SYSTEMS APPROACH TO EPC MATERIAL PROCUREMENT STRATEGY

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ABSTRACT

The criticality of procurement and logistics to the success of Engineering Procurement Construction (EPC) projects cannot be over emphasized, as it has been a large area of opportunities that should be adequately exploited to enhance the overall performance of construction projects. EPC firms, which act as a catalyst for a nation's economy growth, still suffer from work backlog, and this further hinders them from functioning at their optimum level. The work backlog often arises from delay caused by the stakeholders of the complex EPC system. Furthermore, the delay may arise from design or management decisions.

Therefore, there is a need to study the effect of decisions taken by stakeholders to know the behaviour of the material procurement system with a focus on the timely delivery of construction materials to construction sites to ensure a smooth running of the construction process and prevent the work backlog due to shortage of materials on sites, which eventually leads to schedule and cost overrun.

The purpose of this study is to develop a novel Systems Dynamics (SD) decision support model to improve the construction material supply chain performance. The model emphasizes the essence of information sharing, collaboration, and trust among stakeholders; as such, the model may help EPC managers take effective decisions in an EPC material procurement system. The context of EPC, which this study is focused is to bulk construction materials.

This model will be a particularly useful tool to assist decision makers in evaluating the impact of material shortage and time delay by observing the simulated scenarios accordingly and in developing various effective policies.

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DEDICATED

TO

MY FATHER, ADUROTINILOJOISORO

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LIST OF ABBREVIATIONS AND SYMBOLS

ACRONYMS

CLD	Causal Loop Diagram
CMSC	Construction Material Supply Chain
CSCM	Construction Supply Chain Management
EPC	Engineering Procurement and Construction
ERP	Enterprise Resource Planning
JIT	Just In Time
SCN	Supply Chain Network
SD	Systems Dynamics
SS	Safety Stock

SYMBOLS

AD	Time to Average Delivery Rate, Weeks
ADD	Actual Delivery Delay, Week
AT	Time to Average Order Rate, Weeks
CEO	Change In Expected Order, Materials/Week
CMD	Change in Material Delivery Rate, Materials/Week
DDR	EPC Desired Material Delivery Rate, Materials/Week
DEI	Desired EPC Inventory, Material
DP	Desired WIP, Materials/Week
DSI	Desired Supplier Inventory, Material
DSR	Desired Shipment Rate, Materials/Week
DUR	EPC Desired Material Usage Rate, Materials/Week
DW	Desired WIP, Material
EDT	EPC Inventory Adjustment Time, Weeks
EI	EPC Inventory, Materials
EIC	EPC Inventory Coverage, Week
EID	EPC Inventory Discrepancy, Material
EMD	Expected Material Delivery, Materials
EO	EPC initial Order, Weeks

EOR	Expected EPC Order Rate, Materials
ESS	EPC Safety Stock, Weeks
FR	Order Fulfilment Rate Ratio
MDR	Material Delivery Rate, Materials/Week
MIC	EPC Minimum Material Inventory Coverage, Weeks
MSR	Supplier Maximum Shipment Rate, Materials/Week
MU	EPC Maximum Usage Rate, Materials/Week
MUR	EPC Material Usage Rate, Materials/Week
OB	EPC Order Backlog, Materials
OFR	Order Fulfilment Rate Materials/Week
OR	EPC Order Rate, Materials/Week
PR	Processing Rate, Materials/Week
PS	Processing Start Rate, Materials/Week
PT	Processing Time, Weeks
SDT	Supplier Inventory Adjustment Time, Weeks
SIC	Supplier Inventory Coverage, Week
SI	Supplier Inventory, Materials
SID	Supplier Inventory Discrepancy, Material
SR	Supplier Shipment Rate, Materials/Week
SS	Supplier Safety Stock, Weeks
ST	Minimum Shipping Time, Weeks
UR	EPC Usage Rate Ratio
WD	WIP Discrepancy, Material
WDT	WIP Adjustment Time, Weeks
WIP	Supplier's Work in Process Inventory, Materials
δ_3	Third order delay

CHAPTER 1
INTRODUCTION

1.1 Background and Motivation

In the Engineering, Procurement, and Construction (EPC) industry, procurement is a functional link between Engineering and Construction and is highly dependent on external companies. A strong unity among the project functions will improve the coordination and communication within the system (Yeo and Ning, 2002). Delivery of many large construction projects has encountered cost overrun, delay, and loss of productivity. It is interesting to explore the underlying causes. Many practitioners and researchers found that the poor management practice can lead to poor outcomes such as the lack of proper planning and scheduling, scope changes, design errors and omissions, and inappropriate management of material, equipment, and labour among many other factors.

Over the decades, procurement strategies have been implemented in various organisations such as manufacturing and construction to promote optimum performance in terms of cost, quality, and time. In the presence of these strategies, EPC contractors still suffer from work backlog which hinders them from functioning at a satisfactory level by embracing cost and schedule overrun. This has been traced to lack of collaboration among supply chain entities and visibility in the supply network. As depicted in Figure 1.1, the presence of feedforward and feedback flow of information and materials in construction supply chain calls for collaboration for an efficient supply chain system. An efficient supply chain management will require focus, not just on internal resources such as management, engineering, procurement, and construction teams but on external resources like suppliers and sub contractors. Furthermore, a large percentage of value adding occurs outside the boundaries of a single firm (Bruce, Daly, and Towers, 2004; Gomez-Mejia and Wiseman, 2007).

A number of comprehensive analyses have shown the necessity of collaboration as a way to mitigate delay which is costly (Iyer and Jha, 2005; Assaf, Al-Khalil, and Al-Hazmi, 1995; Enshassi, Mohamed, and Abushaban, 2009). Studies have shown that delay in construction is a major cause of negativity on construction projects which must be critically studied to improve project performance. From study on time waste, labor force on site use about 40% of the project time (from start time to finish time) on non-value added activities like waiting for permission or supply on site (Mohamed and Tucker, 1996). Figure 1.2 shows non value adding activities like waiting for material supply have been reported as a major cause of poor performance in construction projects (Jergeas, 2009; McTague and Jergeas 2002). Changing the external factors such as procurement delay, availability of resources, and customer changes alter the original schedule and cost. Schedule overrun occurs due to unpredictable duration for activities such as negotiation, material procurement, and supply, and unnecessarily long approval process with the authorities. Studies have shown that procurement takes about 50 to 70% of the total worth of construction projects (Langston, 2016; Cagno, Giulio, and Trucco, 2004; Murphree, Cate, and Vosburg, 2002; Kaming, Olomolaiye, Holt, and Harris, 1997), therefore, proper management of the procurement function in EPC will significantly and effectively minimize project deviation and save cost.

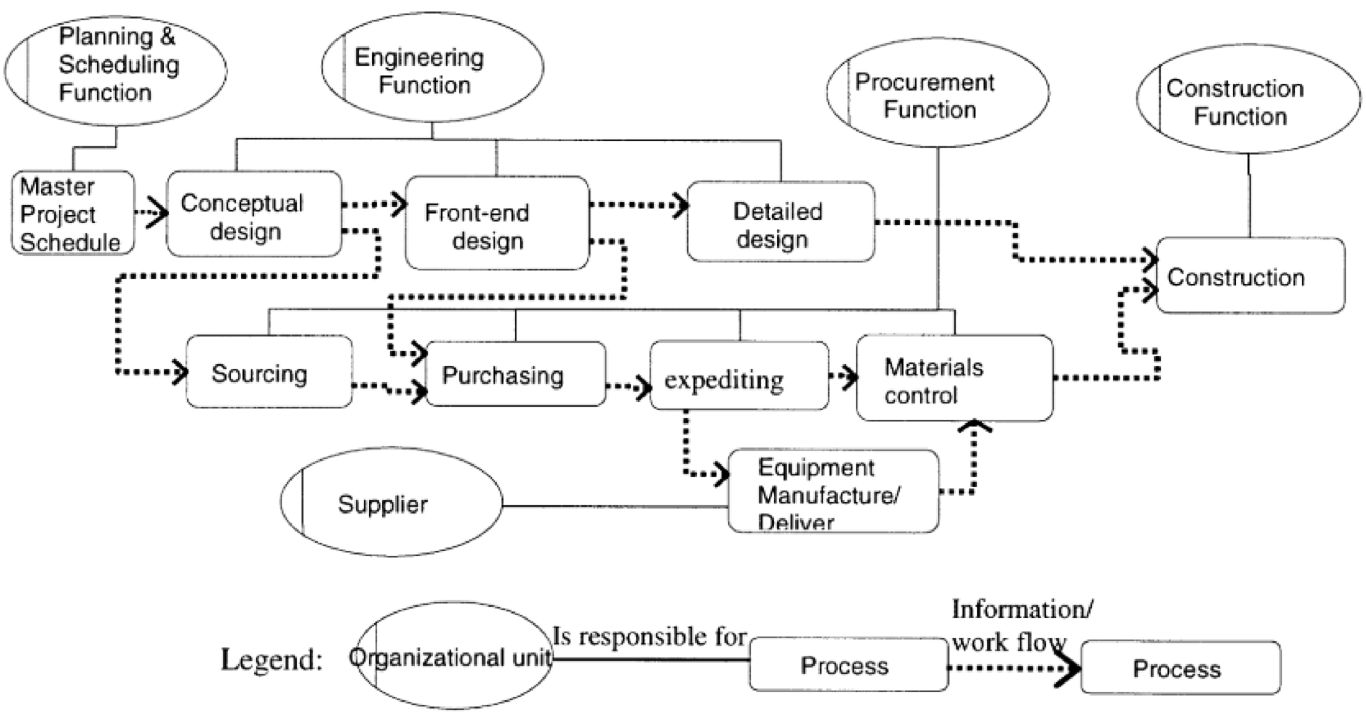


Figure 1.1. EPC Process Model (Yeo, K.T., and Ning, 2002)

To avoid time delay and budget overrun, managers must respond to pressure from tight schedule and cost. It was reported that decisions taken in the past decreased the project performance, which eventually led to a disruptive litigation between the contractors and customers over responsibility of missed project goal (Sterman, 1992). To understand how projects respond to external factors, the management approach and the internal operational structure are crucial.

Unavailability/shortage of material leads to delay and extra cost on construction projects; thus, this thesis particularly concerns construction delay originating from material shortage on the construction site. The study focused on EPC projects and how SD decision support system for material procurement can enhance the timely delivery of construction materials on site, which further leads to the reduced time related cost, reduced time related risk, and prevention of schedule overrun. Westney (2012) reported that many projects in the Canadian oil sand have experienced 50% to 100% cost overruns; as a result of this, organisation's poor performance regarding cost and schedule was marked unsatisfactory by executives. Schedule overrun often leads to cost overrun and this has been established in a work done by Ezenta (2015).

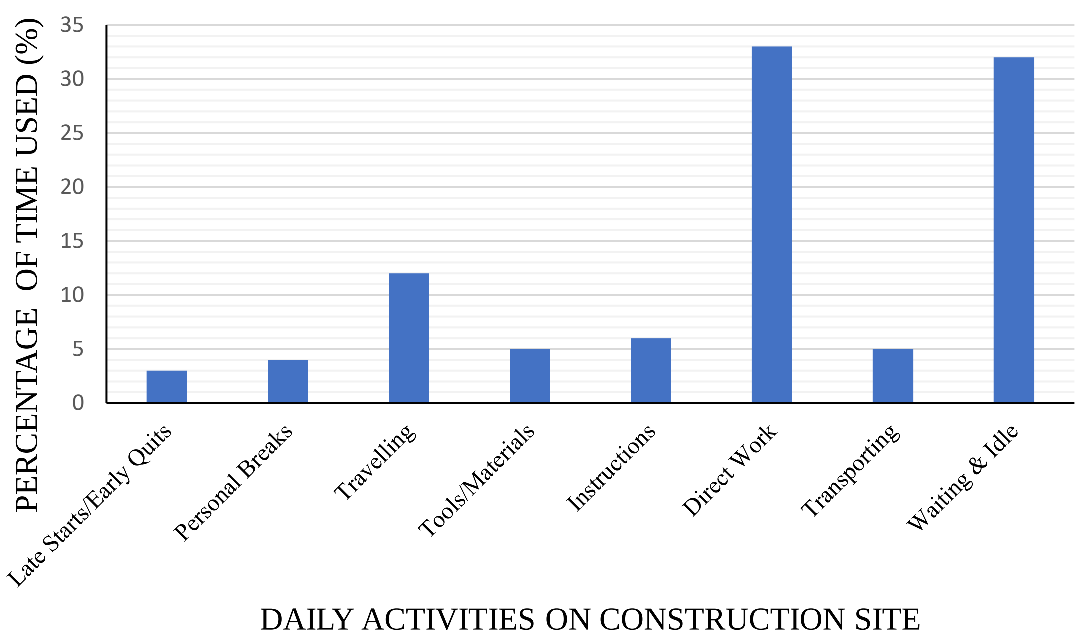


Figure 1.2. Overall Average Time Distribution of a Typical construction day (Modified after McTague and Jeageas, 2002)

With regards to project deviation, the procurement process and strategies can be used as realignment responses. Micheli and Cagno, (2016) used a case study approach with three companies to know the cause of deviation in time and cost performance of projects, they found procurement management to be one of the major causes (Micheli and Cagno, 2016). Several works have been done to quantify the impact of material delay, and how it can be mitigated to improve material supply chain, but few of them have focused on how to improve the gap between material supply operational visibility and management. This shows the need for collaboration and most importantly, helps managers make good decisions to prevent material shortage on the construction site by understanding the dynamics of the material supply system. The intention of material management is to ensure material availability at the right quantity and quality on the construction site and having it in mind that reduction of procurement time and cost boost opportunity of overall project time and cost reduction respectively. Other objectives of material management are procurement and receiving, productive material planning, good contractor-supplier relationship, storing and inventory control, quality control and assurance, and supply and delivery of material. Adequate collaboration is required to achieve these goals.

This study focuses on how EPC contractor can relate with supplier by correctly aligning their business goals. This study will also emphasize the need for information sharing by all participants, which aims at helping EPC contractor in continually strengthening its capability. This study also helps to facilitate optimal decision making during the material supply coordination. To improve material supply performance, bottle necks must be removed by minimizing demand and supply uncertainties, thus, embracing continual improvement. This study will be achieved by using Systems Dynamics (SD), an integrative and holistic approach, which has a fundamental view of studying the dynamic behaviour of a system structure which is caused by delay and feedback.

1.2 Research Objectives and Scope of Thesis

This study attempts to give probable decision support system by using the systems dynamic model. The overall objective to develop a decision support model for material procurement to enhance timely delivery of construction materials. To achieve the overall objective, the following specific objectives were proposed.

Objective 1: To investigate and implement the existing procurement strategies in EPC system, which mitigate material shortage on construction site.

Objective 2: Investigate the impact of time delay and information sharing, demand forecast on material supply system using SD decision support model.

Objective 3: Demonstrate the capacity of the model to suggest policy that will enhance timely delivery of construction materials on site.

This thesis focused on construction material, largely consumed during construction, and are off-the-shelf. This model can be used as a decision-information tool to enhance the understanding of the basic factors that affect the shortage of material on site with a focus on the interaction of the Construction Material Supply Chain (CMSC) entities to improve the project performance.

1.3 Thesis Organization

The remaining part of the thesis is arranged as follows. Chapter 2 gives a background information and literature on work related to the proposed research objectives. Chapter 3 describes the problem and the design of the model using the FCBPSS structure, SD model formulation, parameterization, and construction which aligns with the supply of construction material, using stock and flow diagram structure proposed by Sternman. Chapter 4 presents the model validation, results, analysis and its intervention. Lastly, Chapter 5 discusses the suggested policy, conclusion, and future research.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

2.1 Introduction to Supply Chain Network (SCN)

Supply chain network (SCN) is an inevitable part of engineering management in EPC industry, thus, any form of disruption in the SCN of an organization will expose it to risk. Adequate attention must be given to the SCN of a company as supply, demand, availability, and capability of internal resources are greatly connected to profit gained, and disruption of any of these three will bring failure to the firms in supply network. SCN is a complex network of entities that experiences frequent turbulence which generates potential for unpredictable disruption. Its vulnerability, caused by lots of uncertainties, has gotten the attention of industry and academics, therefore for companies to survive, there is need for management strategists to take proactive steps towards supply chain efficiency and resiliency (Wang, Dou, Muddada, and Zhang, 2017;Wang, Ip, Muddada, Huang, and Zhang, 2013). Although uncertainty in market is on the rise and often unpredictable, business can go a long way towards mitigating damage or the impact of disruption with proactive measures at different phases of disruption. Most times, decision makers use warning means such as sharing inventory, forecast, and logistic data to identify supply chain irregularities and in turn, the possible chain reactions are communicated to the concerned firms. Siau and Tian (2004) made us understand that the road to a firm's continual survival is through a competent supply chain.

Collaboration has been identified as one of the ways to reduce uncertainties in supply chain (Christopher and Peck, 2004). The health status of a supply chain network depends on how well the interdependent firms collaborate to be able to quickly recover from disruption. Firms need to engage in collaboration to lessen vulnerability, increase sustainability, and enable healthy financial status by taking proactive measures towards a resilient inter firm supply network. Currently, the business world is in a challenging time and there is need for partner firms to cooperate more and leverage on both external and internal resources across the various supply chain. It is seen that partnership reduces procurement chain and deviation causes, which is needed in EPC projects as procurement can minimize deviations in the project performance (Micheli and Cagno, 2016). This systems approach (use of systems dynamics modelling, collaboration, use of integrated procurement strategies) will help in decision making by giving insight into the complex dynamic nature of the project procurement system.

Firms are learning to live with uncertainty and the ever-changing market has called for firms to take adequate measures in managing disruptions. This has made researchers explore supply chain dynamics continuously to have a better and solid understanding to aid takes proactive strategies in mitigating risks in firms.

2.1.1 Construction Supply Chain Management (CSCM)

Construction Supply Chain Management can be a complex system which consists of large number of partners (owner, contractor, consultant, regulator, supplier) having different goals and at the same time participating in another supply network. Therefore, it is clear that high level of cooperation and coordination of activities is needed within and among the firms, which will help reduce uncertainties and increase customer satisfaction. Uncertainties in CSCM can emanate from time delay in projects, market fluctuation, changing customers' requirement, project and material cost, government policies, etc.

2.1.2 EPC: How procurement serve as a strategic link from project recovery deviation

EPC is a prominent form of contracting in the construction industry with pre-specified and agreed timeline and cost, one company is responsible for all phases of project which includes engineering design of project, procurement of required equipment and materials, and construction of functioning facility to meet the customer's expectation. The importance of EPC contracting method is largely recognised in the engineering field because of its associated benefits like reduced project cost, tighter project schedule, and risk-bearing attribute, thus, this approach aims at seamless delivery of project. EPC has gained the attention of researchers because of its increased economic relevance, so there is need to address sources of disruption and how the effects can be mitigated on project performance. Construction sectors contributes about 10% to the Gross Domestic Product (GDP) of an industrialized nation (Navon, 2005; Allmon *et al.*, 2000). EPC industry faces challenges like work fragmentation, sophisticated organizational structure, interconnected processes, phase overrun, and vagueness in the correct forecasting of the desired result (Breuer, Fischer, and Member, 1994). Some EPC contractors have suffered huge losses due to inadequate knowledge of supply chain management, which has a strong bond to delivery time and cost incurred on the project, and eventually affects the overall performance of the firm. Therefore, there is a need for EPC firms to engage more in collaborative practices to build a resilient and healthy supply network. This work focuses on the material management process which is usually done at the planning and execution phase of construction projects, where each activity is time-phased according to earlier activities, resources needed, and constraints. Material management has become critical to the success of a construction project. The material management functions can be seen in Figure 2.1 below.

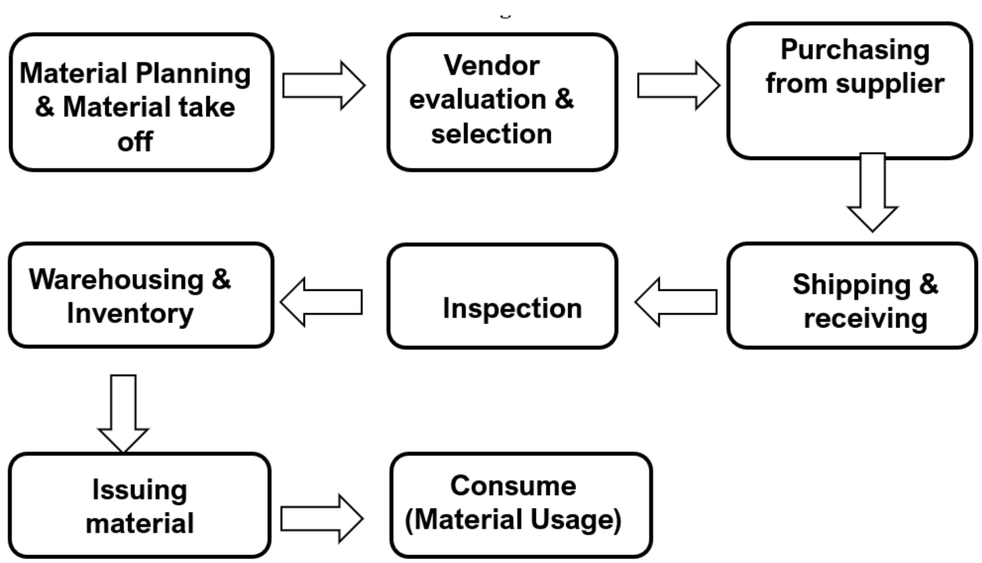


Figure 2.1. Material Management Flow

Material procurement is large percent of the total worth of project, so minimizing its cost will greatly enhance the project performance and lead to opportunities that will reduce the project time and cost. Procurement processes are associated with all phases of the project life cycle, which starts with what is to be purchased and close with confirmation of the conformity of the final product with the required standard (International Standards Organisation, 2010). A procurement process includes: material take-off, supplier research, market price prediction, supplier qualification, purchase requisition, supplier selection and final choice, development of the system supporting relation, order management and inspection, shipping, and knowledge management. Mubin and Mannan (2013) proposed a risk identification model, which showed that the procurement process has the topmost risk. Some challenges faced by the procurement and material management team are the selection of unqualified suppliers and subcontractors, late involvement of the procurement team, material supply and flow to meet construction timeline, lack of experts, poor communication, late delivery of material, availability of material, etc. (Thomas *et al*., 2005; Drew, Tang, and Lui, 2004; Murphree, Cate, and Vosburg, 2002).

Procurement is essential and relevant in the construction project, as it serves as a strategic link to recovery from project deviation. Using a different mix of strategy and process modification, Micheli and Cagno (2016) demonstrated this by using case studies of top-rated EPC companies (Micheli and Cagno, 2016). Ruparathna and Hewage, (2015) reviewed the definitions of construction procurement in previous literature and classified them into two, based on what they focus on: (1) purchasing contracts only and (2) all activities associated with purchasing activities/services necessary to achieve the project objective. According to Miller *et al.* (2009), a procurement method practiced is often selected by the project owner or construction manager, which usually tends towards the route that has worked for them in the past, which should also depend on the price/compensation formation method, project delivery method and conditions for contracts (Eriksson and Westerberg, 2011). Laedre *et al.*, (2006) made it clear that the using an unsuitable procurement method can lead to schedule overrun and money wastage (Laedre, Austeng, Haugen, and Klakegg, 2006). Thomas *et al*., (2005) showed how Out of Sequence (OOS) material delivery promote delay on construction site while Mawdesley and Al-Jibouri (2010) emphasized the criticality of material management to construction productivity. Therefore, adequate and proper management of the material procurement is needed to prevent shortage and excess material inventory on project site so as minimize the project deviation.

In Figure 2.2, the great influence of procurement is just as conspicuous with regards to time and cost, such as studying the time for construction material supply by selected suppliers, procurement process, which takes place before and during construction, and the final quality of product being purchased and delivered.

