONCLUSIONS & LIMITATIONS OF RESEARCH

While revisiting the research questions generated, it is concluded that, after studying the quantitative, and qualitative data and understanding the system dynamic model, the following are the main criteria responsible for the material delivery time variance, and these are the factors that govern the material delivery order reliability.

Reasons for Order Variability:

- 1) Design Changes from the owner's side
- 2) Design mistakes from designer
- 3) Permit Delay
- 4) Adding unnecessary buffer in the schedule creates false demand by the contractor.
- 5) Not involving subs/suppliers/manufacturers in preparing a schedule
- 6) Improper lean implementation
- 7) Suppliers and manufacturers are taking advantage of the assumption that GCs projects are anyway going to get delayed.
- 8) Improper communication and information transparency
- 9) Lack of capacity in a project to keep up with the progress
- 10) Raw material shortage / spare part shortage
- 11) Transportation / global supply chain issues

Structure of Production System:

For the second research question, regarding the structure of the production scheduling system with suppliers and manufacturers to manage contractor's order variability, it was noted that the first and

foremost important thing is communication and information transparency with the contractor. If enough data is not received from the contractors, the supplier/manufacturer's responsibility is to ask for it. Internal supplier meetings play a vital role in forecasting the demand. Still, it is also essential for them to check the order's legitimacy, whether it is a market demand or a bullwhip effect creating ripples in the market. Inventory space and putting a contract clause for not accepting on-time delivery is the solution received from the supplier/manufacturer's side. All suppliers and manufacturers mentioned that it is everyone's supply chain, and hence the responsibility matrix is evenly distributed. For the internal purpose, the crew size on the production system is a competitive task, and the crew should never be overallocated. Assuming that the contractor's job will delay, accepting a new position for self-interest is a bad practice. Suppliers and manufacturers also mentioned that they try to adjust with the GCs as much as possible to build trust and hence the business. It is the fact that, now, due to global supply chain issues, they must take stringent action, but in the pre-pandemic time, there were fewer penalties put on the contractors for any reason. It is to be noted that, while interviewing the participants from the supplier/manufacturer's side, and when asked about some more specific details about the production planning, they were found reluctant to share any detailed information under the hood of confidentiality.

The pattern of the material delivery variance:

Yes, from the quantitative data analysis, with the help of statistics, it can be concluded that there is a pattern in the material delivery variance of the prefabricated products. Six out of eight materials were Skewed right with their delivery variance distribution. Also, the interpretation of Platykurtic distribution denotes that the distribution is stable and predictable, but it is precisely the opposite of Leptokurtic distribution.

The discussion section describes the whole working pattern of the material order reliability. Knowing the listed criteria helps understand how the supplier or manufacturer must plan their production schedule. For the materials, where proper integration of information sharing was done, resulting in on-time delivery at site, for Example, Material 4 – Electrical and Material 7 – Mass Timber. The materials ordered way before the scheduled delivery date were also included in the right-skewed category.

Further, Material-1 and Material-2 showed negative kurtosis for the delivery variance data, and the rest all showed Leptokurtic Distribution and positive Kurtosis. Hence, we can conclude here that the kurtosis being more than three for materials-3 to material 8 creates less reliable results since the confidence level decreases by knowing the fact that leptokurtic distributions have broader fluctuations resulting in heavier tails. Contrary to that, the specialty of Kurtosis is that it ignores the central portion of the distribution and concentrates on the extremities. Hence it is ambiguous whether to rely on the Kurtosis pattern.

By understanding this pattern, suppliers and manufacturers can work on their production schedules. Future research motivates the simulation of the system dynamics model with variables from current research. The regulation of each variable, either individually or in combination, would provide a different output when order variability is kept as the stock.

Limitations:

- 1) The difficulty in obtaining data forced the research to concentrate on post- Pandemic scenarios. Hence, the Pre-Pandemic conditions would defer drastically considering the shorter lead times, availability of the materials and transportation, and thus the behavior of supplier/manufacturers towards production schedule.
- 2) It was not possible for taking the interview all the people who provided the quantitative data or for those interviewed who did not provide quantitative data.
- 3) It is essential to study both the suppliers/manufacturers side and general contractors side considering the material production under consideration to understand the order reliability pattern. Due to lack of participation, this was not achieved.
- 4) The dynamic system model was not simulated since each modeler would prepare the model based on their competency, considering their assumptions for equations. Since this research is to understand the order reliability pattern, it is avoided.

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APPENDIX A INTERVIEW QUESTIONS

QUESTIONS FOR SUPPLIER / MANUFACTURER / DB Sub

- 1) What level of involvement do you observe in the client's CPM schedule?
- 2) How do you coordinate with the contractor in coordinating the delivery schedule?
- 3) Do you have inventory space? Do you keep partial inventory?
- 4) How do you handle contractor's order variability?
- 5) How does your shop team coordinate with the installation team?
- 6) What is the strategy involved in handling the supply chain in two ways?
- 7) Do you forecast demand? What is the peak period for you? How do you handle inventory in that period?
- 8) Strategy to prepare your internal production schedule.
- 9) What do you think? Who controls the supply chain here? You? Contractor? or Owner?
- 10) How do you get compensated in case of excessive inventory costs incurred due to contractors' delivery schedules?

QUESTIONS FOR CONTRACTORS

- 1) Why do you change the delivery dates of materials? What can be the reasons behind falling into such a situation?
- 2) Do you prefer JIT or ordering material early?
- 3) How does your team coordinate with the supplier/manufacturer / Shop team?
- 4) Do you involve suppliers/manufacturers in the meetings, and what type of discussion do you do with them in review meetings?
- 5) What type of quality control system do you prefer?
- 6) Do you keep a buffer in the schedule to address the delivery date change problem beforehand?
- 7) Do you provide a reason to the upstream party behind the demand for material?