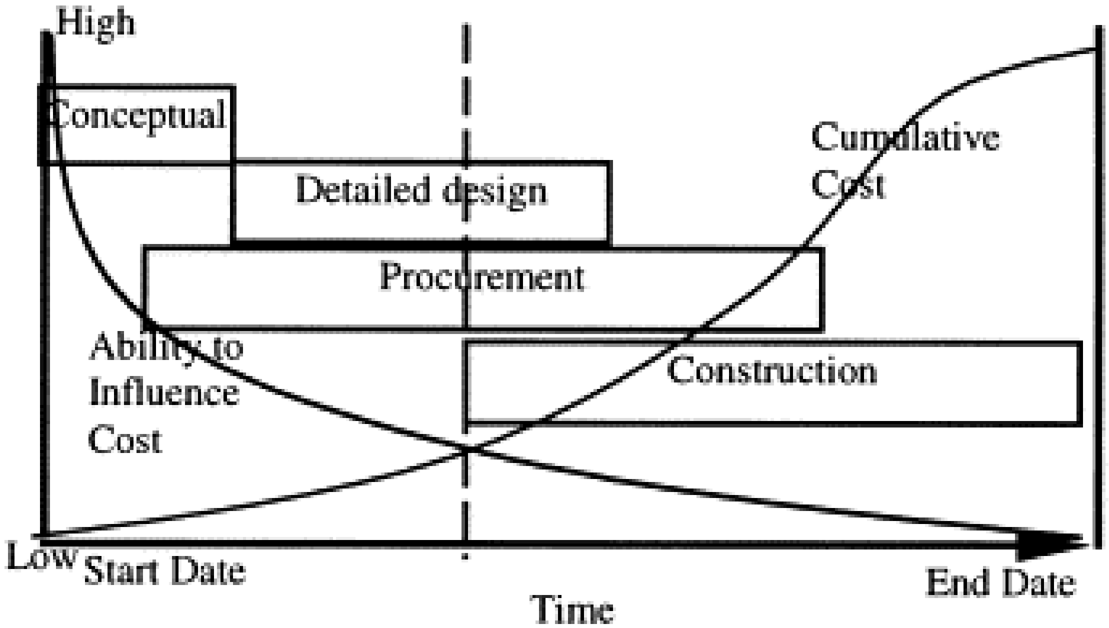


Figure 2.2. Phase Overlaps in EPC process (Yeo, K.T., and Ning, 2002)

2.2 Factors affecting construction project performance

Many studies have focused on factors impacting project performance. Performance is assessed by using various performance indicators which can be grouped in two classes depending on the aspect being considered. Class 1 are those related to dimensions like time, cost, quality (Micheli and Cagno, 2016; Ling, Ong, Ke, Wang, and Zou, 2014; Chan and Chan, 2004) and Class 2 are those related to entities in the CSCM – owner, contractor, subcontractor, consultant (Pheng and Chuan, 2006). Performance indicators predominantly used by most stakeholders to evaluate construction project outcomes are time, cost, quality, health, and safety. It has been observed by Dissanayaka and Kumaraswamy (1998) that time and cost performance is controlled by procurement system, project nature, collaboration, and stakeholder's performance. Some of the factors that affect project performance are discussed below.

2.2.1 Material delay on construction projects

Construction delay has been a reoccurring issue that hinders project success. Researchers have identified causes of project delay to reduce or prevent delay and their associated cost. Using semi structured interviews, Assaf *et al*. (1995) highlighted many causes of construction delay and organised the construction delay into 9 major groups: financing, materials, contractual relationship, changes, long permit approval process, man power, scheduling and control, equipment, and environment (Abd El-Razek, *et al* 2008; Assaf, Al-Khalil, and Al-Hizami, 1995). Material delay ranked high. This was seen in other works by Murphree *et al*., (2002) and Thomas *et al.*, (2005), who also highlighted inefficient material management as a major cause of project delay and financial loss. Wang *et al*. (2016) carried out a survey which identified the five major important risks to EPC namely, inflation, government inefficiency, shortage of material in the locality, fluctuating financial market, and unstable political situation (Wang, Tang, Du, Duffield, and Wei, 2016). From the study by Enshassi *et al*., (2009), the top most factors affecting construction project performance emanated from the material management with the stakeholders giving the highest rank to shortage/unavailability of materials and resources (Enshassi, Mohamed, and Abushaban, 2009). Horman and Thomas, (2005) reported that the delay that evolved from material management was the most documented probable after study of about 125 projects.

Literature shows that shortage of materials has been a reoccurring source of project deviation for EPC contractors. Material-related causes that affect project performance include: slow delivery of material, shortage of construction materials onsite, damage of materials in storage, change of material specification and type during construction, and imported material items (Abd El-Razek *et al.*, 2008). Transportation can be integrated into the cause of material shortage. There is usually an exchange of information and drawing between supplier and contractor, which often brings time delay into the procurement.

2.2.2. Impact of material supply delay on construction performance

Project construction usually depends on material supply needed, and the delivery of these materials affects the project schedule. Delay in supply of material has been found to be a major cause of time overrun (Dey, 1996). Proper material planning would help give direction to all the successive activities which will have a huge impact on project success. The planning process includes record upkeep, target inventory level determination, and material delivery frequency (Payne *et al*. 1996).

Construction materials like pipeline, rebar, tiles, glass, rubber, cement, bulk filling materials (soil, rocks etc.), ceramics, gravel, lead, paints, plastics, plywood etc. which are consumed in large quantity can hinder construction progress. Some materials are required earlier (i.e. long-lead items), thus, the project schedule is included in the contracting plan. Beyond identification of risk factor in construction, there is need to assess the impact of the risk and how it can be mitigated to prevent or reduce poor project performance. (Enshassi *et al*., 2009). Said and El-Rayes, (2011) proposed an optimisation model-Construction Logistics Planning model to show the impact of material shortage on site. Various studies on impact of material delay/management on project performance have been carried out, these includes Horman and Thomas, 2005; Thomas, Riley, Member, Sanvido, and Member, 1999; Thomas, Sanvido, Member, and Sanders, 1990.

2.3 Stakeholders of a construction industry and their impact

The poor performance of projects can also be attributed to the participating parties like owner, consultant, contractor, supplier. The owner and contractor, who look at performance from both macro and micro viewpoint respectively, have the largest impact on the construction performance. Material supply delay, a contractor-related risk is seen to be common in most construction projects and the timely completion of projects is profitable to all parties concerned. Various studies have shown how supply chain relationship can affect project performance (Meng, 2012; Chen and Chen, 2007; Beach, Webster, and Campbell, 2005; Paul Humphreys, Jason Matthews, and Monan Kumaraswamy, 2003; Black, Akintoye, and Fitzgerald, 2000). To deal with risks, EPC contractors must have a good relationship with all stakeholders (Yang, Shen, Drew, and Ho, 2010; Newcombe, 2003), who are regular sources of risks and find way out to prevent or lessen the risks (Tang, Li, Qiang, Wang, and Lu, 2013). Risks that can be avoided or minimised include: conflicts, design deviation, uneconomical material, and equipment procurement.(Grau, Back, and Prince, 2011; Pulaski and Horman, 2005)

2.3.1 Contractor-Supplier Relationship

Each entity in a supply network has its role to play to make the network a resilient one (Wang, Dou, Muddada, and Zhang, 2017). Therefore, there is need for supplier relationship agreement, which helps in early selection of supplier (Slootman, 2007; Chu, Tso, Zhang, and Li, 2002) and joint model development which helps mitigate time delay. Customer satisfaction, reduced cost, and improved performance can be accomplished through contractor-supplier relationship improvement (Beach *et al*., 2005; Larson and Larson, 1995). According to Yeo and Ning, (2002), to improve supply chain relationship, good and reliable partners must be selected and these partners must protect each other's interest (Yeo and Ning, 2002). Past studies have shown how factors of the supply chain relationship can affect the project performance (Meng, 2012; Chen and Chen, 2007). Factors such as supplier's service level, supplier's delivery reliability, joint continuous improvement, and efficient problem solving have tremendous impact on the project success (Pal, Wang, and Liang, 2017). A good supplier–contractor relationship will help to avoid and resolve conflict early, increase serviceability ability which will in turn contribute positively to the project performance. In opposition to the traditional SC relationship relation which is cost based, Greasley (2000) reported that supply chain relationship is dependent more on factors such delivery capability, quality, flexibility, and commitment of partners. (Greasley, 2000). It has been observed that having a long-term contract with suppliers can minimize or prevent price increase. Factors of a successful supply network relationship are commitment and collaboration among partner headed for improved supply chain performance (Cao, Vonderembse, Zhang, and Ragu-Nathan, 2010; Griffith, Harvey, and Lusch, 2006; Cao and Zhang, 2011). In the construction industry, lack of trust makes the main contractors give favourable surplus quote, while supplier or subcontractor hide their cost information to prevent the main contractor from reducing its profit (Du *et al.*, 2016; Manu, Ankrah, Chinyio, and Proverbs, 2015; Beach *et al*., 2005). The EPC contractor needs the supplier to deliver quality material and support the project schedule. Suppliers, who usually supply to more than one contractor usually organise their supply plan based on their customer's demand, contract's terms and condition.

2.4 Supply Chain Procurement Strategies

Firms need to come up with designs to make their logistic and procurement efficient and effective in project performance (Dainty, Briscoe, and Millett, 2001 ; Vrijhoef and Koskela, 2000). Disruption has an adverse effect on the performance of a firm, therefore for firms to survive, there must be strategic thinking towards proactive strategies to mitigate uncertainties and vulnerability. Suitable and efficient procurement route will be based on each project's characteristics or specific situation, objectives and project performance expectations, as no two projects are the same, so also no approach is suitable for all types of projects. According to Laedre *et al.*, (2006), rigidity of an organisation to a new procurement strategy is common, as often times the usual procurement route is followed even when the route in not appropriate for a specific project type which is against the recommended practice (Laedre *et al.*, 2006). Existing procurement studies will be discussed below.

Inventory / Buffer Management: Buffers are used to reduce uncertainties in projects**.** Procurement chain can be improved by coupling supply chain management and critical chain project management. They used the buffer management approach to reduce the uncertainties in procurement (Yeo and Ning, 2002). Time buffer helps to safely reduce time waste on construction by incorporating a float on the project schedule which includes all the planned dates from starting and completing project activities and milestones. In material management, a float is inserted between the promised delivery date and the required on site date (Yeo and Ning, 2006). Inventory buffer for construction material is needed to enhance construction performance (Horman and Thomas, 2005). Good inventory management by entities in the supply network can help mitigate supply delay (Huang, Yang, Zhang, and Liu, 2012).

Early Sourcing and Purchase Order: Early sourcing strategy was used for solving procurement problems in EPC firm (Azambuja, Ponticelli, and O'Brien, 2014), while, Jergeas (2009) proposed early purchase order of material as a way to minimize material delay in construction project. Seshadri, Chatterjee, and Lilien, (2008) developed a model to show the relation between multi sourcing and its effects which includes seller's profit, buyer's profit, and numbers of bids. To increase reliability of supply, multiple sourcing has been embraced as a way out. Back up strategy is not a common practice in construction because of the cost and time associated in the selection of suppliers.

Expedite: Procurement team should brainstorm with the suppliers on how to expedite the manufacturing and transportation of the material and equipment to enhance timely delivery. This is regarding purchase order, the project's requirements, and schedule. This process must be well planned because information sharing is practiced regularly between the contractor and the supplier. In the service supply chain, we have backlogs which is managed by capacity adjustment (Akkermans and Dellaert, 2005).Through exchange of expediting report between the project control and procurement team, delay can be minimized. Lead time reduction and information sharing on demand enhance SC performance. Anderson, Morrice, and Lundeen, (2005) showed this in their work and proposed some policies to minimize backlogs, which usually indicate the level of responsiveness of a system.

Lean Concept: An aspect of lean concept is just-in-time (JIT) strategy, a process improvement approach, which is often practised in the delivery of construction material to minimize material inventory, double handling, and material waste, and enhance quality and maintenance. This approach aims at reducing response time from suppliers. Close relationship with the suppliers is vital for successful implementation of JIT strategy (Akintoye, 1995; Pheng and Hui, 1999; Shmanske, 2003; Polat and Arditi, 2005a). The random flow of material and inadequate information sharing cripple the extensive use of lean principles to construction supply chain (Fearne and Fowler, 2006; Forsman *et al.,* 2012; Eriksson, 2010)

Material Decision Support Models: Researchers have proposed decision support systems to help managers and decision-makers make good decisions to enhance timely delivery of material on construction site by considering the material inventory level and storage need. The model will give insight to the behaviour of the procurement system over time and help in developing effective principles and policies for material management. Past studies looked into the development of policies and their impact on various aspect of construction projects such as: material supply decision on construction labour productivity (Thomas, Riley and Sanvido, 1999; Thomas, Sanvido and Sanders, 1990), development of principles for site material management (Thomas, Riley, and Messner, 2005), and decision support system for material supply (Tserng, Yin, and Li, 2006; Polat, Arditi, and Mungen, 2007). Jaśkowski, Sobotka, and Czarnigowska, (2018) proposed a decision model by solving a fuzzy model with the aim to reduce the inventory cost for large construction material. Other existing decision models focused of selection of suppliers. (Cengiz *et al.*, 2017; Patil and Adavi, 2012; Lam, Tao, and Lam, 2010; Ho, Nguyen, and Shu, 2007).

Material - logistics Models: Said and El-Rayes (2011) proposed an optimization model - Construction Logistic Planning model to help contractors reduce material logistics cost. This model also enhanced the material procurement decisions and site layout policies which considered material storage space and temporal facilities for the project duration. Existing studies considered material storage capacity alongside with construction site layout (Elbeltagi, Hegazy, and Eldosouky, 2004 ; El-Rayes and Said, 2009). Ghodsypour and O'Brien (2001) developed a mixed inter nonlinear programming model to find the least cost cyclic ordering for the customer by examining multi sourcing problem with multiple criteria and capacitated suppliers.

Simulation- based Approaches: Modelling and simulation are an efficient means to solve complex systems. Systems Dynamics (SD) re-emerged about two decades ago with research focus on supply chain design and integration, demand amplification, inventory decision and policy development, time compression, and international supply chain management. SD model can be used to carry out what-if-analysis to study the impact of policy developed, giving project managers foresight of the behaviour of the system under various desired scenarios (Boateng, Chen, Ogunlana, and Ikediashi, 2012)

Researchers have supported the use of simulation-based approach for a strategic design and quantitative analysis for the impact of disruption on supply chain (Vanany, Zailani, and Pujawan, 2009), as supply disruption can hinder cash and operation flow and may eventually stop it. In a whole supply chain, all nodes must make appropriate purchasing and inventory strategies to lessen the impact of supply disruption in both upstream and downstream (Ellis, Henry, and Shockley, 2010). Sterman, (2000) proposed that the multi-limitation to flow in a firm makes it necessary for most activities to be captured by the SD model. Various works have used SD to show the impact of delay and information sharing which limits the flow in a supply chain (Ge, Yang, Proudlove, and Spring, 2004; Feng, 2012). Using the SD approach, Tang and Ogunlana, (2003) modelled the factors affecting construction performance, and Love, Mandal, Smith, and Heng, (2000) identified the factors causing schedule overrun. Several software tools such us Enterprise Resource Planning (ERP), Advance Planning and Scheduling (APS) and Material Requirement Planning (MRP) can be used to manage supply chain but their incapability to handle the feedback, delay, and dynamic nature of the supply chain limit their application (Akkermans and Dellaert, 2005).

Systems dynamic works by modelling the internal structure of the complex system, analysing the causal relation feedback and developing a policy and strategy from the verification and validation done during simulation. Systems dynamics is a continual improvement process that takes into consideration the (information) feedback causal relation and policy structure. This understanding gives insight to the managers when taking decisions which affect the project performance

2.4.1 Supply Chain Collaboration: Abd El-Razek *et al.* (2008) concluded after comprehensive analysis that, to decrease delay in construction projects, collaboration is needed. Wang *et al.*, (2016) reported that a good knowledge of cause and effect relationship between firms will help EPC contractors manage project risk very well by blending both inter and intra organisation resources to achieve the goal which is project success. One of the major characteristics of collaboration is sharing of information (risk, objectives, problems, resources etc.) accurately and with velocity. The procurement department engages more in communication and negotiation with the external parties of the construction, therefore, there is need for the function to bond well with the suppliers. Collaboration, which helps prevent opportunistic behaviour among supply chain partners, is defined as a “glue that holds supply chain firms in crisis together” (Richey, 2009). Simatupang and Sridharan, (2008) identified decision synchronisation and incentive alignment are two essential element of supply chain collaboration useful for disruption response**.** Firms that will survive in this competing business world must embrace collaboration. Several studies showed how supply chain improvement can be attributed to collaboration among partners in the network. (Cao, Vonderembse, Zhang, and Ragu-Nathan, 2010; Griffith, Harvey, and Lusch, 2006).

In this inter-firm SCN, the resiliency of a firm does not guarantee the resiliency of the entire network of firms, therefore, there is need for each firm to play its role for its survival and in the best interest of the whole supply chain (Wang, Dou, Muddada, and Zhang, 2017), thus, to drive this in EPC projects, collaborative attitude among all chain members, timely information sharing, and organized procurement procedures should be practiced. According to Cao *et al*. (2010), SC collaboration has been studied from four viewpoints, namely: transaction cost economics, resource based view, uncertainty reduction, and transfer of knowledge (Cao *et al.*, 2010). Risk-related problems can be solved when partners exercise trust, joint analysis, and resource sharing (Cho, Hyun, Koo, and Hong, 2010;Yeung, Chan, and Chan, 2009; Bower, Ashby, Gerald, and Smyk, 2002). Network of firms needs adequate knowledge of supply chains for the smooth running which involves flow of material, cash, information from suppliers to end-users (Crum, 1999; Mentzer *et al*., 2001). In the network of inter-firm, coordination is not enough, as collaboration must go along for the efficient performance (Malindretos and Binioris, 2012). Past studies have shown the power and the importance of partnership collaboration (Singh, Gu, and Wang, 2011; Yeung, Chan, and Chan, 2009; Cho, Hyun, Koo, and Hong, 2010; Brahm and Tarzijan, 2016 ; Broft, Badi, and Pryke, 2016; Babaeian Jelodar, Yiu, and Wilkinson, 2017). The struggle of control and visibility of supply chain is rampant with companies, there is need to leverage on technology to have a platform, where supply partners can collaboratively share information and coordinate operations. Eldabi and Keramati, (2011) also reported inter-firm supply chain give better visibility and helps organisations compete greatly in the world of business and sustain their financial health. Researchers recommended quick response, collaborative planning, and efficient customer response as way out of bullwhip, amplification, and distortion effect in supply chain.

2.4.2 Material Management Policies

Dealing with collaboration challenges among entities in a supply network involves balancing profits on each sides of the supply network members, concerns with resource and information sharing, lack of trust, commitment, investment preference, risk management, and intellectual property security. Thus, this introduces complexity and diversity into the decision making process of the managers, hence, improving SC operation visibility has been established as one of the ways of improving decision and policy making, which has positive effect on profit and customer satisfaction (Natour, Gibson, and Gibson, 2011). In addition, improving the SC operation visibility can also reduce uncertainty in SC (Sarimveis, Patrinos, Tarantilis, and Kiranoudis, 2008; Sterman, 1989; Sterman, 1992). One of the demanding responsibilities of policy makers is to generate value by building integrated supply chain (Wadhwa and Saxena, 2007). Although supply chain collaboration has good impact on the supply chain performance, according to past works, its implementation still remain a complex one (Chen, Daugherty, and Landry, 2009).

To minimize uncertainties, decision makers must investigate the observable attributes of the material supply system, which is controlled by some dependent factors such as dissimilar objectives, uncertainties, and mutual distrust. Transparency and openness in decision making process will enhance information and resource sharing (Denize and Young, 2007). Managers/ policy makers should investigate how information can be distributed in the network to enhance collaboration. The higher the uncertainties awareness by partners, the lesser their flexibility to collaborate (Riddalls, Bennett, and Tipi, 2000); the better the information sharing culture (capacity utilisation, production plan, customers demand/order rate), the lesser the risk attached to material stock out or excess inventory. Christopher and Lee (2004) reported that partners' confidence can be created by allowing all entities have control over the SC activities. (Christopher and Lee, 2004), but control-oriented management hinders expected benefits such as cooperation in the supply network (Ramon Gil-Garcia, Chengalur-Smith, and Duchessi, 2007; Griffith *et al.*, 2006; Jensen and Meckling, 1976; Eugene and Jensen, 1983).

Some suggestions given on construction material management include IT integration during project planning, continuous material management training, selection of qualified suppliers, consideration of material cost and logistics during the early project planning, development of strategic plan as a proactive measure (Caldas *et al.*, 2015). SD approach helps to determine decision – making policies that are not beneficial and the policies that can be used to enhance project performance.

2.5. Conclusion

Researchers have investigated several procurement strategies that can mitigate material shortage in construction, but lack of collaboration still makes the problem to be persistent in the construction industry. The knowledge of the how the construction industry contributes to the GDP of a nation's economy calls for a need for immediate solution to further mitigate risks like material shortage, thus, improving the performance of the construction industry. Researchers have also developed decision support tools to help decision makers or managers make effective policy to enhance project performance but none of it has studied how the relationship between the EPC contractor and its supplier can enhance the construction performance through the decisions made. The expected contribution of this work is to develop a decision support SD model which will help understand the material supply chain dynamics between the EPC firm and its supplier, which often emanates into material shortage on site and how this risk can be mitigated to enhance project performance. In conclusion, the proposed research in terms of the research objectives may make some meaningful contribution to the construction management in general and EPC management specifically.

CHAPTER 3

METHODOLOGY AND MODEL DESCRIPTION

3.1 System Dynamic (SD) Approach in Supply Chain

The System dynamics approach was formulated by Jay W. Forrester in the 1960s. SD is a powerful management tool for modeling and simulating complex real-life systems to understand the complex nature of the system and strategic decisions/policy execution. The model is based on causal feedback that balances or reinforces complex relationship between system variables (Richardson, 2011). The concept of feedback permits the past behaviour to control the prospective action. In this computer-based simulation environment, the differential equation is graphically represented and the discrete step is computed by the computer over a predetermined time frame (Sterman, 2000). According to Van Ackere *et al.* (1997), SD approach is suitable for systems which contain and are hugely affected by core variables that adjust over time and when it is well known that dynamic feedback occurs. A SD model gives a holistic view of a system, how it changes over time, and interactions within the system and outside with exogenous factors. For the smooth running of operations, organisations should be able to determine delay and disruption in activities affecting the incoming customer order, processing operations, and long-term revenue.

The SD approach gives insight into the factors affecting the nonlinear dynamic behaviour of a system under certain conditions or assumptions or contexts. The concept of context is gotten from Zhang and Wang (2016) and Zhang (1994). This approach provides analysis to ‘what-if’ question by decision makers. Systems dynamics, a continuous time approach, enhances supply chain visibility and this visibility ensures confidence into supply chain and help prevent ineffective decisions in a risk event situation (Christopher and Lee, 2004). Supply chain visibility looks into information about the entities and activities regarding end to end orders, inventory, shipment and distributions in a systems (Wei and Wang, 2010). Also, SD suggests ways the current process can be improved.

SC performance has great influence on a firm’s success, moreover, an efficient SC should enhance control and better understanding of a system, to help firms obtain reduced cost, improved response time, lowered inventory, and minimised demand uncertainty which often spring from unstable delivery services, demand projections, lead time delay, and altered information. The literature has established that collaboration by sharing needed information within firm and among SC partner will greatly improve construction firm's performance, as they are able to make adequate plans for the availability of construction materials.

From the perspective of SD, supply chain (SC) can be described as a structure of chain of stock and flow which controls stock of inventory, rate of shipping, processing and capacity. This structure harbors delay from decisions regulating the flow. Systems dynamics methodology follows a sequence of activities. Figure 3.1 shows the steps involved, they include: problem definition, system conceptual model, model formularisation, model testing and simulation, model understanding and alternative input, and policy decision design.

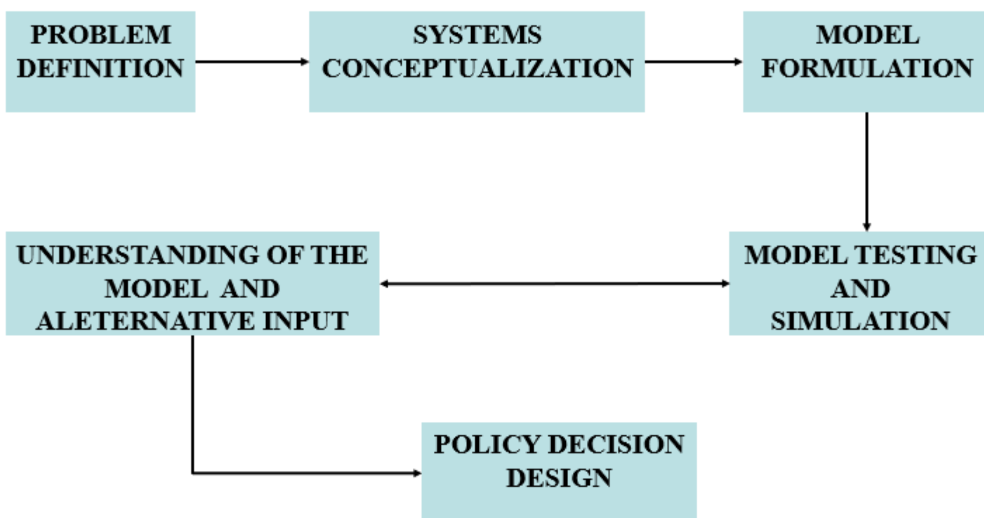


Figure 3.1. The Simulation Method (Sterman, 2000)

3.2 Problem Description of the Construction Material Supply Chain

The construction material supply chain (CMSC) is a two-echelon supply chain of EPC contractor and its supplier, aimed at providing construction materials at the right time, in the right quantity. Inadequate and untimely supply of construction material is a major constraint to the construction progress in the construction industry, which can be traced to lack of or inadequate information sharing (Zhao, Xie, and Zhang, 2002) on EPC contractor's order, actual inventory level, accurate processing time, and delay encountered. However, EPC supply chain managers desire to know all information related to the management of materials from the beginning, when the contractor makes order to the end, when the materials are delivered by the supplier, but lack of access to information can cripple the decisions or plans on being proactive to minimize or avoid material shortage on a construction site. Therefore, for the supplier to satisfy the EPC contractor, the contractor must be willing to give timely and accurate information and vice versa. The supplier seeks to know the order backlog to effectively strategize how the order will be fulfilled without delay or with a minimal delay by considering the inventory and processing schedule.

Supply chain performance is not a function of one entity in the system, therefore, adequate information sharing, and collaboration is essential. Else, the aftermath of the material supply coordination will be experienced by all SC members in a different proportion, depending on the type and condition of contract made. For collective interest, a collaborative culture will promote achievement of common and unobjectionable goals by sharing adequate information, namely preventing time delay, cost overrun, surplus stock, and slow feedback in material acquisition.

In this study, a holistic view of material management with focus on material supply and usage with its relation to procurement strategies was taken. This SD model considers key variables and management efficient viewpoint, thus, enhancing effective decision making. Furthermore, observing the behaviour over time will give a better understanding of the significant relationships, evolved pattern, and determinants of the desired state and impact of prospective decisions or policies. Performance metrics used are material usage rate, supplier’s inventory coverage, unfulfilled order (order backlog), and order delivery delay.

As seen in Figure 3.1, after the problem description, the system conceptualisation was done by using the FCBPSS framework and the Causal Loop Diagram (CLD), which are discussed in the subsequent section.

3.3 FCBPSS Framework

The FCBPSS was proposed by Lin and Zhang (2004), which was adapted in this work as a tool to design the model. This modelling methodology has been applied in various domains of systems such as telecommunication system, electric power generation, transportation systems, water supply system, robotic system, educational system, and biological system. Zhang and Van Luttervelt, (2011) applied FBS model in a manufacturing system. According to Zhang (ME 886 class note), the FCBPSS is a modelling tool that helps gives a framework, a set of concepts upon which a system can be built and information architecture, a system where its functions and concept is expected to realize the expected function. The FCBPSS has six canonical concepts, which are Function (F), Context (C), Behaviour (B), Principle (P), Structure (S), and State (S). A system has a boundary which interacts with other systems through the structure that contains input and output variables that cause change in the state of the system. In system analysis, along the path of the structure to function, one can evaluate whether a given structure can achieve a required function. In system design, the required function and context are given, and one needs to determine the required state and behaviour and eventually the structure (Zhang, ME 886 class note).

3.3.1 The FCBPSS framework of the Construction Material Supply Chain (CMSC) model.

This modelling tool gives the framework and concepts upon which the CMSC system is developed.

FUNCTION: This answers the question "what is the purpose of the system", which can be achieved by the structure and state variables of the CMSC. The usefulness of the model is to support decision makers to gain insights on CMSC and take effective decisions towards mitigation of construction material shortage on construction site, thereby minimizing project deviation in construction project.

CONTEXT: This considers the pre-condition, post-condition, and environment where a structure say A is operated. The environment indicates where A is operated, pre-condition describes the condition that needs to be satisfied such that A can be operated, and the post condition refers to the condition, as a result of the operation of A, which may affect other systems that succeed the operation of A.

This model is applicable to the construction industry, specifically the EPC contractors and construction material suppliers. This CMSC model was studied under step input signal, varied parameters and variation on contractor's orders.

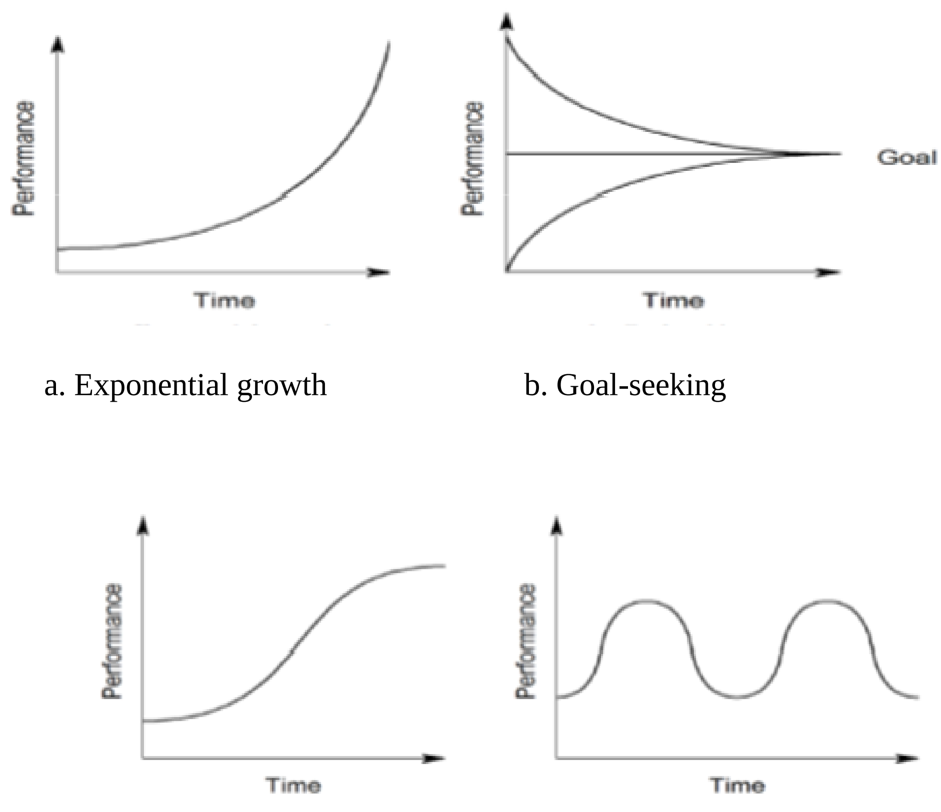
Precondition as a form of design setting: Assumptions made affect the behaviour and function of the structure of the design (structure). Assumptions used in the setting of the model design are listed below:

- Assumed contractor has available storage space for quantity of material ordered.
- Assumed the supplier has capacity for the specified contractor's demand at the beginning of the contract, however, the capacity is subject to time.
- Assumed material, labour and capital are always available for the supplier, processing start rate will always be equal to the desired processing start rate.
- Assumed material delivered is immediately available for construction.
- Assumed all orders are shipped immediately if the material is available in the supplier's inventory.

In the development of the model, it was assumed that all information shared are accurate and timely, however, in the presence of faulty information, the model will not give result that can help make accurate informed decisions. Unavailability of storage space with the EPC contractor will lead to site congestion and increased inventory level, while insufficient supplier's capacity will lead to unavailable material for shipment. Also, if material, labour and capital are not always available as assumed, then time delay will be encountered. When material delivered is not available for construction immediately, then the EPC contractor's inventory level will increase which might lead to site congestion or increased holding cost or reduced material usage. In addition, when the supplier does not ship out material immediately, it will lead to reduced shipment and material delivery rate, increased inventory level, higher holding cost.

Precondition as a form of reference frame: Most time in construction industry, there is no conspicuous external reference point to determine goals. Every project is unique, and no two projects are the same. In this model, the desired state of the system is influenced by the real states of the system itself and principle of the system which can then be adjusted based on experience and external pressure (e.g. contractor's order). The formulation responds to part of the gap between the desired and the current state of the system. The desired inventory is based on the contractor's order and inventory coverage. Decision made on a corrective action is based on the gap between the desired and real state of the system.

BEHAVIOUR: The behaviour is the response of the system to factors (like change in contractor's order, time delay) which can be observed by the interaction among the input variables and the output variables. This interaction regularly leads to feedback which determines the complex behaviour in the system. Stock management is often used to describe the source of behaviour. These behaviours include but are not limited to oscillation, system stability, rapid changes, and instability. There are two types of feedback loops and each loop's behaviour is characterised by the systems' structure, and the polarity of the variables in the loop. The positive loop (reinforcing loop) represented as "+"or "s" produces different types of behaviour such as: growth, destabilising, accelerating while the negative loop (balancing loop) represented as "-" or "o" produces various forms of behaviour such as counteracting, goal seeking, and stabilizing. Figure 3.2 shows typical forms of dynamic system behavior



a. Exponential growth b. Goal-seeking

c. S-shaped d. Oscillation

Figure 3.2: Typical forms of behaviour in a dynamic system (Kirkwood, 2013)

From the base model (an hypothetical representation of the system's properties and its behaviour, which is valid across the model), the behaviour of the whole system is performing as desired i.e. the contractor's order rate correlated with the rate at which order are fulfilled and materials delivered.

PRINCIPLE: It is a set of mathematical equations that explain why a system changes in relation to the process. It is the basic law that governs the behaviour of the system and describes the relation between the state variables and the constraints among the variables. To simulate the behaviour, the SD uses mathematics to describe and relate model variables, that is, the stock and flow construct. In the stock and flow construct, stock provides a form of memory which is mathematically represented by integral while flow is the rate of change, mathematically represented by first order differential equations which describe the function (Little's law) and its derivative. Littles law explains the relationship between the throughput (R, rate of flow), the capacity (I, Inventory/WIP/Backlog) and the lead time (T, processing or waiting time). Mathematically, the above principle is written as $I=R\times T$.

For example, using Little's law, the Deliver Delay at any point is the ratio of the Backlog to Order Fulfilment Rate, i.e., Delivery Delay= Backlog/Order Fulfillment Rate.

STRUCTURE: The polarities of the link depict the structure of the system. The structure of a CMSC refers to the sets of elements which may be at the physical level and must be related in a meaningful and purposeful way. The structure is represented as a stock and flow diagram with basic elements such as EPC contractor, its suppliers and their relationship on how to achieve timely supply of construction material. This stock and flow diagram consist of stock (accumulation of system entities), flow (rate of change), time delay and feedback. Stock is the source of dynamic behaviour in the system, as it creates gaps and delay. To initiate correction to get rid of any discrepancy/gap, a comparison is done between the desired and actual state of the system of the negative feedback. The stock is reduced by outflow and increased by inflow. An example of stock and flow diagram is seen in Figure 3.3

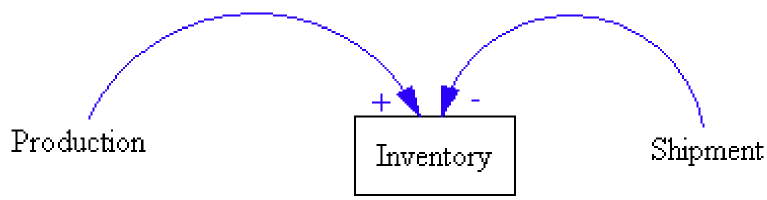


Figure 3.3 Stock and Flow Diagram

The relationship between stock and flow can be mathematically represented **by**

$$\frac{dstock}{dt} = Inflows(t) - Outflows(t) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.1)$$

Systems structure can be visualized mentally by means of causal loop diagram, with the arrows indicating systems elements. The major concept behind this type of modelling is defining the aspects of the system. Assigning polarity shows the characteristics of the relationship between variable based on the directions of the change. Structures considered in this work are order fulfilment structure, processing structure and material management structure which are discussed in detail in section 3.4

STATE: The stock, also known as the memory of the system, collectively describes the state of the system, and passes messages which are considered in decision making. The state depends on the function or interested area of the system. These states are expressed as variables which change over time. A variable can be endogenous and exogenous variable. The future state of the system is determined by the current state and the current state is determined by the preceding state. The states include:

Stock Variables: Order backlog**,** Expected Order**,** Work-In-Process**,** Supplier Inventory**,** Contractor Inventory, and Expected Material Delivery.

Auxiliary Variable: Desired Order**,** Contractor's Order rate**,** Actual delivery delay**,** Desired shipment rate**,** Order fulfilment rate ratio**,** Maximum shipment rate**,** Desired Supplier inventory**,** Supplier Inventory Discrepancy**,** Desired Work-In-Process, WIP discrepancy, Desired processing Rate, Desired Processing Start Rate, Desired Material delivery rate, Contractor Inventory Discrepancy, Maximum Material Usage Rate, Material Usage Ratio, Desired Contractor Inventory, and Desired material usage rate.

Flow Variables: Processing Rate**,** Shipment Rate**,** Change in Expected Demand**,** Order fulfilment Rate**,** Material delivery rate**,** Material Usage Rate, and Change in Material Delivery Rate

3.4 SD Model Development and Formulation

This work uses two-step SD method – conceptual and experimentation used in a work done by Größler, Thun, and Milling, (2008). The FCBPSS and the Causal Loop Diagram (CLD) were used for the conceptual modelling and to illustrate the conceptual feedback structures which provides good understanding of the construction material supply chain (CMSC) behaviour. The Sterman (2000) stock management structure was adopted to develop the CLD. The generalised structure of the 2-echelon Construction Material Supply Chain (CMSC) is basically EPC contractor and their supplier**.**

Table 3.1: Notation for Construction Material Supply Chain (CMSC) model

Parameters		***Units***
DD	Target Delivery Delay	Weeks
EO	EPC initial Order	Materials
ST	Minimum Shipping Time	Weeks
AT	Time to Average Order Rate	Weeks
AD	Time to Average Delivery Rate	Weeks
SS	Supplier Safety Stock Inventory Coverage	Weeks
ESS	EPC Safety Stock Inventory Coverage	Weeks
PT	Processing Time	Weeks
SDT	Supplier Inventory Adjustment Time	Weeks
EDT	EPC Inventory Adjustment Time	Weeks
WDT	WIP Adjustment Time	Weeks
MIC	EPC Minimum Material Inventory Coverage	Week

Stock Variables		
SI	Supplier Inventory	Materials
EI	EPC Inventory	Materials
OB	EPC Order Backlog	Materials
EOR	Expected EPC Order Rate	Materials
EMD	Expected Material Delivery	Materials
WIP	Supplier's Work in Process Inventory	Materials
Flow Variables		
OR	EPC Order Rate	Materials/Week
PS	Processing Start Rate	Materials/Week
SR	Supplier Shipment Rate	Materials/Week
PR	Processing Rate	Materials/Week
CEO	Change In Expected Order	Materials/Week
CMD	Change in Material Delivery Rate	Materials/Week
MDR	Material Delivery Rate	Materials/Week
MUR	EPC Material Usage Rate	Materials/Week
OFR	Order Fulfilment Rate	Materials/Week
Auxiliary Variables		
DSR	Desired Shipment Rate	Materials/Week
ADD	Actual Delivery Delay	Week
FR	Order Fulfilment Rate Ratio	
UR	EPC Usage Rate Ratio	
EIC	EPC Inventory Coverage	Week
SIC	Supplier Inventory Coverage	Week
MSR	Supplier Maximum Shipment Rate	Materials/Week
MU	EPC Maximum Usage Rate	Materials/Week
DSI	Desired Supplier Inventory	Material
DEI	Desired EPC Inventory	Material
SID	Supplier Inventory Discrepancy	Material

EID	EPC Inventory Discrepancy	Material
WD	WIP Discrepancy	Material
DW	Desired WIP	Material
DP	Supplier Desired Processing	Materials/Week
DUR	EPC Desired Material Usage Rate	Materials/Week
DDR	EPC Desired Material Delivery Rate	Materials/Week

3.4.1 Causal Loop Diagram (CLD) for CMSC model

Systems structure can be visualized mentally by means of Causal Loop Diagram (CLD), with the arrow indicating systems elements. This is built on the positive and negative causal relationship between the variables, feedback and delay. Assigning polarity shows the characteristics of the relationship between variable based on the directions of the change. The behaviour a loop is characterised by the systems structure the polarity of the variables in a loop. Negative feedback is goal seeking or stabilising while the positive feedback is diverging from the equilibrium or destabilising. The CLD serves as draft for the stock and flow diagram. Figure 3.4 shows the construction material coordination system unit. The causal loop diagram contains positive and negative polarities. The positive polarity (+) means variables change in the same direction while the negative polarity (-) means that change of a variable in one direction causes the second variable to change in the opposite direction.

The construction material supply chain has various processes in each echelon such as the order placement, order fulfillment, inventory control, and order processing and material management. The behaviour of these processes is discussed below:

i. Order fulfilment: The EPC contractor starts with placing an initial *EPC Order* ***(EO)***, *EO* leads to an increase in EPC Order Rate **(*OR*)**. In the absence of adequate inventory in stock for construction, *OR* leads to an increase in EPC *Order Backlog* **(*OB*)** (Sterman, 2000) which indicates the unfulfilled/unsatisfied orders (Venkateswaran and Son, 2007; Wilson, 2007). An increase in *OB* provokes *Supplier Desired Shipment Rate*

(DSR) which refers to the supplier target delivery rate. *DSR* verifies that the construction material is supplied within a specified time termed *Supplier Target Delivery Delay* ***(DD).*** *DD* is calculated to satisfy the EPC order on time. If the *Supplier Inventory* ***(SI)*** in stock is enough, the *DSR* leads to an increase in *Supplier Shipment Rate* ***(SR).*** Therefore, *SR* leads to an increase in the *Supplier Order Fulfilment Rate Ratio* ***(FR)*** (Kamath and Roy, 2007; Venkateswaran and Son, 2007)**.** The moment orders are fulfilled within *FR, OB* and *Order Delivery Delay* ***(ADD),*** the actual average delay between the placement and the receiving of the construction material reduces respectively. Else, *OB* will increase *ADD*. The SD equations for the order fulfilment process are in Appendix A.

ii. Inventory control: Adequate *SI* in stock increases the *Supplier Maximum Shipment* Rate ***(MSR).*** *MSR* indicated the maximum rate of shipment given the *SI* and the *Minimum Shipping* Time ***(ST).*** *ST* refers to the time taken to ship construction material to the EPC contractor. Thus, an increase in *ST* leads to decrease in *MSR. MSR* decreases *SR*, since supplier cannot ship out more than *MSR*. In contrast, an increase in *SR* leads to a decrease in *SI.* To avoid material shortage, it is needful to know whether the supplier *SR* has enough inventory to meet *EO*. *Supplier Inventory Coverage* ***(SIC)*** refers to the number of weeks the supplier can ship out at the current *SR*, given their *SI* level which shows the service level of the supplier. The lesser the *SIC*, the higher the desired *SI* to match the *EO.* The inventory level required to keep the desired service level of supplier to offer high delivery performance is called *Desired Supplier Inventory* ***(DSI).*** *EO* is estimated by the *Expected EPC Order Rate* ***(EOR)*** which depends on *ST* and the *Supplier Safety Stock* ***(SS)***. An increase in *EO* over time leads to increase in *EOR* and *DSI* respectively (Georgiadis, Vlachos, and Tagaras, 2006). The supplier considers EPC *Order Change In Expected Order* ***(CEO)***, when adjusting the *DSI. CEO* refers to the discrepancy between *EOR* and the *OR* over a time frame determined by the *Time to Average Order Rate* ***(AT)***. The *EO* information is used to generate EOR by smoothing the order quantity with the past duration's anticipated order. The supplier aims to maintain the *DSI* set equal to *EOR* (Venkateswaran and Son, 2007). *DSI* leads to an increase in the *Supplier Inventory Discrepancy* ***(SID)***, the gap between *DSI* and *SI.*

Supplier Inventory Adjustment Time ***(SDT)***, the time needed to take the inventory to the desired level, regulate *SID*, over a definite period. The SD equation for the inventory control process are in Appendix A.

iii. Material management process: This begins with *EO*, which is to be satisfied by the *Material Delivery Rate* ***(MDR)*** of the supplier**.** The *MDR* and *SR* are analogous**.** An increase in *MDR* increases the *EPC Inventory* ***(EI)*** in stock**.** *EPC Desired Material Usage Rate* ***(DUR)*** leads to an increase in the *EPC Material Usage Rate* ***(MUR).*** *DMU* refers to target usage rate EPC**.** Therefore, *MUR* leads to an increase in the *EPC Usage Rate Ratio* ***(UR).*** Adequate *EI* in stock increase the *EPC Maximum Usage Rate* ***(MU)*** by increasing the usage ratio. *MU* refers to the maximum rate of usage given the *EI* and *EPC Minimum Material Inventory Coverage* ***(MIC)***. *MIC* refers to the minimum time required to inspect, arrange and use the material. Hence, an increase in *MIC* leads to a decrease in *MU*. *MU* decreases the MUR, since EPC cannot construct more than *MU.* On the other hand, an increase in *MUR* leads to a decrease in *EI.* To prevent material shortage on construction site, it is essential to determine whether the EPC contractor *MUR* has enough inventory to match with *EO*. *EPC Material Inventory Coverage* ***(EIC)*** refers to the numbers of weeks the EPC can carry out construction at the current *MUR* given *EI*. The lower the *EIC*, the more EPC contractor desires an increase in the *EI* level in order to match with the *EO.* The inventory level needed to maintain the desired material usage rate of the EPC to give good project performance is called *Desired EPC Inventory* ***(DEI)***. *MDR* is estimated by the *Expected Material Delivery* ***(EMD)*** and depends on the *EPC Safety Stock* ***(ESS)*** and *ST.* An increase in the *EO* after a while leads to an increase in *EMD* and *DEI* respectively. The EPC considers *Change in Material Delivery Rate* ***(CMD)*** when setting the *DEI. CMD* refers to the discrepancy between *EMD* and *OR* over a period determined by the *Time to Average Delivery Rate* ***(AD)***. The *MDR* information is used to generate *EMD* by smoothing the construction material delivery quantity with past periods of perceived delivery. An EPC seeks to maintain the *DEI*, set equal to the *EMD*. *DEI* leads to an increase in the *EPC Inventory Discrepancy* ***(EID)***, the discrepancy between *DEI* and *EI*. *EPC Inventory Adjustment Time* ***(EDT)***, the time required to take the inventory to the desired level,

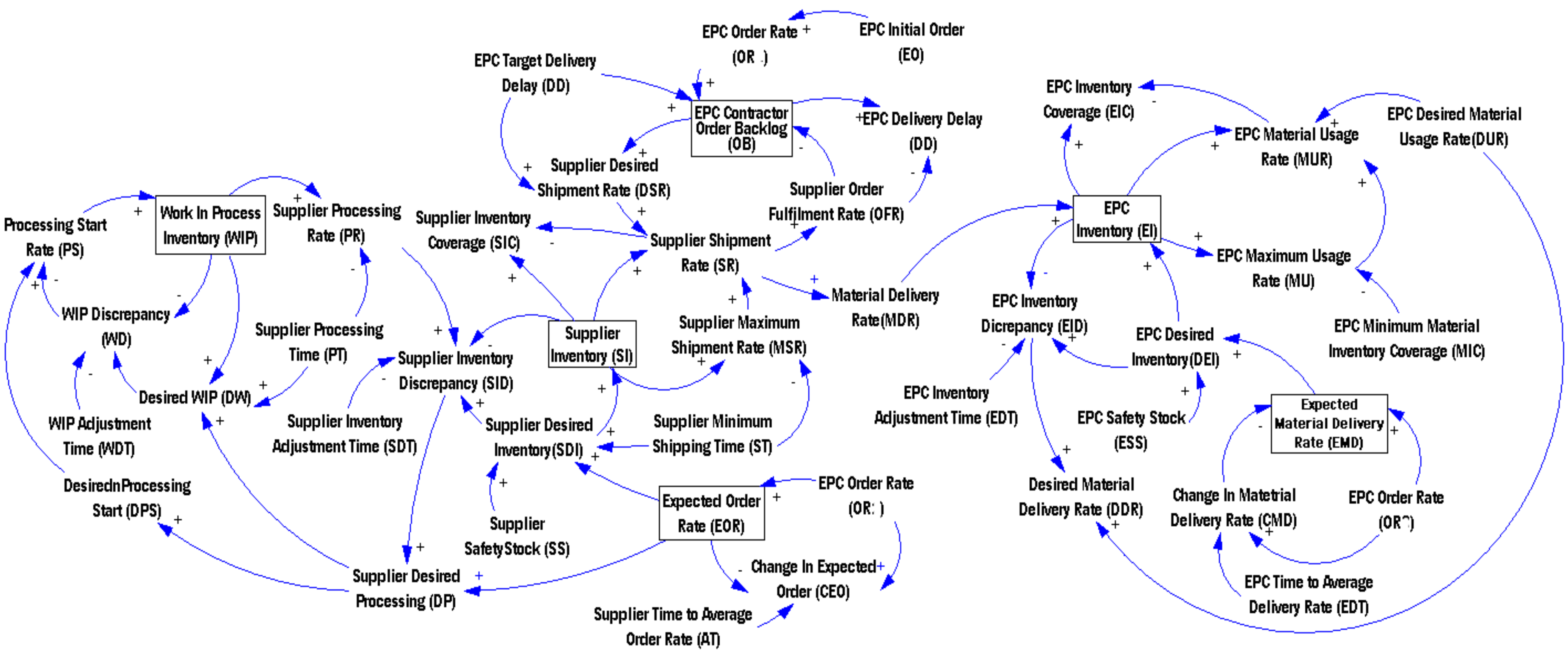


Figure 3.4. Construction Material Coordination System Unit.

corrects *EID*, over a period. The SD equations for the material management are in Appendix A.

iv. Order placement: As *EPC Inventory Discrepancy **(EID)*** increases, the EPC contractor needs to place more order with the supplier which leads to order change. As *Supplier Inventory Discrepancy **(SID)*** increases, the supplier needs to place more order with the producer which is out of the scope this study.

v. Order processing: An increase in *EOR* increases the *Supplier's Desired Processing **(DP)***. *DP* leads to an increase in *Processing Start Rate **(PS)*** (Venkateswaran and Son, 2007) and increase in *PS* leads to an increase in *Supplier's Work in Process Inventory **(WIP)*** (Georgiadis *et al*., 2006). *WIP* accumulates the difference between processing starts *PS* and *Processing Rate **(PR).*** *WIP Discrepancy **(WD)***, the awaiting processing line refers to the gap between *the Desired WIP **(DW)*** and *WIP*, which is adjusted by the *WIP Adjustment Time **(WDT)*** (Sterman, 2000)**.** *WD* adjust *PS* to keep up with *WIP* and *SI* in line with the *DW* level. *Processing Time **(PT)*** reduces the *DW* while leading to a decrease in *PR* as result of third order delay ($^{\delta}$**)**. The *PR* increases the *SI* level. A sufficient level of *SI* decreases *WD* (Wilson, 2007). The lesser the *WD*, the lesser the *DP* or vice versa. Increased *SI* level also leads to an increase in *MSR and SR* respectively. The SD equations for the order processing are in Appendix A.

3.4.2 SD Model Development Structure and Parameters.

List of constant parameters used in this model include: Target delivery delay, Initial EPC contractor order, Minimum shipment time, Supplier safety stock coverage, Supplier inventory adjustment time, Time to average order rate, Time to average material delivery rate, Processing time, WIP adjustment time, EPC contractor inventory adjustment time, EPC contractor safety stock coverage**.** Table 3.2 shows the values the parameters are set to when the time is equal to zero.

Development of the SD model comes after defining the problem. This SD model consists of stock (accumulation), flow (rate of change), time delay and feedback. To simulate the behaviour, the SD uses mathematics to describe and relate model variables. Stock provides a form of memory which is mathematically represented by integral while Flow is the rate of change, mathematically represented by first order differential equation.

Table 3.2. Illustrative Parameter for SD model

Parameters	***Parameter values in CMSC model***
DD (Target Delivery Delay)	1 week
EO (EPC initial Order)	5000 material
ST (Minimum Shipping Time)	1 week
AT (Time to Average Order Rate)	8 weeks
SS (Supplier Safety Stock)	2 weeks
ESS (EPC Safety Stock)	1 week
PT (Processing Time)	8 weeks
SDT (Supplier Inventory Adjustment Time)	1 week
WDT (WIP Adjustment Time)	1 week

The Vensim and AnyLogic software were used to develop and simulate the material supply model in this work. Systems dynamics professionals attempt to step up the process by developing collections of templates or libraries of commonly used component from Sterman's Business Dynamics (Sterman, 2000) and Hines' Molecules (Hines, 1997). The model in this thesis is built upon components from Sterman's Business Dynamics (Sterman, 2000), however, these components are generic. Therefore, some of these components were modified into construction material supply chain (CMSC) model.

The structure of a model consists of two main components namely: the physical environment and the decisions policy made by managers in relation to the physical environment. The CMSC model includes supplier's processing capacity, inventory management, order fulfillment, order placement which contributes the fluctuation in the processing capacity, material management, and shipment and order fulfilment. The SD equations are developed and discussed in Appendix A. In this study, we assumed EPC contractor demand 5000 materials per week and the SD model is simulated for 52 weeks (1 year). The SD model is simulated using AnyLogic software.

The CMSC model consist of three sub model which are 1) Supplier Processing, 2) Shipment and Order Fulfilment and 3) EPC contractor Material Management. Chapter four gives the simulation result and analyses that enhanced better understanding of the behaviour of the of the CMSC model.

1. **Supplier's Processing Model**: The processing capacity is driven by the EPC contractor's order which eventually builds up inventory for shipment. The processing model in Figure 3.5 captures the causal relationship. It illustrates the supplier's processing and shipping mode for the construction material. The supplier operated under the make-to-order inventory policy and the supplier's processing model was built based on the generic Production Starts model from Sterman's Business Dynamics (2000). This model was tailored to fit the Construction Material Supply Chain (CMSC). Firstly, the Production Start Model's variable names were modified to match the CMSC nomenclature, variables, constants and unit conversion were added to the model. Secondly, the material producers (exogenous factors) were captured in processing model as supplier Work in Process Inventory (WIP) stock. The CMSC model operates as a pull process i.e. the EPC contractor must "pull" the material off -the-shelve after the contractors ordered for it.

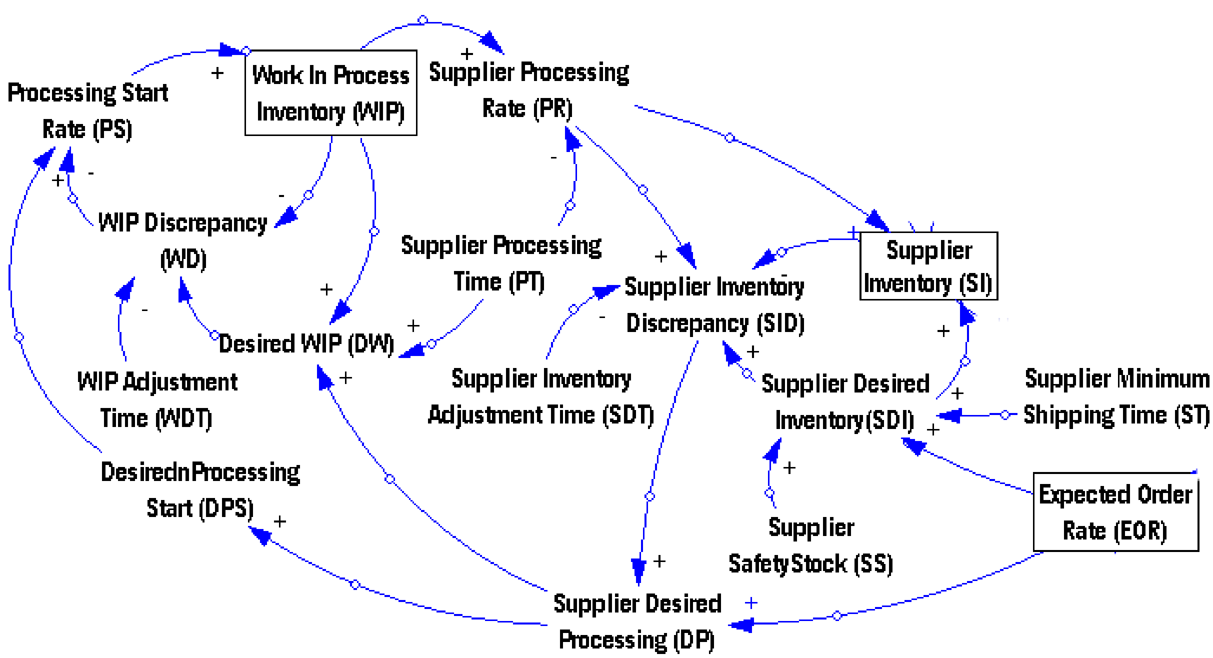


Figure 3.5. Supplier Processing Model

2. **Supplier's Shipment and Order Fulfilment Model:** This sub model consists of supplier inventory, order backlog and shipment, and the expected order which is a smooth function of EPC contractor order for construction material as shown in Figure 3.6. It was developed based on Order fulfilment model from Sterman's Business Dynamics (2000). From the supplier's inventory, construction material is shipped to EPC contractor; however, in practice, this material cannot be delivered instantly, which calls for the use of order backlogs that aggregate the discrepancy between EPC fulfilled orders (*SR*) and EPC Order (*EO*). First order material delay is used here because there are no capacity constraints on the normal *Delivery Delay* (*DD*). The average delay to deliver EPC order is given by the ratio of order backlog to current shipment rate. In the numerical study, *Order Fulfilment Ratio (FR)* regulates the shipment rate *(SR)* from the supplier to the EPC contractor. Sterman, (2000) study was used, relating *Order Fulfilment (FR)* to *Maximum Shipment Rate (MSR)* and *Desired Shipment Rate* (*DSR)* as shown in the Table 3.3. The *Order Fulfilment (FR)* of the all the trial runs of the simulation model were obtained through the Table 3.3.

Table 3.3. Order Fulfillment Ratio Table

MS/DSR	*0.0*	*0.2*	*0.4*	*0.6*	*0.8*	*1.0*	*1.2*	*1.4*	*1.6*	*1.8*	*2.0*
FR	0.0	0.2	0.4	0.58	0.73	0.85	0.93	0.97	0.99	1.0	1.0

Figure 3.7 shows the Order Fulfilment ratio as a function of *MSR/DSR*. For example, when the obtained ratio is 0.8, the look up value from Table 3.3 for *FR* is 0.73. When shipment is equal to desired shipment i.e. (*SR=DSR*), the order fulfilment ratio is equal to 1 (*FR=1*). The derivation of SR is shown in Appendix A. Thus, we assume that the supplier will ship the order if material is available and adequate in their store. They will not hold back material or keep for forthcoming order.

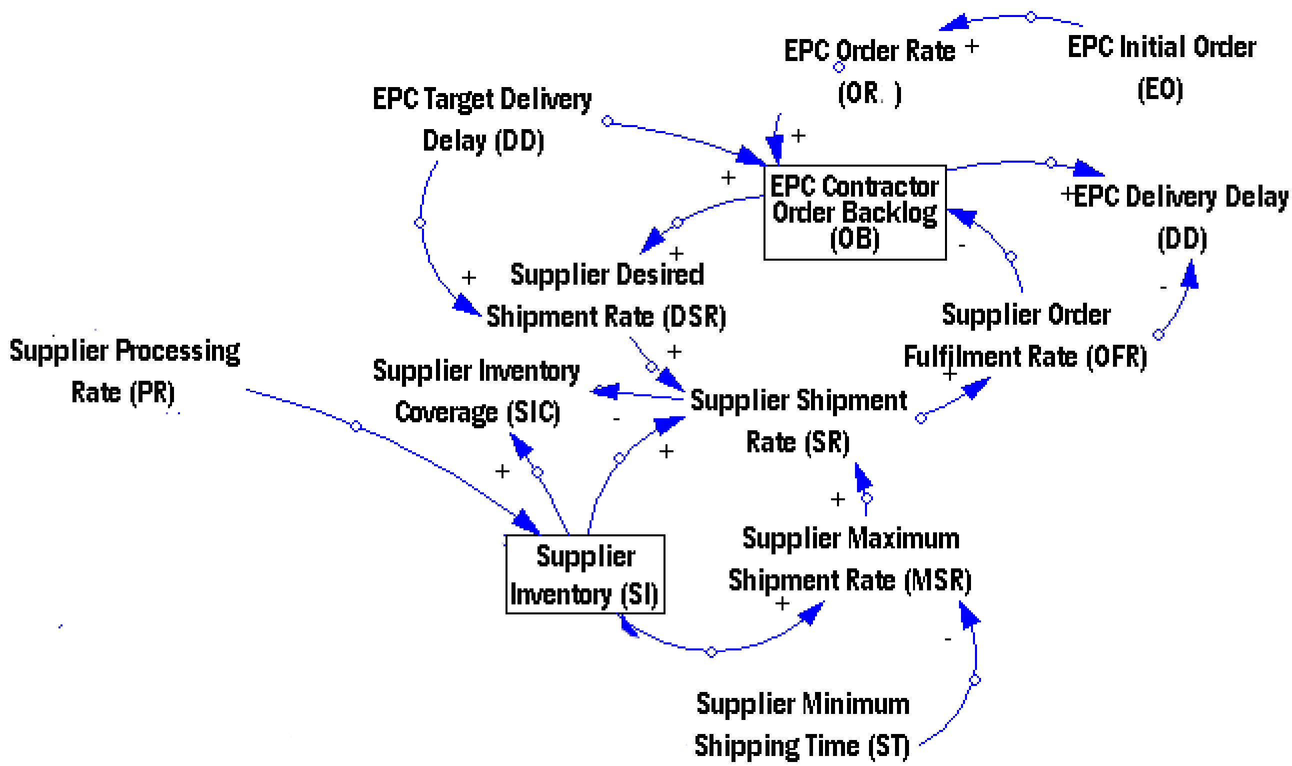


Figure 3.6 Supplier Shipment and Order Fulfillment Model

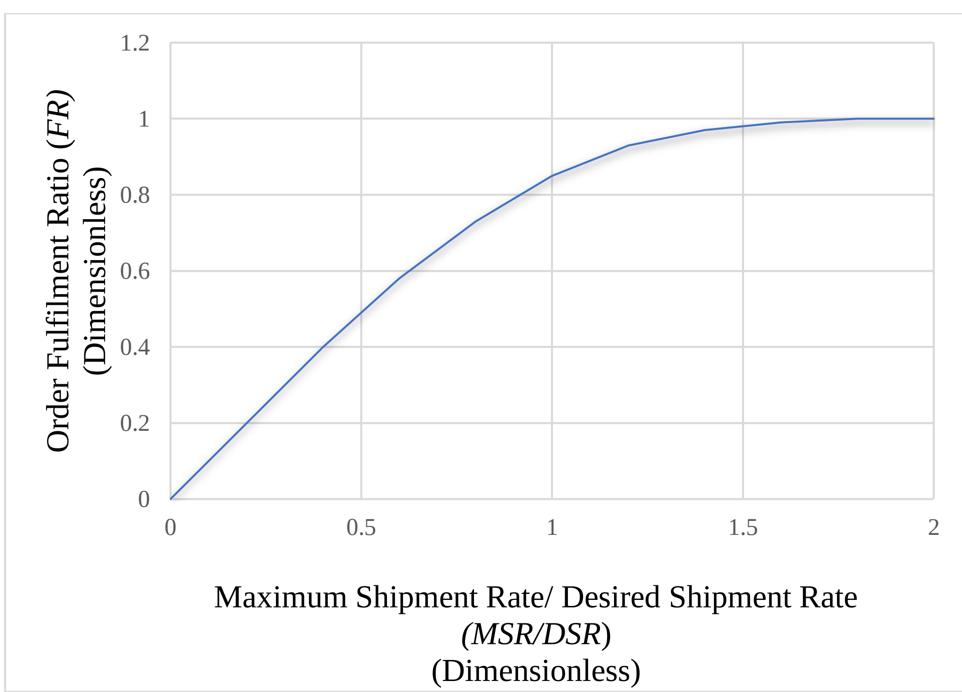


Figure 3.7 Order Fulfillment as function of supplier's inventory

3. **EPC Contractor's Material Management Model:** This structure is like the supplier's inventory of processed goods. Unless there are construction materials, construction will not start or progress, therefore, EPC contractor must have ordered enough materials to absorb any disruption and keep the construction work going. The material delivery rate is analogous to the shipment rate. Figure 3.8 shows the stock management structure of the material inventory. The Material Usage Rate *(MUR)* is related to the Material Delivery Rate *(MDR)*, but the real material usage rate is the desired material usage rate when the material is adequate for construction, else, material usage rate (construction progress) reduces as a result of material shortage on site which in turn gradually decreases the material usage ratio. The EPC contractor must have enough material to keep the construction going. The coverage depends on proportion of actual rate to the desired rate which is based on the availability and sufficiency of EPC contractor's material inventory. Just like the Order Fulfillment Ratio, the function that regulates it is the same for the Material Usage Ratio. Table 3.4 shows the material usage ratio and the Figure 3.9 shows the Material Usage Ratio as a function of *MUR/DMU.* The desired material usage rate is familiar to the EPC contractor's order while the maximum usage rate is determined on the actual contractor's material inventory. The desired material inventory is determined by the desired usage rate of material and the desired material inventory coverage i.e. minimum material inventory coverage which is based on the quantity of material needed per time. This is the period between when the material gets inspected, stocked and the time it is required for construction.

   All the production stages are shown as *WIP* in this work. Processing time is the average transit time for all the materials amassed in the model. The lesser materials accumulate, the lesser the deviation in the material cycle time and the higher the order of the delay that best describes production.

Table 3.4. Material Usage Ratio Table

MUR/DMU	*0.0*	*0.2*	*0.4*	*0.6*	*0.8*	*1.0*	*1.2*	*1.4*	*1.6*	*1.8*	*2.0*
UR	0.0	0.2	0.4	0.58	0.73	0.85	0.93	0.97	0.99	1.0	1.0

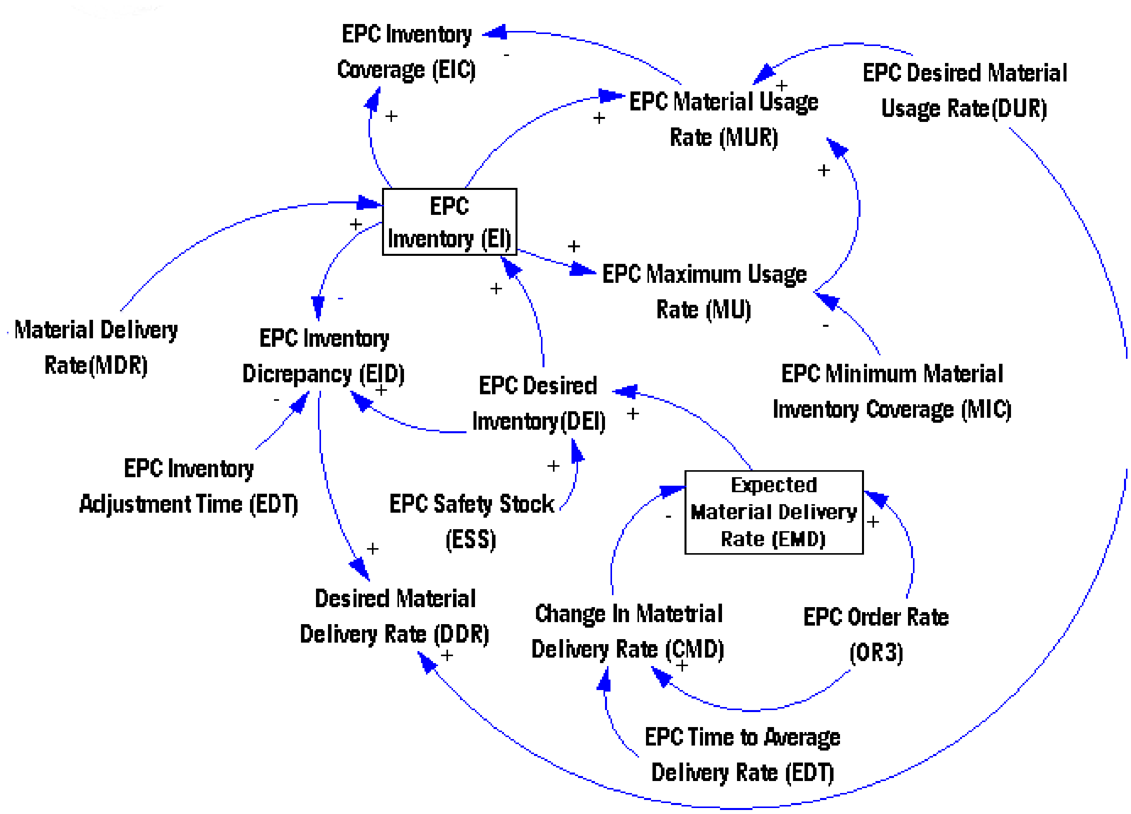


Figure 3.8. EPC Material Management Model

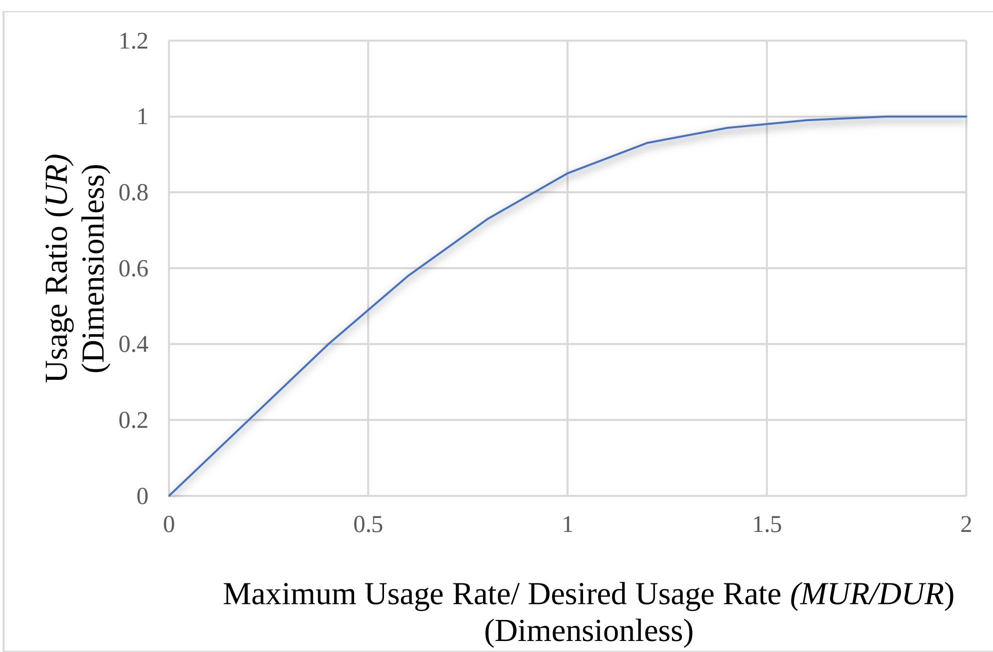


Figure 3.9. Material Usage as function of EPC contractor's inventory

CHAPTER 4

MODEL TESTING, RESULTS AND ANALYSIS

4.1 Model Validation

The main aim of a SD study is to explain the behaviour of the system and give alternatives to help obtain the desired system behaviour (Saysel and Barlas, 2001). After the development of the CMSC model, using the stock and flow diagram, model equations (nonlinear differential equations), initial values and constants were applied to the model. Simulating a real-world problem helps provide better insight on how to solve the problem. Systems Dynamics (SD) model requires validation of practicability and confidence transmission for the users (decision makers, managers), even after conformance of the model to physical laws of the system. Confidence has its root in the ability of the model to realize results which are the same as the decision maker's mental model while practicability is a function of whether the model addresses the research problem, where decision makers need support. Various tests were conducted to build confidence in the CMSC model. These included the consistency of variable dimensions, which was tested through the AnyLogic software which reported no dimensional consistency or error found. Then, various scenario tests were taken up to test consistency of the CMSC model behavior and the realistic operation. One of the tests which had a scenario of no EPC order, showed that there were no working activities i.e. processing=0, shipping =0, material delivery=0 and material usage =0. The behaviour of the model aligns with what is obtainable in the industry and past works on how demand variability affects performance and how safety stock can be used to improve the performance. Instead of validating model, the model can be run through several tests to gain confidence in it (Barlas, 1996).

Base Model: In the delay-free base model, there was no form of discrepancy between the desired state and the actual state. This ideal state also describes the situation where there is timely and accurate information between the supplier and the EPC contractor. This information includes inventory data, order status tracking report, supply chain operating parameters like material lead time and time delay.

In this section, numerical example was considered which assumed EPC order of 5000 material per week for a period of 52 weeks (1 year). Table 3.2 shows the parameters and the values used in the numerical study. Accordingly, when the EPC contractor makes the material order continually from its supplier, who then makes decisions on the safety stock level required to maintain adequate service level. Finally, the construction material was shipped to the EPC contractor. The outcome of the delay free scenario shows that construction material was always available in the store for shipment and usage. The formulation of EPC order rate is robust, orders remained nonnegative no matter how large the demand shock may be, the supply line and stock never fell below zero. The order fulfilment sector was also tested with its response which had increased backlog. The shipment formulation allows supplier to meet their delivery goal without capacity constraints.

4.2 Test Input Built-in

4.2.1 Introduction

Testing the CMSC model's components i.e. the supplier's shipment and order fulfillment sub model, processing sub model and EPC contractor's material management sub model, CMSC model should give steady behavior when assessed for simple ideal scenarios with progress evolving towards the planned goal.

To analyse the CMSC model and study its dynamic behaviour, the model was simulated under equilibrium condition by varying the input signal level and parameters of the model. Dynamic behaviour was generated when the system was disrupted at equilibrium. The focus of this CMSC model is the EPC contractor's and its suppliers' inventories, which are major constraints to the availability of construction material on site. Inventory level affects the supplier's ability to ship material to EPC contractor, thereby affecting the contractor's desired inventory level which eventually affects the construction rate. The model was disrupted by various levels of input signal (step function). This facilitated the conduction of controlled experiment on the CMSC model, by observing how the model responded to the input signal when the system was in equilibrium state. This is a state where the discrepancy between the desired and actual state is 0 i.e. all stocks in the system, were unchanging and the inflows and outflows were the same. This study used inventory coverage, order backlogs, delivery delay, and material usage rate as performance metrics, which have been studied in other sectors of life such as health. (Gonul Kochan *et al.*, 2018; Bijulal *et al.*, 2011; Bijulal and Venkateswaran, 2008; Ovalle and Marquez, 2003).

4.2.2 Step Response Simulation

The step input is a simple test that checks the response of the system to an unpredicted permanent change in the EPC contractor's demand. The input test signal was also considered because it is supply chain variability effect. The CMSC model was disturbed from equilibrium on the 6th week by EPC contractor's demand shock of a 10% step increase (0.1) of 5000 materials per week, which relays the signal to the supplier who responded by increasing its ordered materials from the producer. Supplier tries to balance order processing and production (which is out of their reach) with the EPC contractor's demand which results in a negative feedback. Several delays often occur while the EPC contractor and supplier try to update orders and the producer try to update production (such as time to adjust inventory in the production). The delayed encountered by producers is not considered in this work. Figure 4.1 shows the response behaviour of EPC contractor's material inventory. The expanding gap between the desired contractor inventory and the actual inventory pushes the EPC contractor to increase its subsequent order. Figure 4.2 shows the response behaviour of supplier's inventory which is a major criterion for the timely delivery of construction material to EPC contractor. Due to lack of space, supplier plan with the EPC contractor's demand to know which material to store or put on the shelf. Supplier must increase its processing speed or expand its capacity, if need be, to ensure the EPC contractor are satisfied. The expanding gap between the desired supplier inventory and the actual inventory push the desired processing rate to accelerate above the expected EPC order rate, thereby causing a growth in the work in process (WIP) inventory to satisfy its processing target, so the desired processing start rate accelerates higher than the desired processing rate. At the time the EPC contractor's order increased, its inventory level has not yet changed and gradually fell over time unlike the supplier's inventory level which dropped immediately. Furthermore, these inventories' behaviour had effect on the EPC contractor's material usage rate and supplier's reliability overtime.

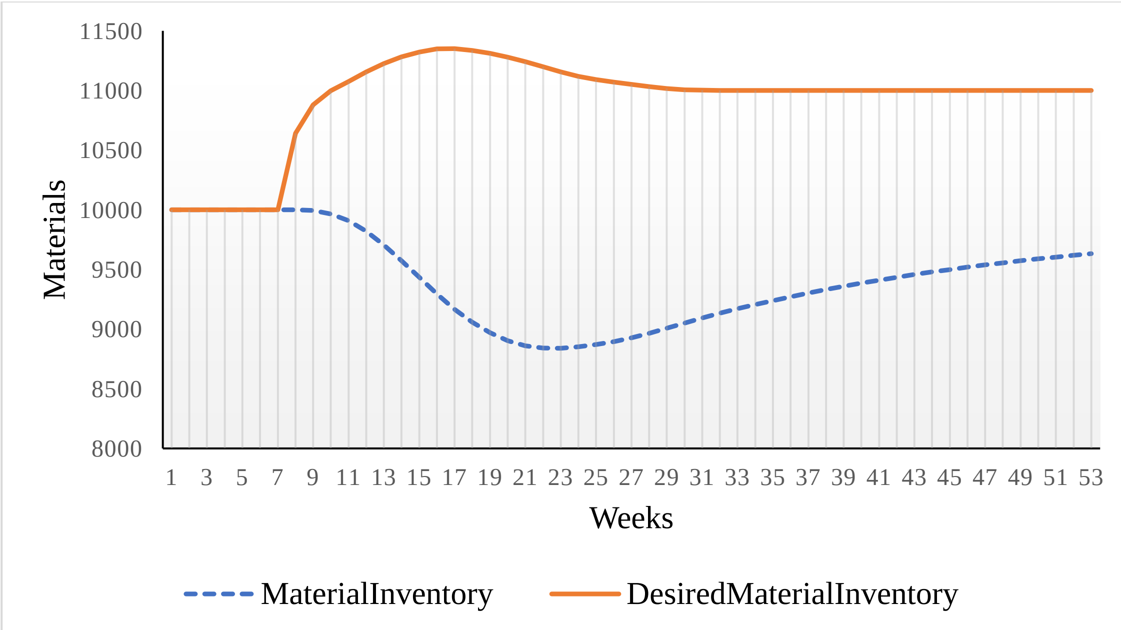


Figure 4.1. EPC contractor's Inventory behaviour to 10% EPC order increase

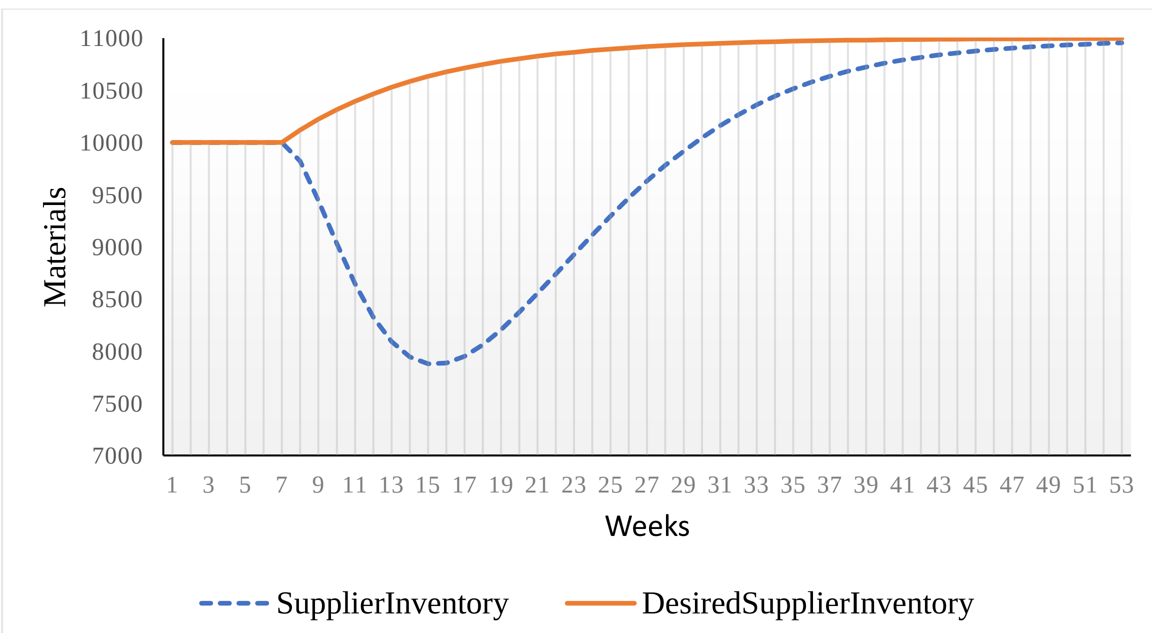


Figure 4.2. Supplier's Inventory behavior to 10% EPC order increase

4.3 Model Analysis of the CMSC Model

4.3.1 Behaviour of the Supplier's processing and shipment model

After the 0.1 step increase in EPC contractor's demand on the 6th week, shipment rate became steady after 25 weeks of the demand shock and the accumulated order backlog led to an increased desired shipment rate as shown in Figure 4.3. Order backlog implies there is a delay between the EPC contractor order release and material delivery. Such a delay may include processing time, shipment time to construction site, decision making time and other organisational activities. When the shipment rate falls, the delivery delay increases, and this is due to the low level of supplier's inventory. The simulation in Figure 4.3 tests the shipment formulation with a step increase in EPC contractor's orders from 5000 materials/week to 5500 materials/week, taking capacity as constant. The initial order backlog is 5000 materials because there is normal delivery delay of 1 week. The shipment smoothly approaches the new equilibrium of 5500 materials/week. This test showed the expected inference of the formulation for order fulfilment.

The supplier often does not have timely information on EPC contractor's order change. This reflects on the supplier's inventory: it is forced to increase the expected order rate from the EPC contractor and work in process (WIP) when the gap between the desired and actual inventory increases. It took the supplier 15 weeks longer than the specified 8 weeks (normal processing time) to recover from the 10% increase in change order. This is seen in Figure 4.4, where the processing start rate is higher than the desired processing rate. The processing start gets to a peak of about 19% higher than its original level about 4 weeks after the demand shock to quickly fill the supply line of WIP, this happened with an amplification of 1.4. Processing rate did not exceed shipment until more than 8 weeks passed, when the supplier's inventory was at its lowest level as seen in Figure 4.2 and 4.5, while the processing rate which lags the EPC contractor's order by 8 weeks had to rise above the shipment in the 15th week so as to consistently satisfy the EPC contractor.

As shown in Figure 4.6, the 10% step increase causes a drop in the supplier's inventory coverage from initial of 2 to 1.4 weeks, 10 weeks after the change in EPC contractor's order. If the processing rate continues at 5000 materials/week, it will affect the supplier's timely delivery ability.

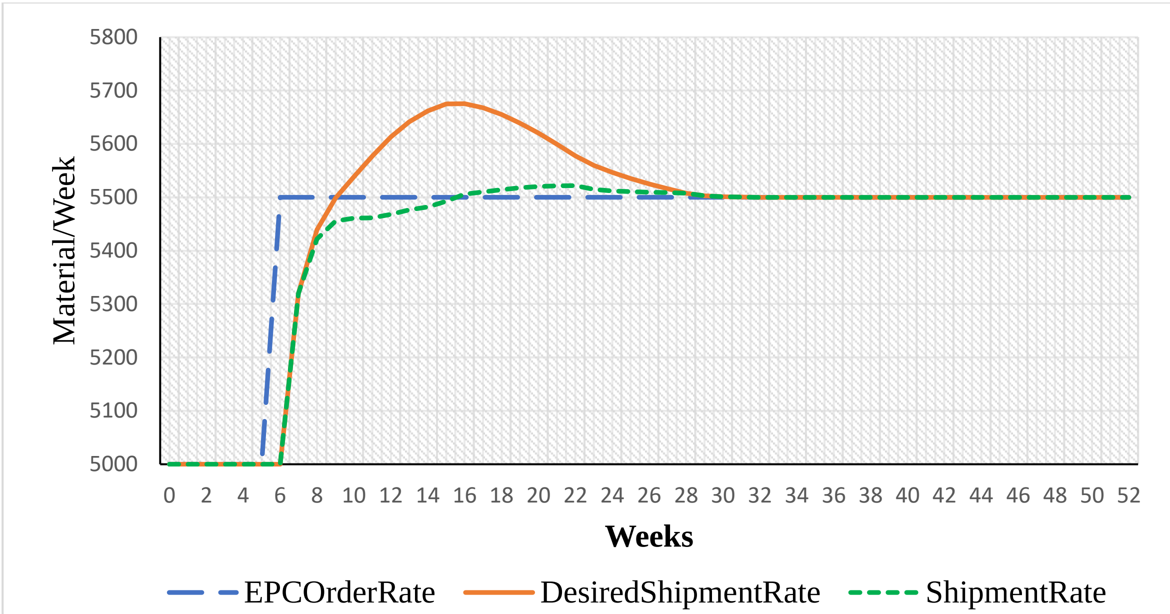


Figure 4.3. Supplier's shipment behaviour to 10% increase in EPC order

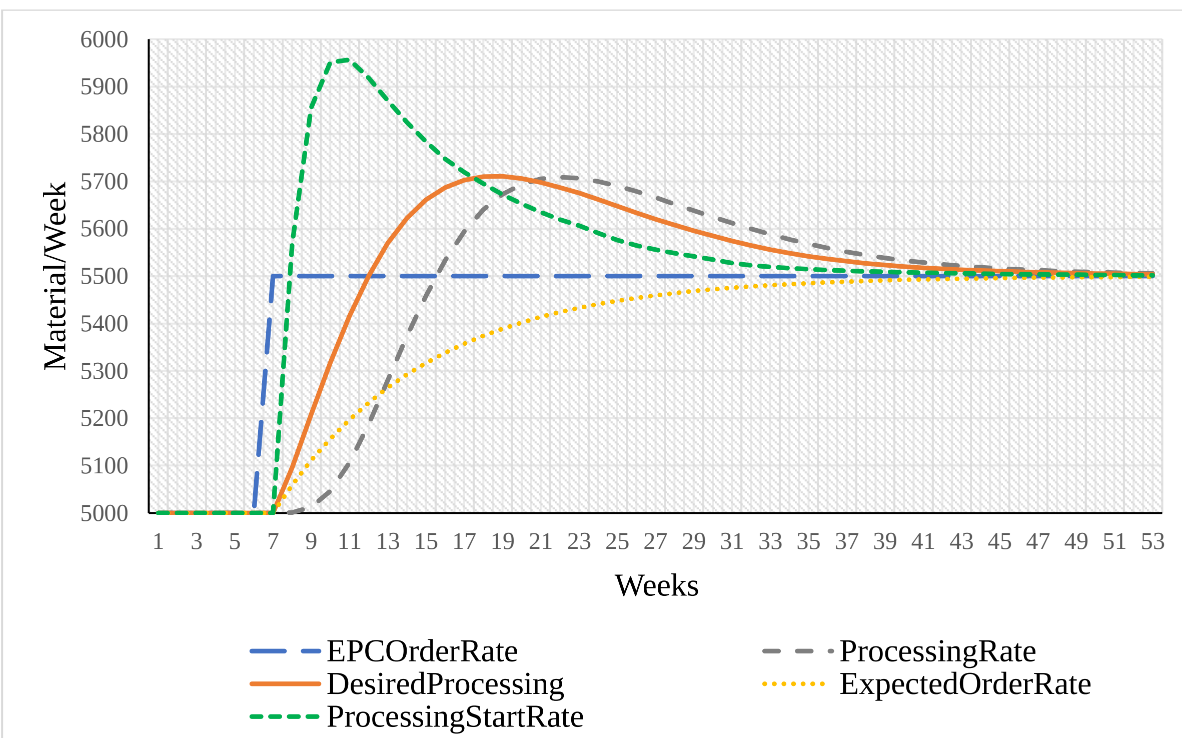


Figure 4.4. Supplier's Processing response to 10% increase in EPC order

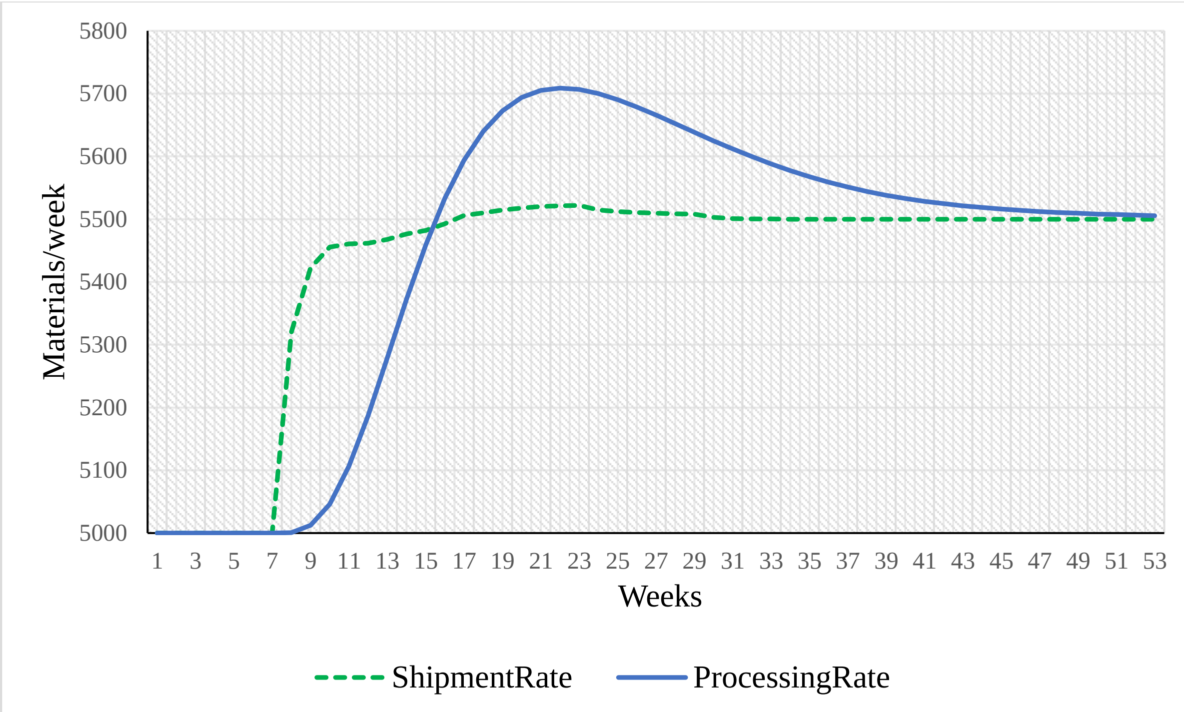


Figure 4.5. Graph showing when the supplier's inventory falls

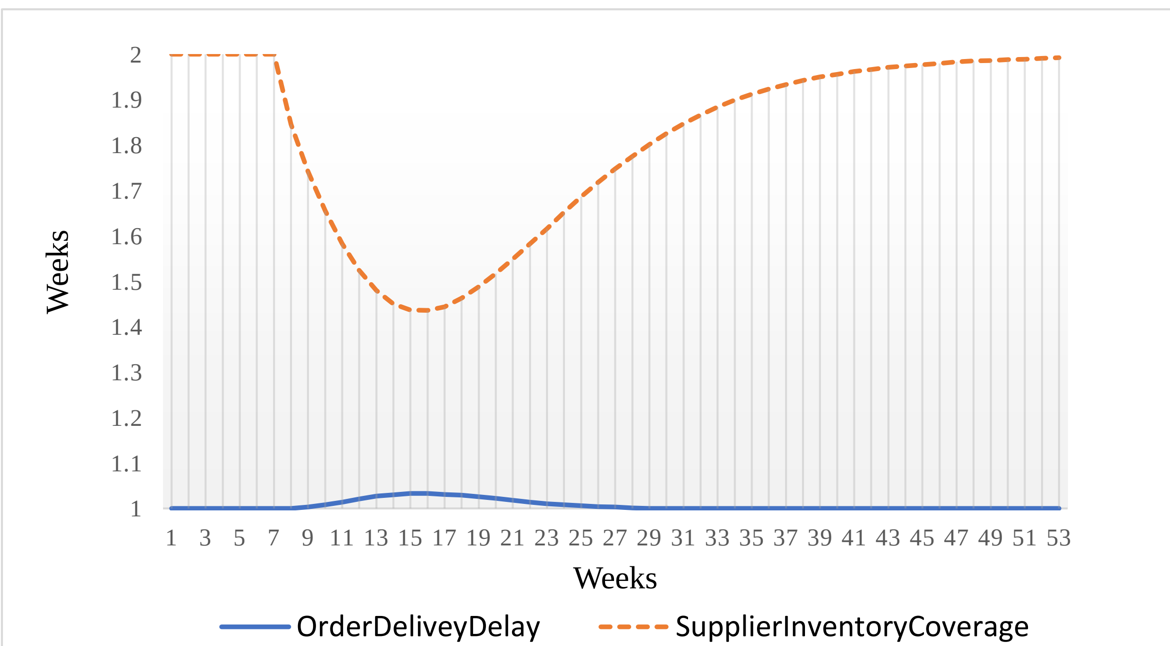


Figure 4.6. Supplier's service level to 10% increase in EPC order

4.3.2 Behaviour of the EPC contractor material management model

The SC manager keeps an eye on the supply line of materials ordered and makes orders based on the desired delivery rate which is adjusted to keep inventory at the desired level. The desired material inventory is determined by the desired material usage rate and the contractor's belief about the delivery delay for the receipt of materials i.e. expected delivery delay. A huge fall in the EPC contractor's inventory forces it to consequently increase its order so that the material delivery rate can exceeds the material usage rate to keep the construction going at the desired rate. The material delivery rate did not exceed the material usage rate until more than 9 weeks passed (16th week). Figure 4.7 shows the EPC contractor's order rate, the material delivery rate and the material usage rate depicting the construction rate. The construction rate stabilised 15 weeks (21st week) after the order change.

The analysis of construction materials delay during construction was proposed to focus on the risk related to EPC contractor which is untimely delivery of material need for construction. This was done by comparing the EPC ordering rate with the material usage rate which depends on the availability of the material for construction. Lack of information sharing among the supply chain entities causes bullwhip effect, distortion and amplification of customer demand which is due to the inability to forecast correctly (Sterman, 1989; Lee *et al.*, 1997).

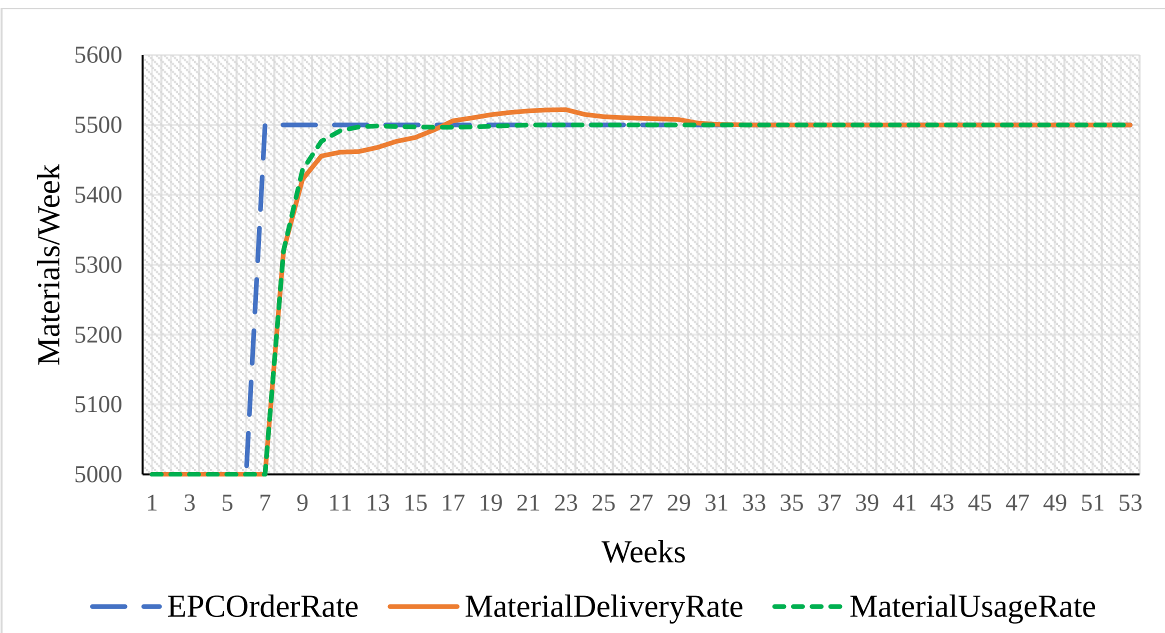


Figure 4.7. EPC contractor's usage rate response to 10% increase in their order change

This simulation explains some basic supply chain behaviour such as amplification, phase lag, and fall in inventory level in response to unpredicted increase in EPC contractor's order. The presence of processing and shipment delays generated amplification and phase lag. Due to fluctuation in material demand of the EPC contractor, supplier may have surplus or too little inventory depending on the management policies which affects its delivery reliability.

The model testing is carried out by using the sensitivity analysis (single variable and multi variable) as discussed in section 4.4 below and intervention analysis which is discussed in section 4.5.

4.4 CMSC Model Sensitivity (What-If) Analysis

Sensitivity analysis is a "what-if" analysis that gives insight into outcomes of decisions given a certain range of variables. This will help us know how changes in one variable influence the chain reaction and the understanding the chain reaction will help decision makers make effective policy or decision. The what-if analysis helps us understand the impact a range of variable has on the system.

In this section, I investigated selected parameters and examined their impact level on the model results through sensitivity analysis. The sensitivity analysis of the model parameters will reveal the influence of the parameters in the CMSC model. Parameters such as processing time, shipping time, safety stock coverage are studied in this work. These test variables were selected because of the influence of flow rate and material availability in the store. The simulation timeframe is 52 weeks (one year). By varying the values of the chosen parameters, the changes on the model outputs was examined and the impact levels was determined from the changed parameters. These results variables are plotted into graphs to explain the changes.

Several simulations were carried out and studied by varying one parameter at a time or two at the same time. Varying the EPC contractor's order with increment of 20%, 40%, 60%, 80%, 100% of the initial order, this section explains the behaviour of the CMSC model entities in terms of order backlog, delivery delay, inventory coverage and material usage rate.

After the sensitivity analysis, several interventions were carried out based on the observed results. Comparing the results from the interventions can be tailored into likely intervention policy for construction industry and its suppliers.

4.4.1 Single Variable Sensitivity Analysis

The section below studied the effects of different step input heights on the CMSC model, illustrating the unpredicted change order that happens in the construction industry. By varying the EPC contractor's order with increment of 20%, 40%, 60%, 80%, and 100% of the initial order. This analysis studied the effects of one test variable at a time on the system performance, which is also used as basis for the multi variable sensitivity analysis. The EPC contractor's order change has different impacts on order backlog, delivery delay, inventory coverage, and material usage (construction progress)

4.4.1.1. Behaviour of the CMSC model to EPC contractor order change

As the EPC contractor's order varies, the supplier experiences fall in its inventory level with reduction in supplier's inventory coverage while EPC contractor encounters instability in the construction progress. The supplier will eventually get a point where it will not be able to deliver material due to inventory level drop, which translate to unavailability of materials for the EPC contractor to use. So, there is need for collaboration to be emphasized to enable healthy supply chain network. Figures 4.8-4.17 show the response of the CMSC model to different step increase in EPC contractor's order. Figures 4.8 a and 4.8b show the response of material delivery and supplier's service level to 10% increase in EPC order. The effects of the change order on order backlog, delivery delay, inventory coverage, and material usage (construction progress) were also studied**.**

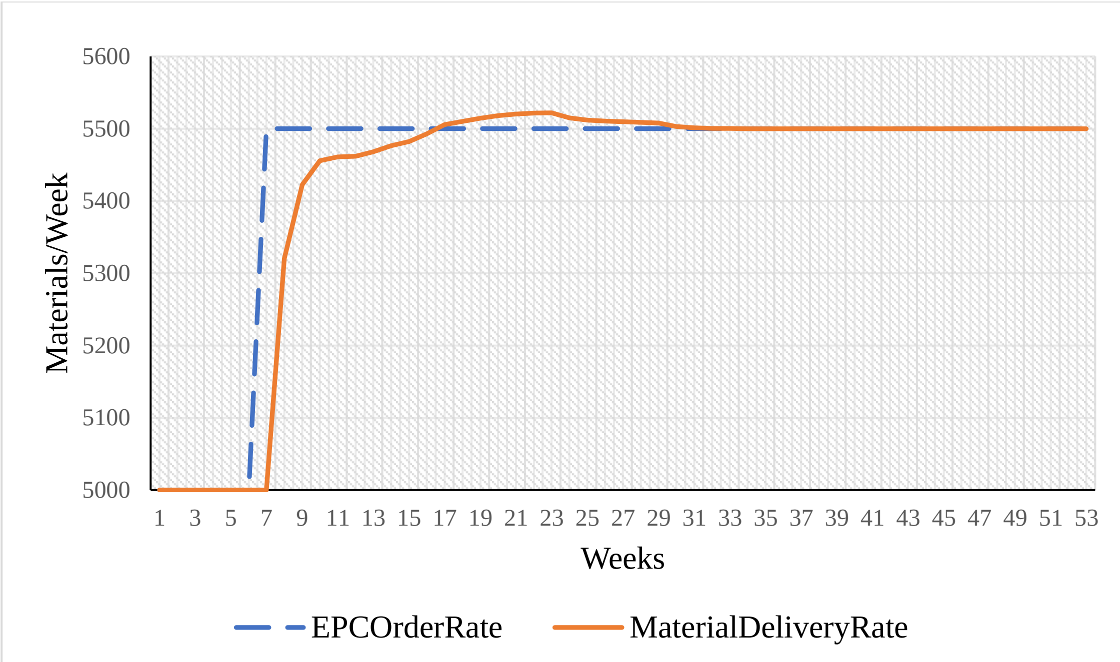


Figure 4.8a. Effect of 10% increase in EPC order on supplier's service level: material delivery rate

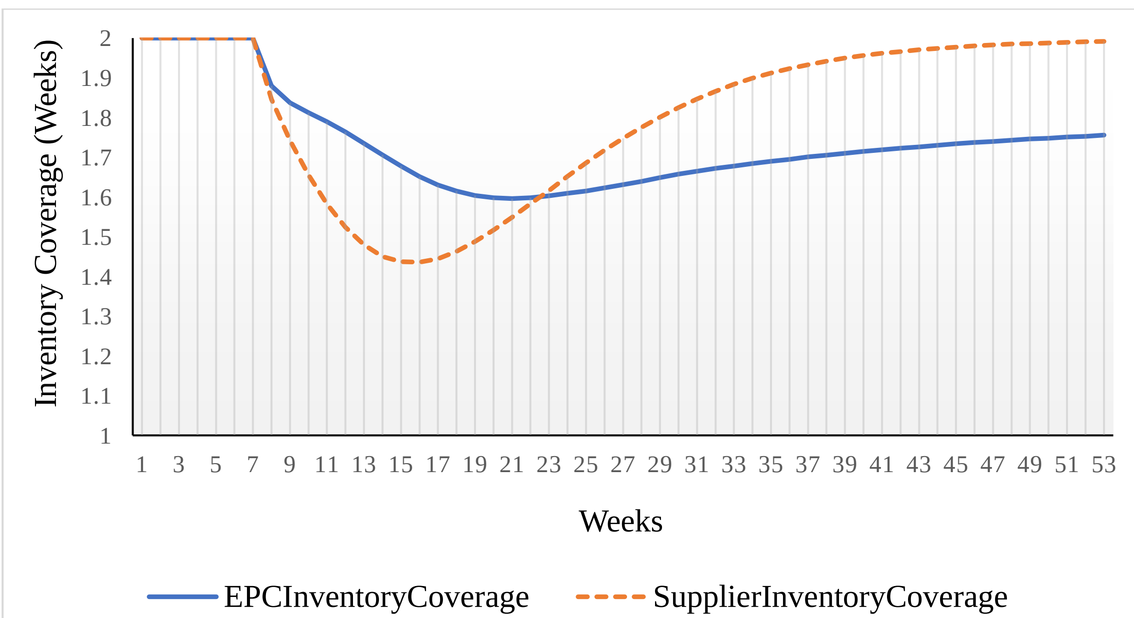


Figure 4.8b. Effect of 10% increase in EPC order on EPC and supplier's inventory coverage.

The effects of the change order on order backlog, delivery delay, inventory coverage and material usage (construction progress) were studied by varying the EPC contractor's order with increment of 20%, 40%, 60%, 80%, and 100% of initial order.

(1) Order backlog effect and delivery delay: Order backlog accumulated, and delivery delay rose with increase in EPC order change as seen in Figure 4.9a and Figure 4.9b respectively.

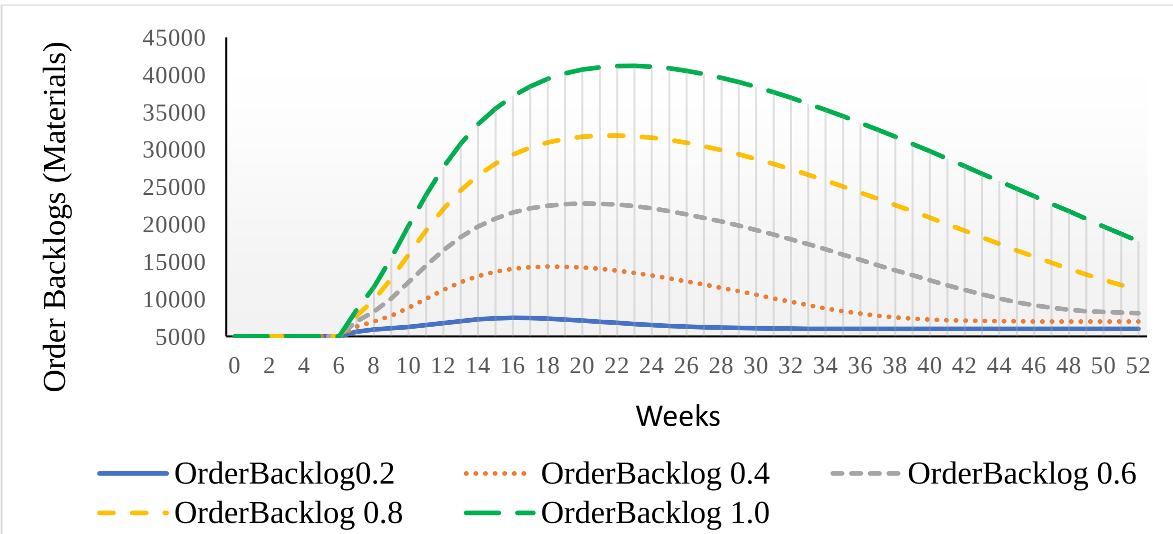


Figure 4.9a. Resultants Order backlogs to sudden material order increment

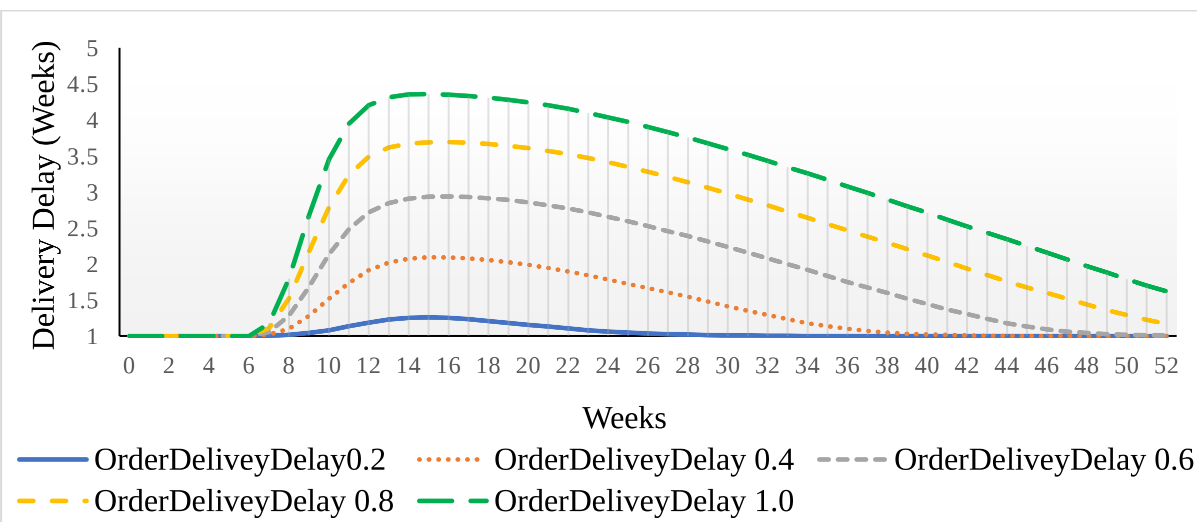


Figure 4.9b. Material Delivery Delay as a result of sudden material order increment

(2) Supplier's Inventory Coverage: The inventory coverage expressed in weeks shows the service level of the supplier. As the inventory level of the supplier fall, it reduces its ability to ship materials to the EPC contractor thereby leading to reduced reliability level as revealed in the Figure 4.10. Availability of material in the inventory will help the supplier maintain and increase its delivery reliability.

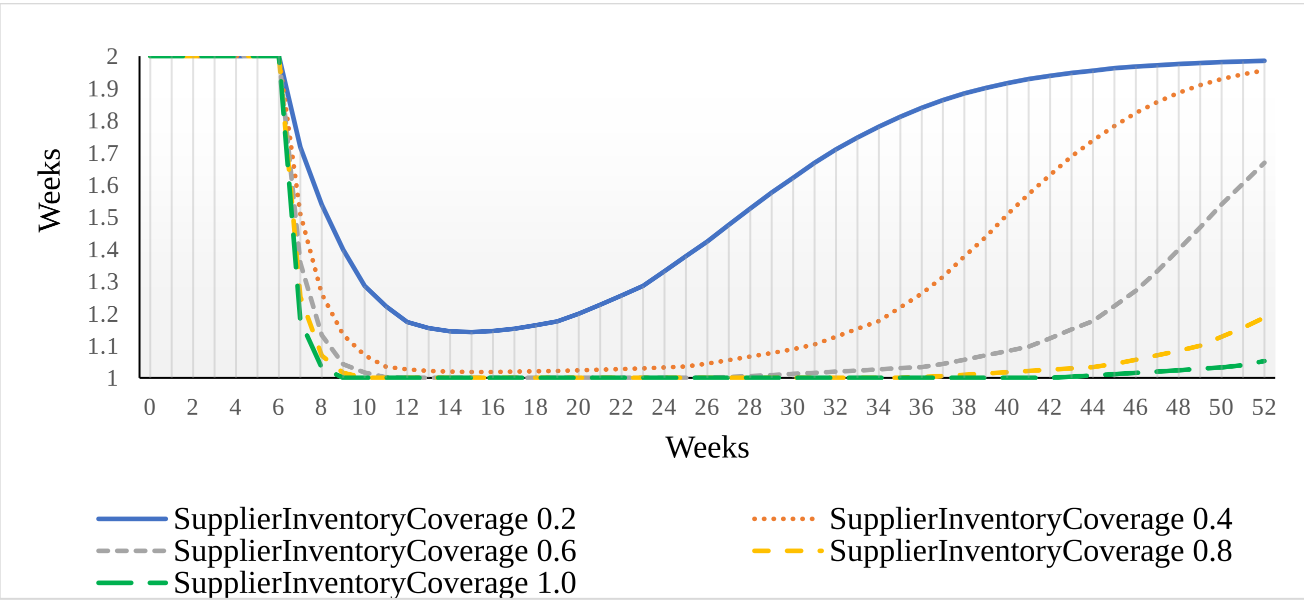


Figure 4.10. EPC change order on supplier's service level

(3) Material Usage rate (construction progress): The EPC firm can not maintain or increase its construction rate unless material is available in its store i.e. the material must have been delivered by the supplier on the construction site. Figures 4.11 a – e show the construction progress of the EPC contractor by comparing the actual material usage rate (dependent on material availability) to the its order rate which is needed to accomplish its target construction progress. It is observed that the construction progress experiences more instability as the order change increase. With a 10% increase in the EPC order, the construction rate stabilized 15 weeks after the order change i.e. the EPC firm experiences instability in the construction progress as the order change increases. Figure 11f shows the disruption the EPC firm encountered in respect to the construction rate which was caused by order changes in the absence of materials for construction.

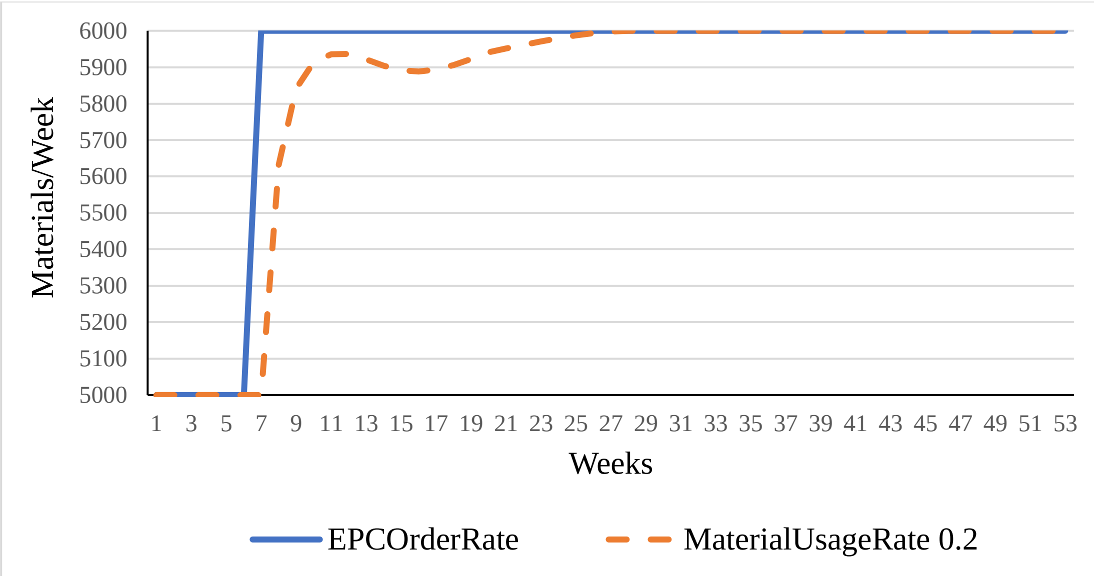


Figure 4.11a. Construction rate in response to 20% increase in material order

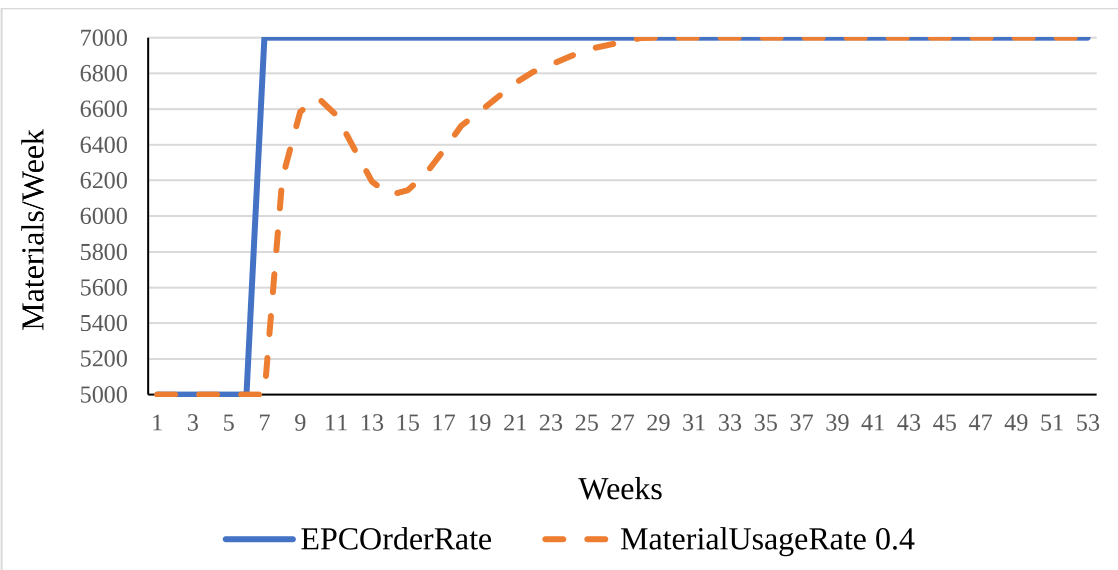


Figure 4.11b. Construction rate in response to 40% increase in material order

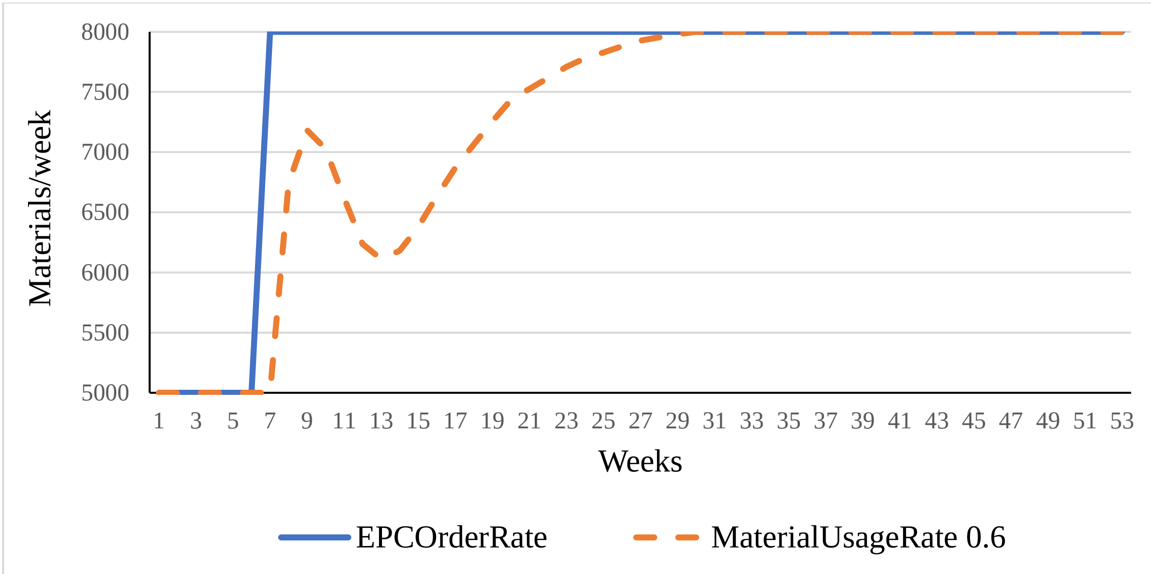


Figure 4.11c. Construction rate in response to 60% increase in material order

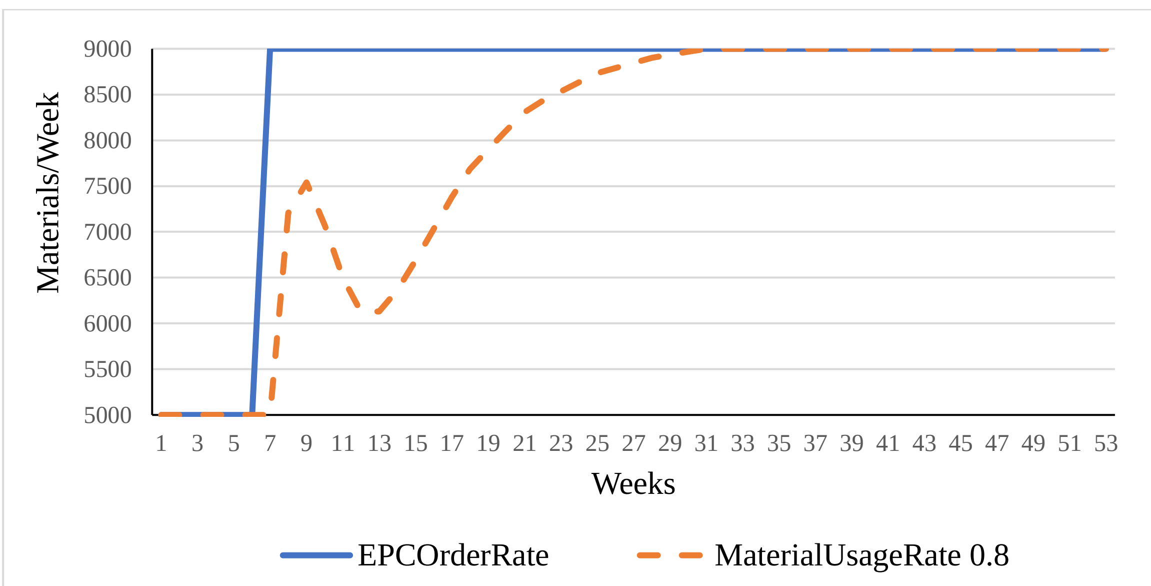


Figure 4.11d. Construction rate in response to 80% increase in material order

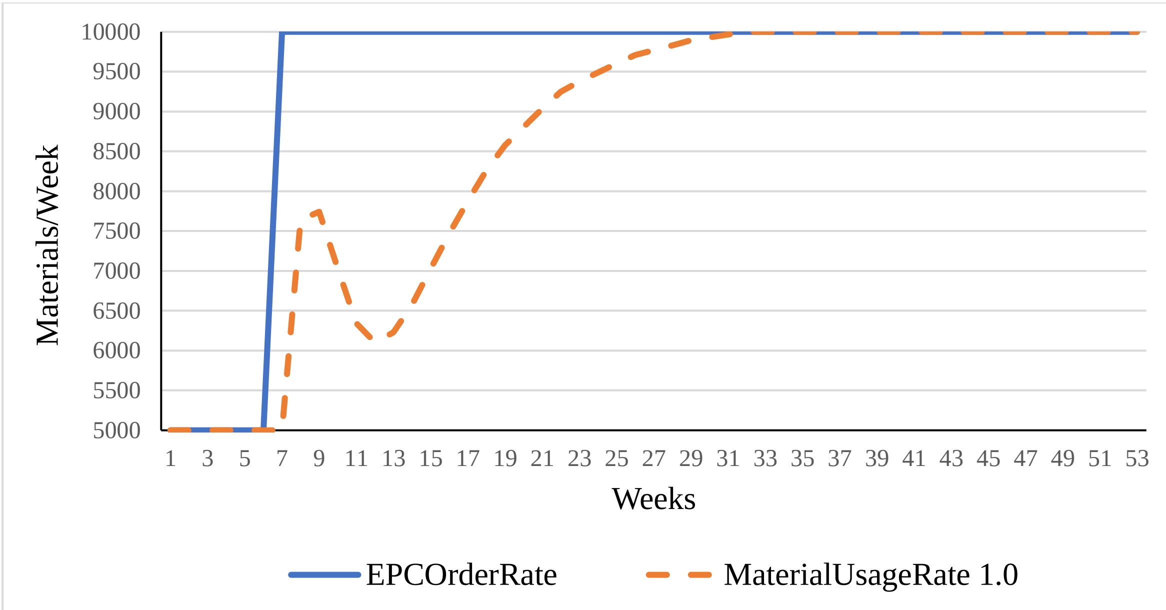


Figure 4.11e. Construction rate in response to 100% increase in material order

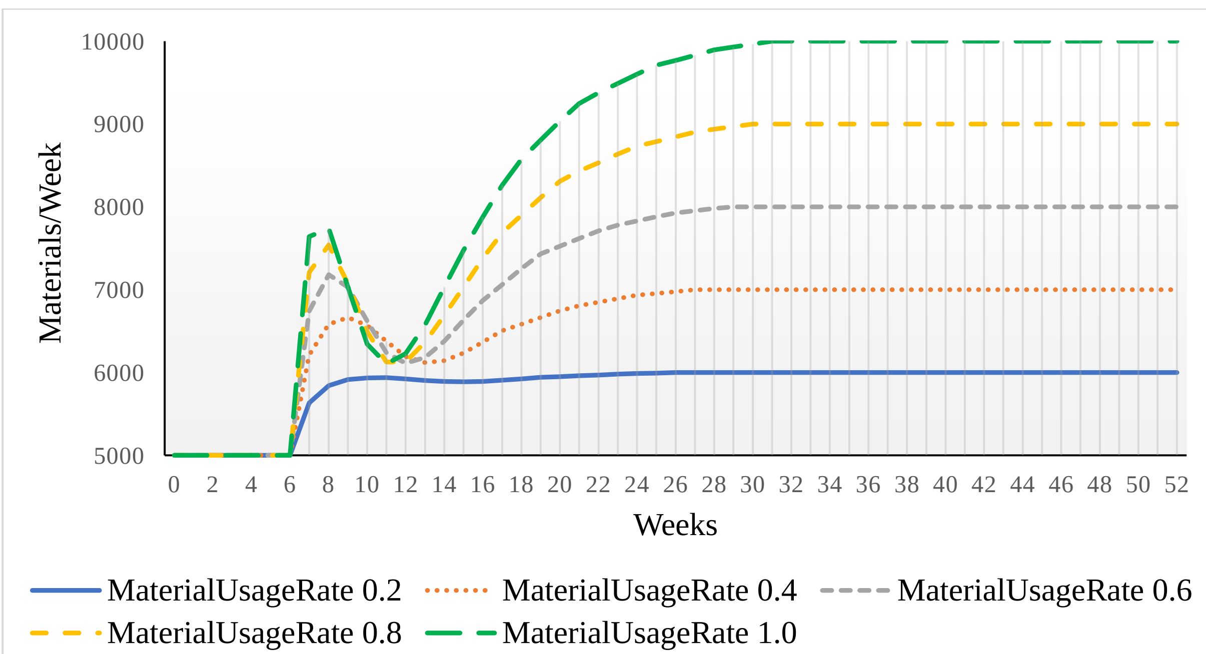


Figure 4.11f. Construction rate behaviour to different material order increment

4.4.2 Multi Variable Sensitivity Analysis: Time Response Simulation with EPC Order Change

Exploring the responses of different delays to step input and fluctuations helped developed another insight for the model's behaviour. Delay input are endogenous part of the feedback structure. Feedback occurs when there is change in decisions on the state of the system, which in turn changes the information and condition that control the prospective decision.

Time delay usually occurs between the times when an order is placed to when the materials are delivered to the construction site. The delivery inefficiency of the supplier can sometimes be traced to the EPC contractor's demand fluctuation and the supplier, being unaware of the unpredicted EPC contractor's change make its decision on only the number of units ordered per period (Ovalle and Marquez, 2003; Bhakoo, Singh, and Sohal, 2012; Kelle, Woosley, and Schneider, 2012). This lack of communication on order change and time delays show the non-collaborative attitude of the entities in the CMSC. This analysis helped in understanding how different delays respond to variation in the delay time. The CMSC model cycle time consists of processing time and shipping time.

4.4.2.1 Shipping Time Analysis

This analysis studied the effect of delayed shipping time on the supplier's service level and construction progress in the presence of 10% increase in EPC order. It was observed that when there is shipping time delay, the supplier's inventory level increases as shown in Figure 4.12a and the construction progress is hindered due to unavailability of materials on the site which leads to reduction in the rate of construction as shown in Figure 4.12b. The construction rate experience instability in the presence of material usage reduction and time lag. There might be a need to use premium freight to expedite the delivery of material to the construction site for the EPC firm to meet its target construction progress. This is a decision that needs to be taken by the EPC contractor and the cost allocation depends on the contract among the entities in the supply chain and the party responsible for the shipping time delay. It is recommended that the firms calculate the delivery time from when the material leave the supplier not when the order was placed.

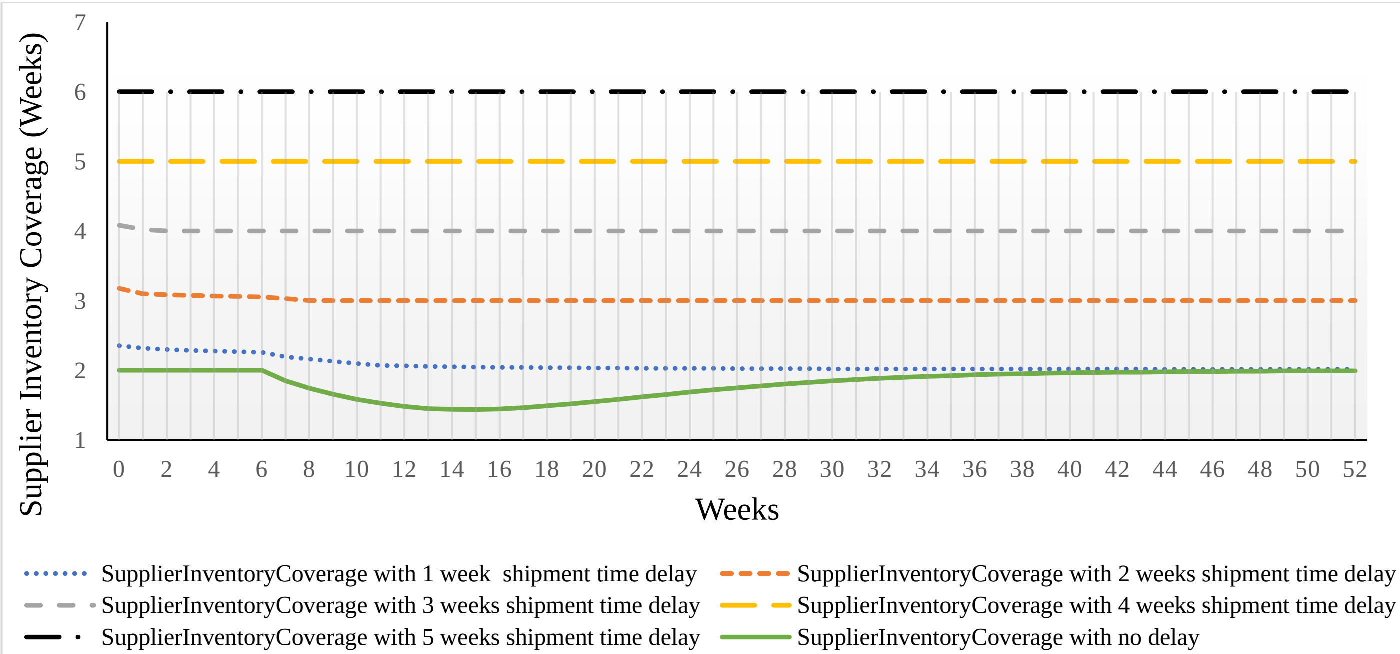


Figure 4.12a. Response of supplier's inventory coverage to shipment time delay

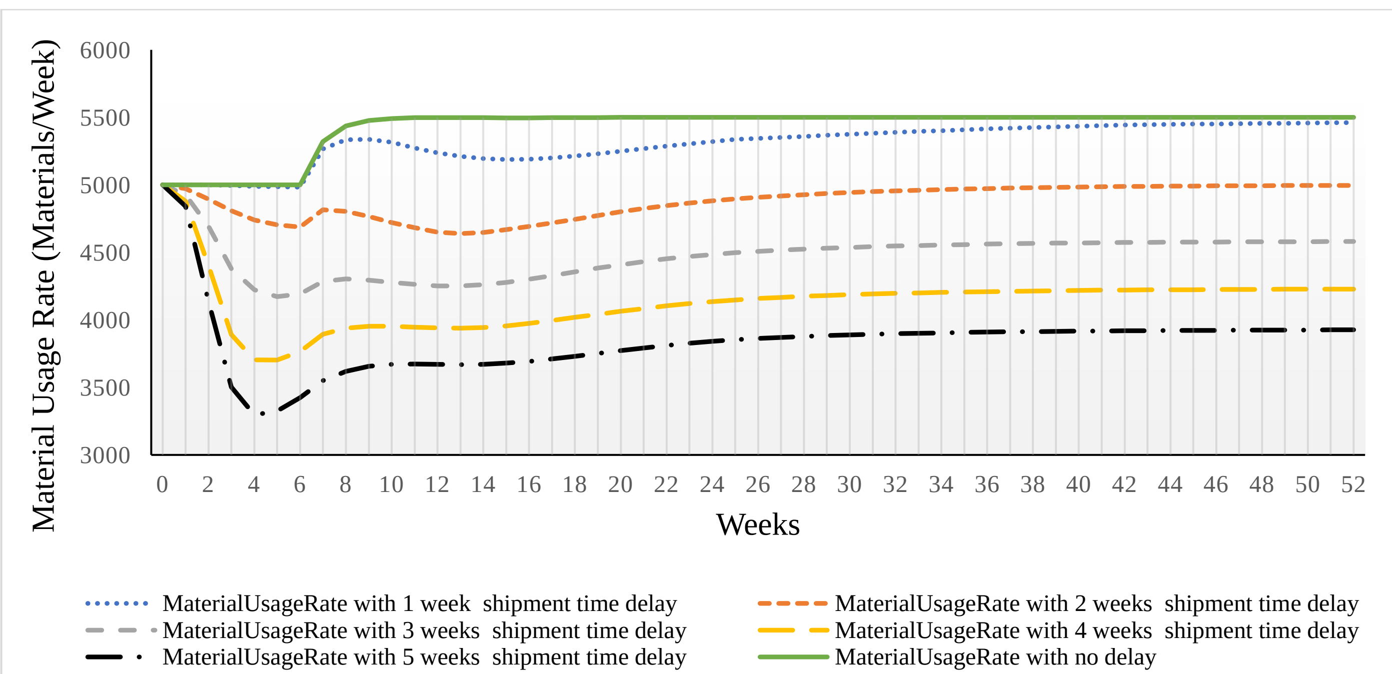


Figure 4.12b. Construction rate due to shipment time delay

4.4.2.2 Supplier’s Processing Time Analysis

The order processing time is the time taken by the supplier to get the material from the producer and make them available for shipping out to the EPC contractor. Long order delay contributes to shortage of materials in the supplier’s store (reduced inventory coverage) and in turn make construction materials unavailable to the EPC firm leading to lag in construction progress as shown in Figure 4.13a and Figure 4.13b respectively. Figure 4.13c is a close view of the construction progress response. Figure 4.13a shows a continuous one-week delay in the processing time which causes drop in the supplier’s inventory coverage overtime, reducing the supplier’s reliability level with every one-week delay. The supplier’s processing model incorporates a base inventory coverage to help protect the supplier’s reputation. Figure 4.13c shows the impact of a continuous one-week processing delay on the construction progress. The construction rate experiences instability in the presence of material usage reduction and time lag. With one-week delay in processing time, it took the EPC firms 10 weeks after the order change to stabilise back to the desired construction rate. It has been studied that late delivery of materials affect supply chain performance which can be improved by effective inventory management practice (Yu, 2011; Fullerton, McWatters, and Fawson, 2003) and safety stock keeping (Buzacott and Shanthikumar, 2008).

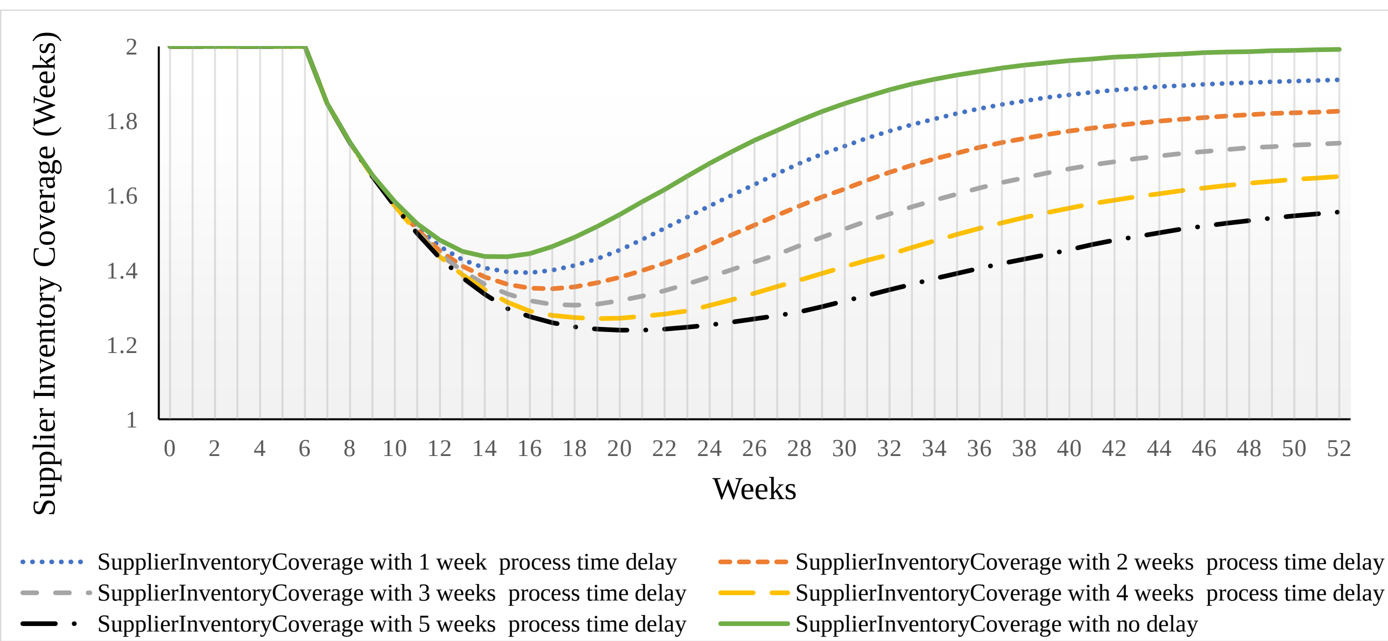


Figure 4.13a. Supplier's service level response to process time delay

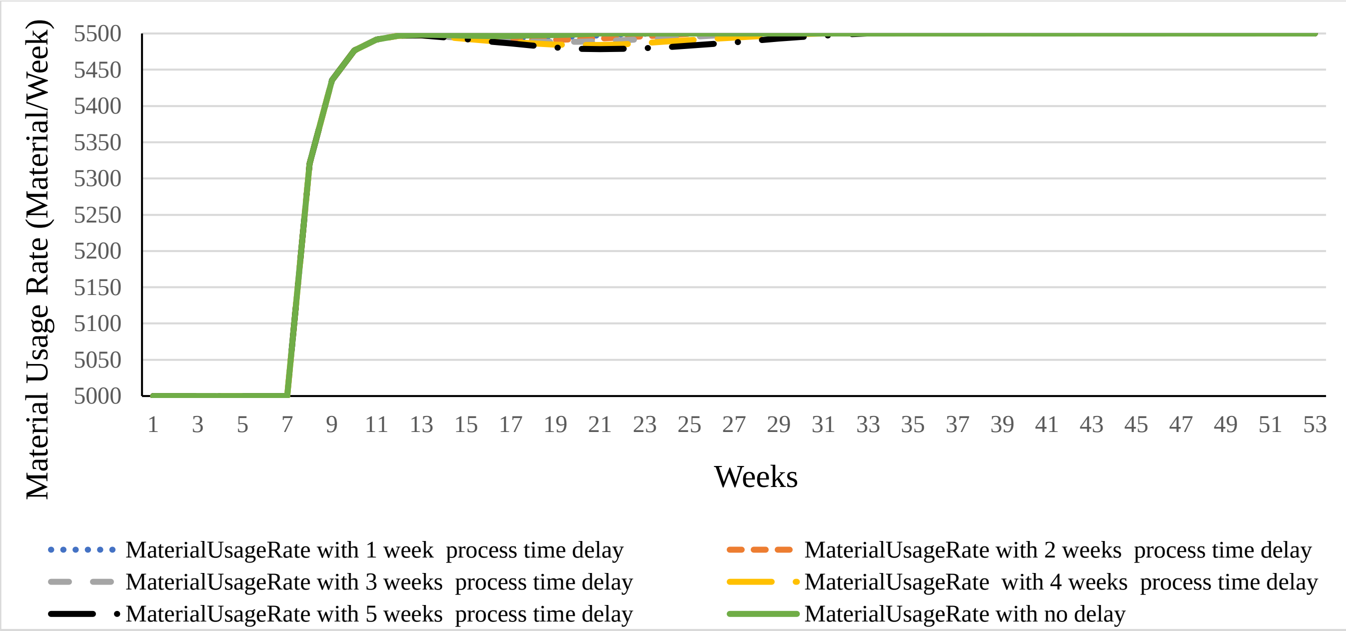


Figure 4.13b. Construction rate response to process time delay

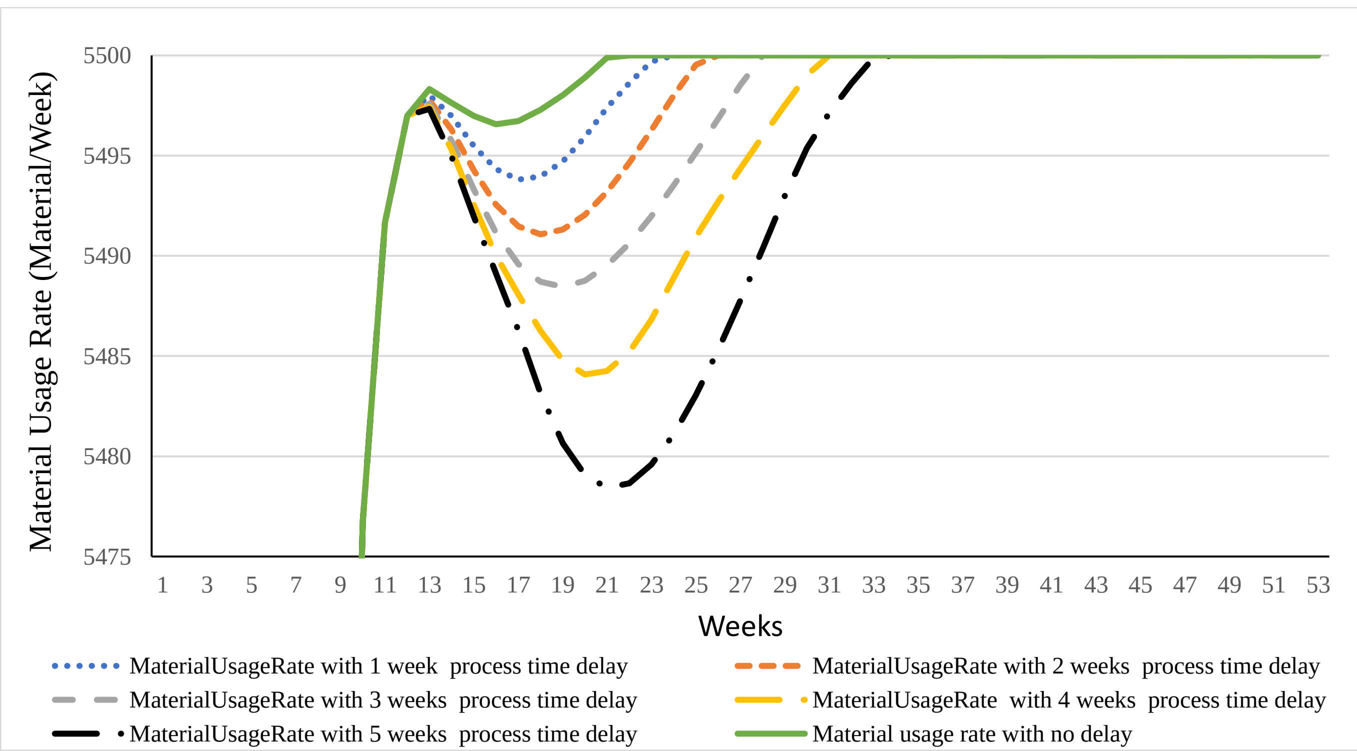


Figure 4.13c. Closer view of construction rate response to process time delay

In conclusion, the shipping time delay has more effect on the construction progress than the processing time delay, whereas, the processing time has more impact on the inventory coverage of the supplier. This is because the supplier can always get materials from another producer, as these off-the-shelf materials are easily obtained from the market compared to equipment with high lead time. When the materials are being shipped to the EPC contractor, the EPC contractor will have to wait until the materials are delivered. Supplier will be ready to go out of its way to ensure customer satisfaction and maintain its reputation.

4.5 Intervention Using Safety Stock

4.5.1 Introduction

After the sensitivity analysis, the effect of safety stock intervention was examined based on the observed results in section 4.4. This intervention analysis agrees with previous studies done on the effect of safety stock on demand variation. Comparing the results from the interventions can be tailored into likely intervention policy for construction industry. This section gives the relation between safety stock and material shortage by studying the output of safety stock intervention on the service level of the EPC firm and its supplier. Supplier is often under pressure to provide high service level to EPC contractor while operating productively with low inventory level. Supply chains are exposed to so many risk such as demand uncertainty, supply uncertainty, lead time uncertainty, supply cost uncertainty, supply capacity uncertainty, and natural and man made disaster (Tang, 2006), and various strategies were used to mitigate them. Such strategies include but are not limited to incorporation of safety stock and safety time (Buzacott and Shanthikumar, 2008).

A safety stock should not be set to zero as it will not only reduce the inventory level but the service level which will cost much more than the cost of the extra inventory. Putting a safety stock is the decision of the supplier to satisfy the EPC contractor in the presence of unpredicted changes. For firms to have adequate inventory as buffer against sudden variation in demand or production, they keep a certain coverage of expected demand. Therefore, for high level of supplier’s service, their desired inventory coverage will include firstly, adequate inventory coverage to ship at the supposed rate which needs a base coverage level equal to the minimum shipment time. Secondly, it must keep supplementary safety stocks. Thus, their desired inventory includes base coverage level i.e. minimum material coverage and the additional safety stock.

4.5.2 Behaviour of the inventories to supplier's safety stock inventory coverage

Inventory coverage is the number of weeks the firms keep inventory to enable delivery reliability or performance reliability (regarding material availability). These are inventory policies/ decisions taken by the management of firm which depends on the holding cost of the construction materials, but then who takes up the holding cost? The factors which affect the inventory coverage includes finances, lead time, management and external factor (e.g. economic downturn). Supplier often increases its inventory coverage to buffer against fluctuations in EPC contractor's demand, in addition, safety stock reduces logistic cost. In determining inventory coverage, the processing and shipping time are essential to sustain reputation, but the safety stock is optional because of the additional cost attached to it. On the other hand, EPC contractor considers the periodic use of the construction materials. The supplier's processing depends on the location of the producer, the farther the location, the longer the waiting time (processing time), and the stock level adjustment will be done accordingly. The success of the EPC contractor depends on reliable suppliers. The question to be answered in this section is, does the intervention enhance the stability and help meet the target goal of the CMSC system, in the face of sudden order change?

4.5.3 Response of the CMSC model to sudden EPC order change with different safety stock (SS) level.

The effects of the various safety stock level (i.e. SS2, SS3, SS4, SS5) on order backlog, delivery delay, inventory coverage and material usage (construction progress) were also studied in the presence of the EPC order change (increment of 20%, 40%, 60%, 80%, 100% of initial order).

(1) Order backlog and delivery delay response to sudden EPC order change with different safety stock level: Figures 4.14a to Figure 4.14e show the how the order accumulated as a result of order increase and the effect of safety stock (SS) on the accumulation. To reduce the order backlog, it is recommended that the supplier increases its safety stock level with increase in order change. Figures 4.15a to Figure 4.15e show the effects of safety stock on the material delivery delay which is the same with the order backlog described above. Order backlog will not reduce if the materials ordered are not delivered to the EPC contractor, thus, the material delivery delay causes order backlog. Therefore, the supplier needs to keep different level of safety stock to absorb the different unanticipated increase in the EPC order, to reduce the backlog of order and material delivery.

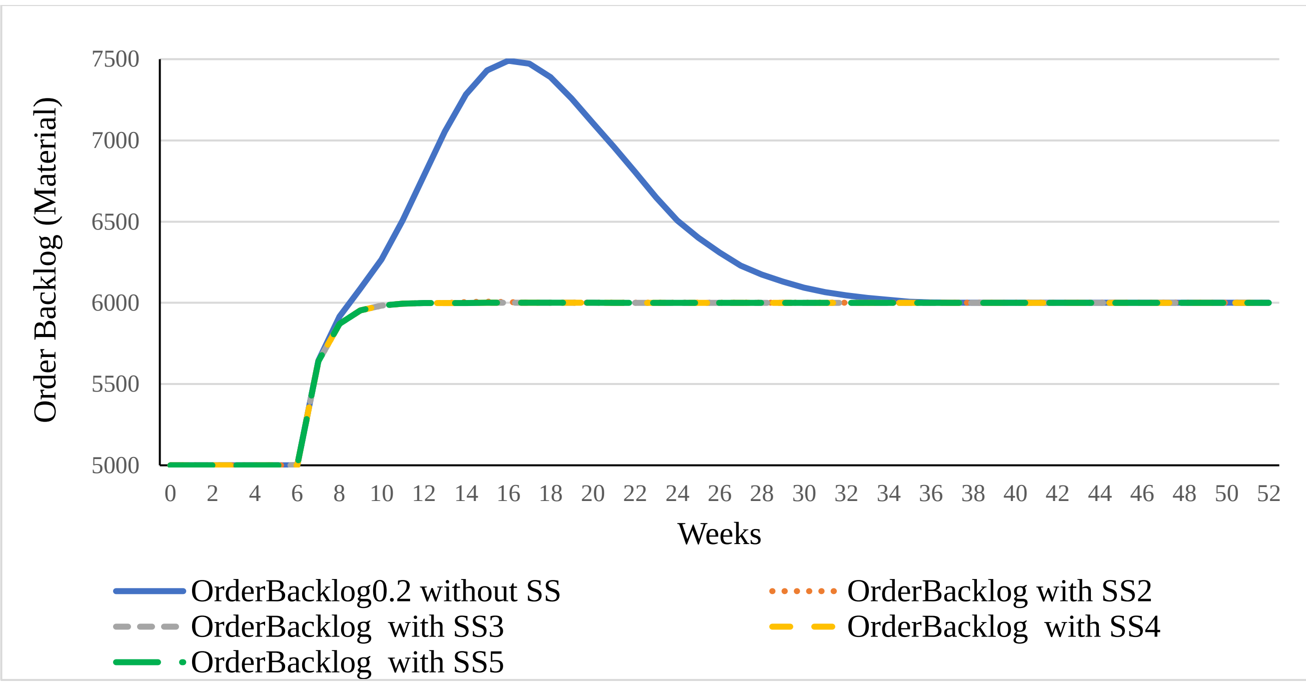


Figure 4.14a. Order backlog response to different safety stock level under 20% EPC order increase

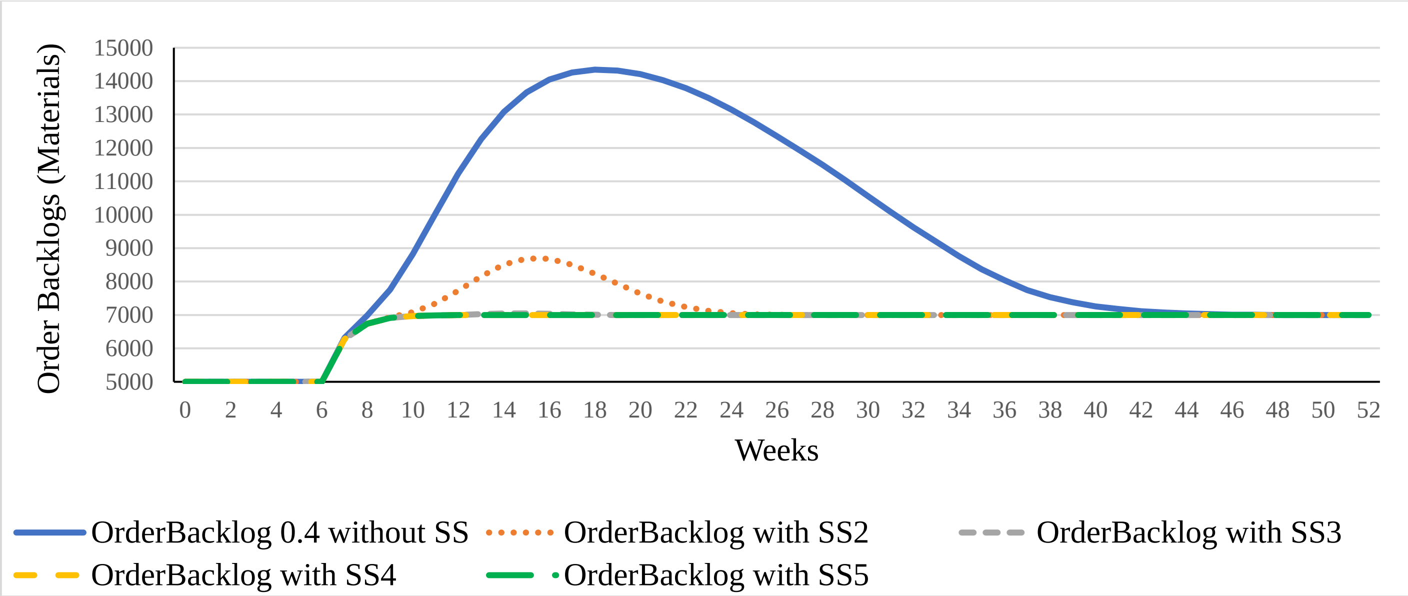


Figure 4.14b. Order backlog response to different safety stock level under 40% EPC order increase

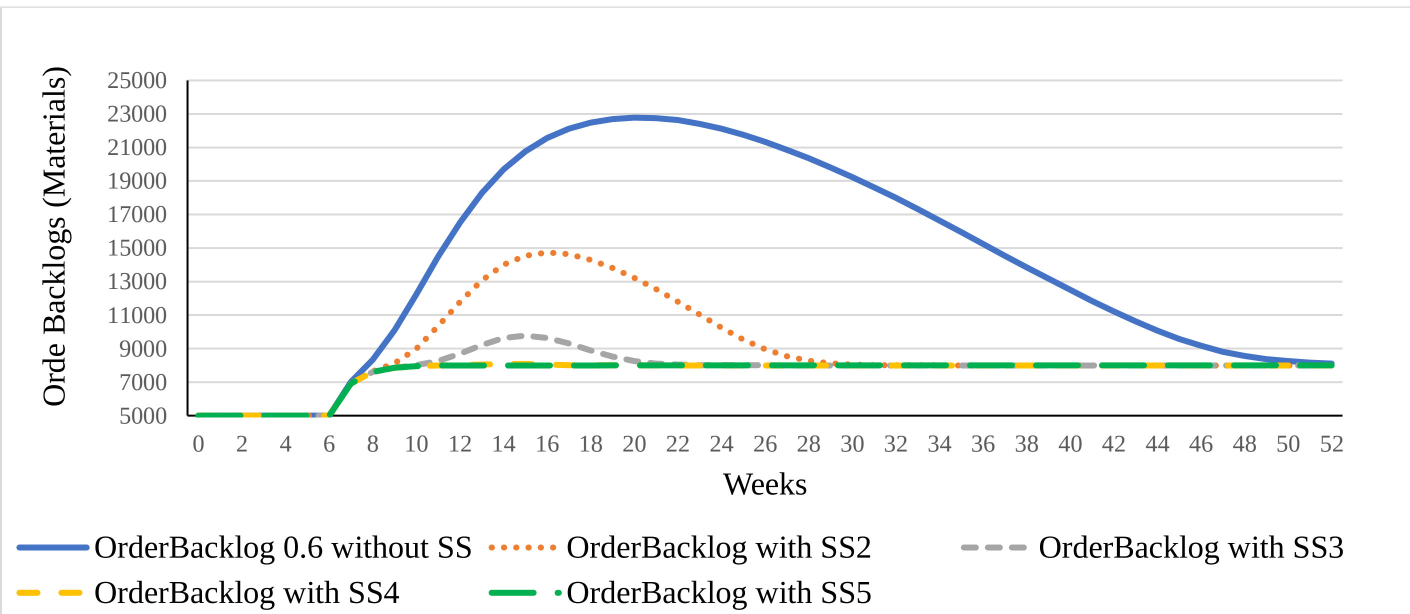


Figure 4.14c. Order backlog response to different safety stock level under 60% EPC order increase

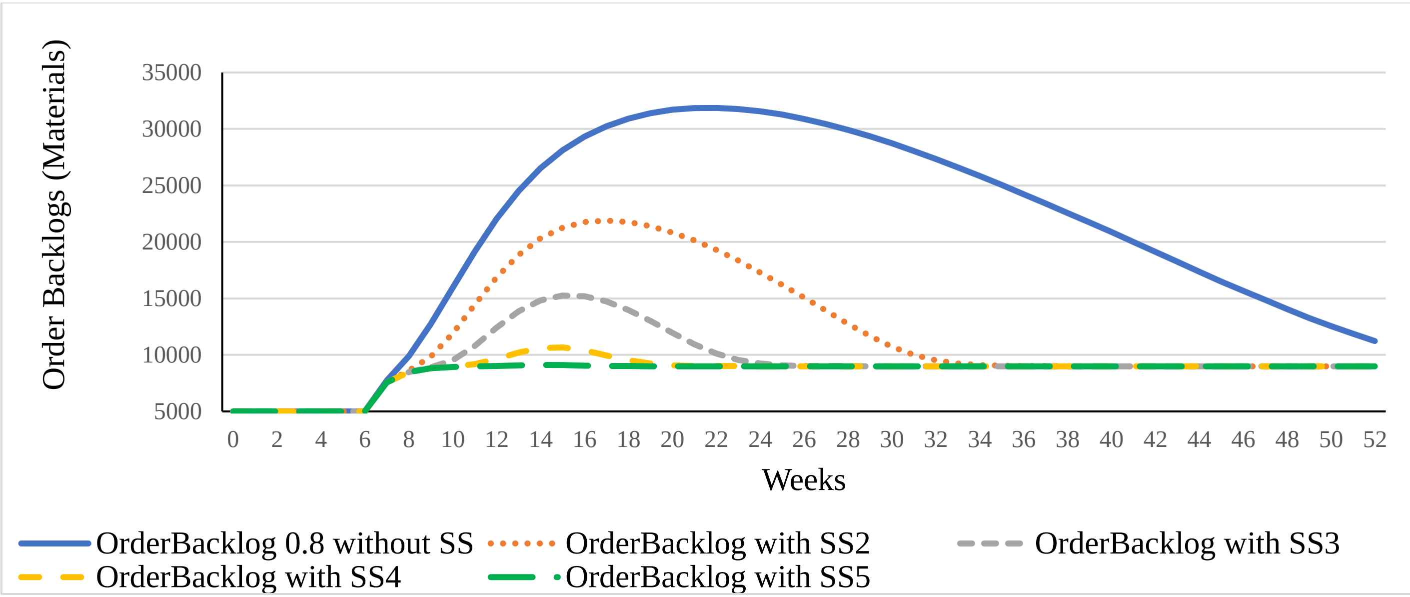


Figure 4.14d. Order backlog response to different safety stock level under 80% EPC order increase

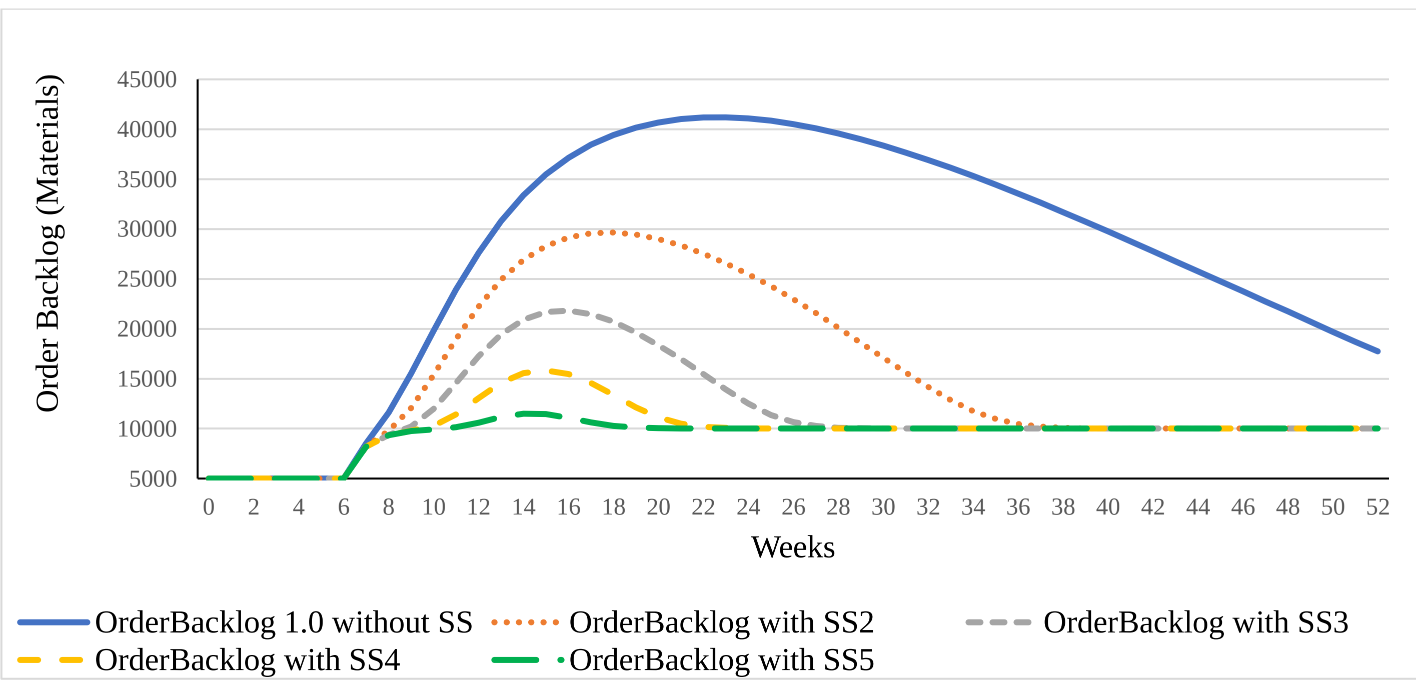


Figure 4.14e. Order backlog response to different safety stock level under 100% EPC order increase

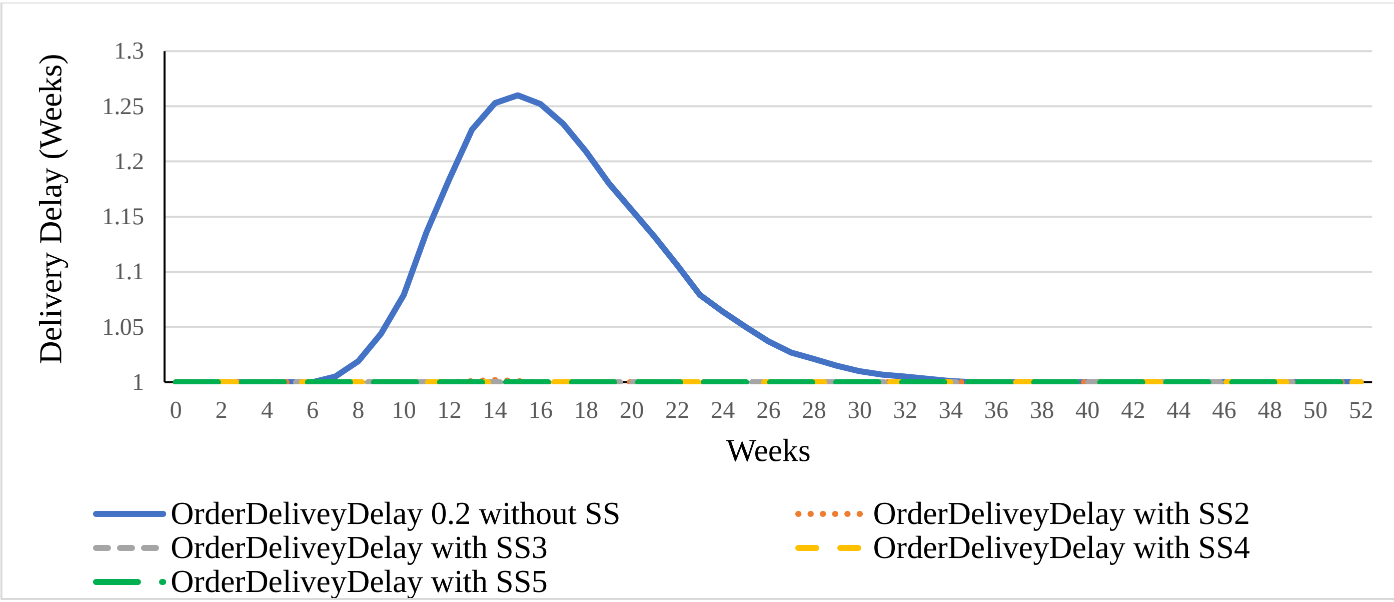


Figure 4.15a. Order delivery response to different safety stock level under 20% EPC order increase

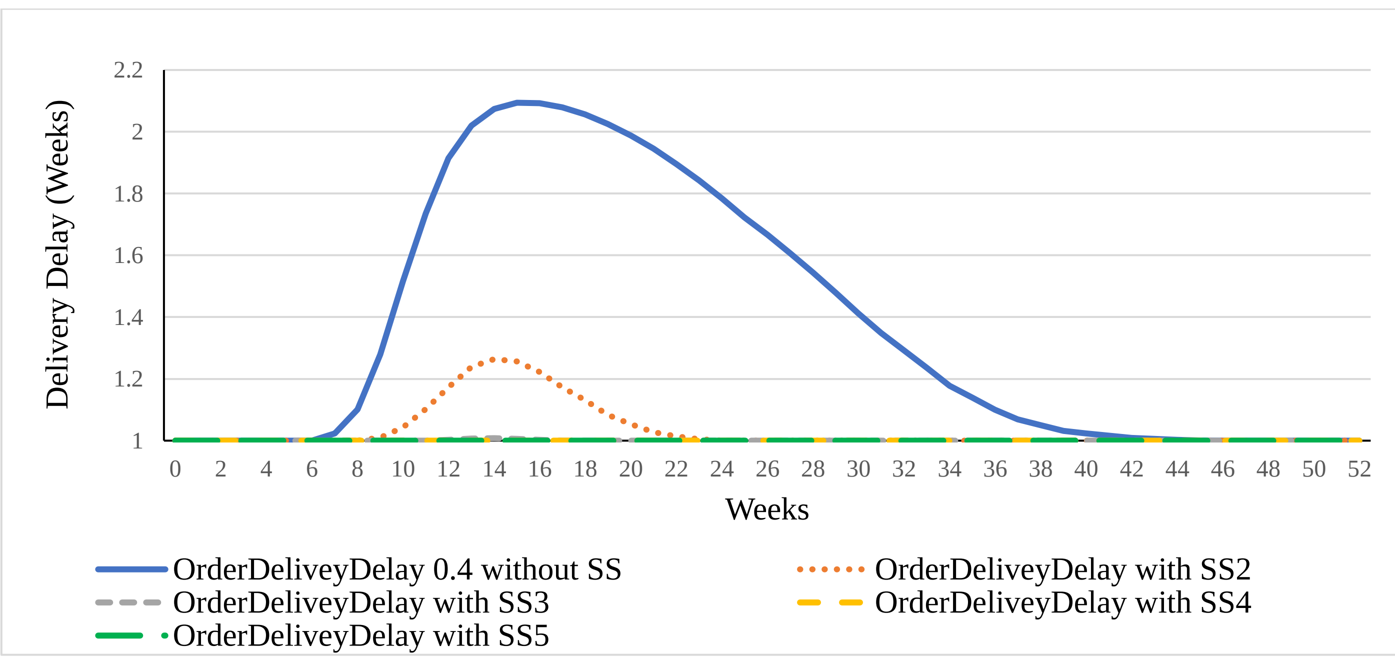


Figure 4.15b. Order delivery response to different safety stock level under 40% EPC order increase

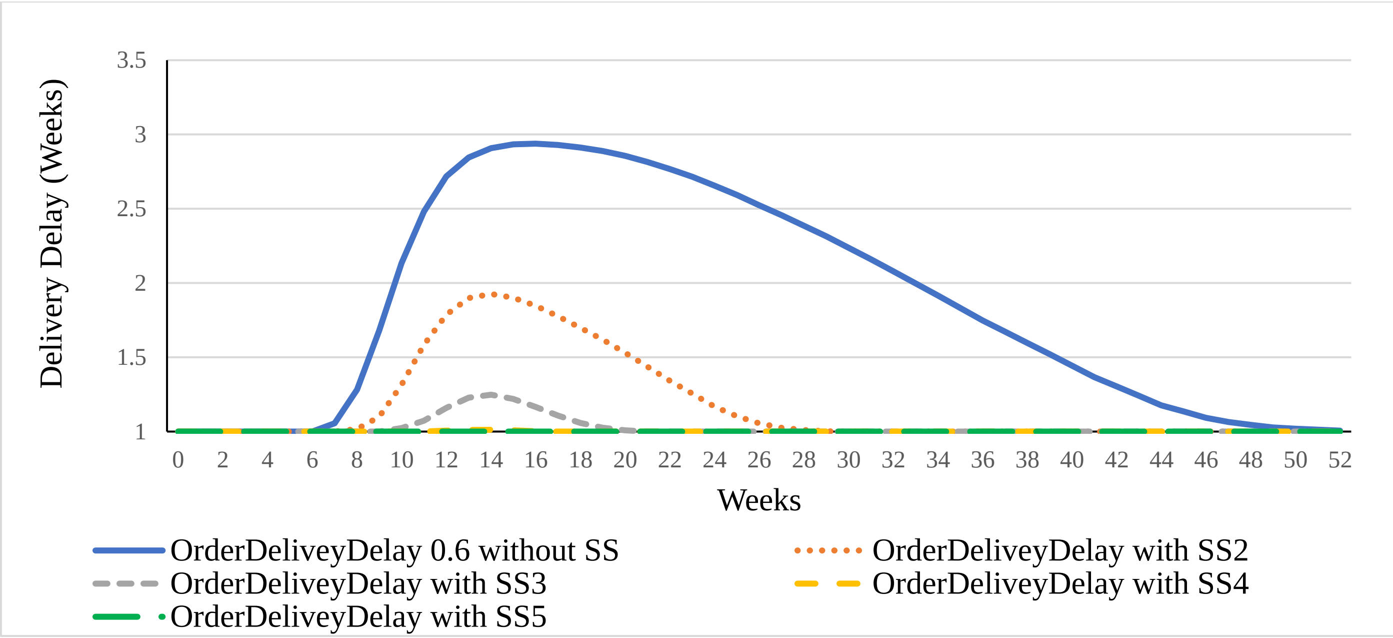


Figure 4.15c. Order delivery response to different safety stock level under 60% EPC order increase

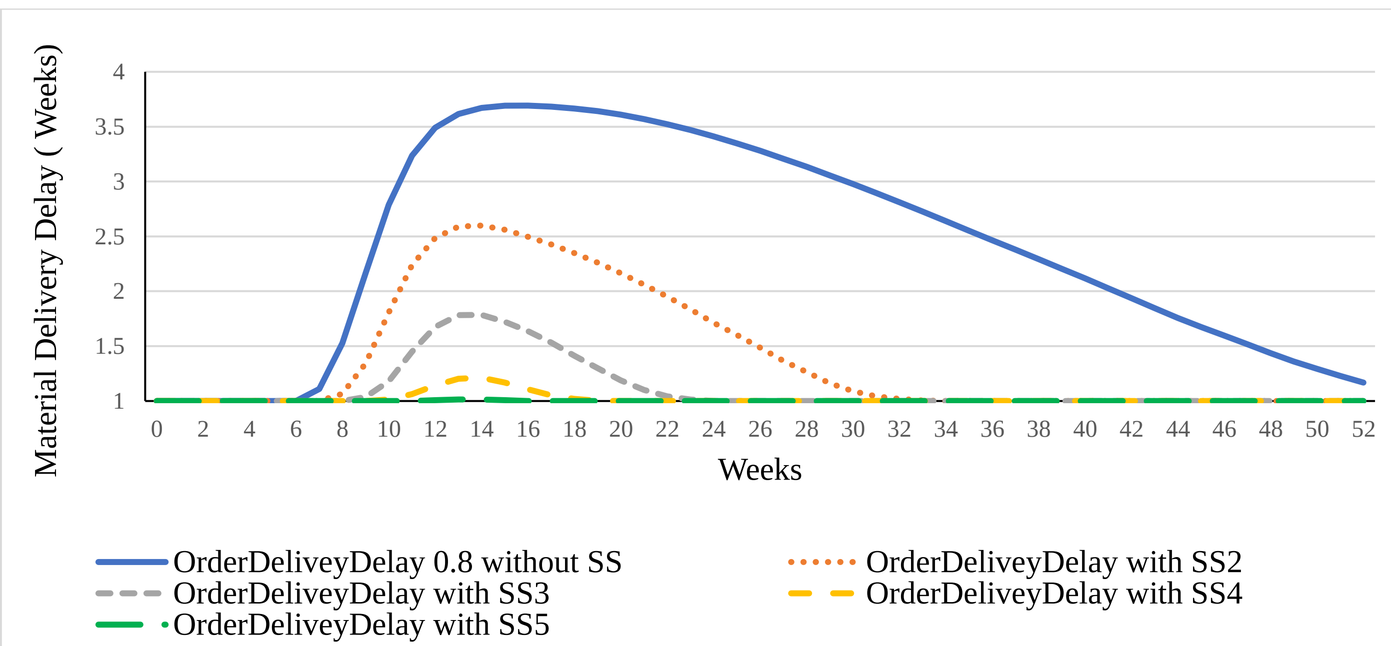


Figure 4.15d. Order delivery response to different safety stock level under 80% EPC order increase

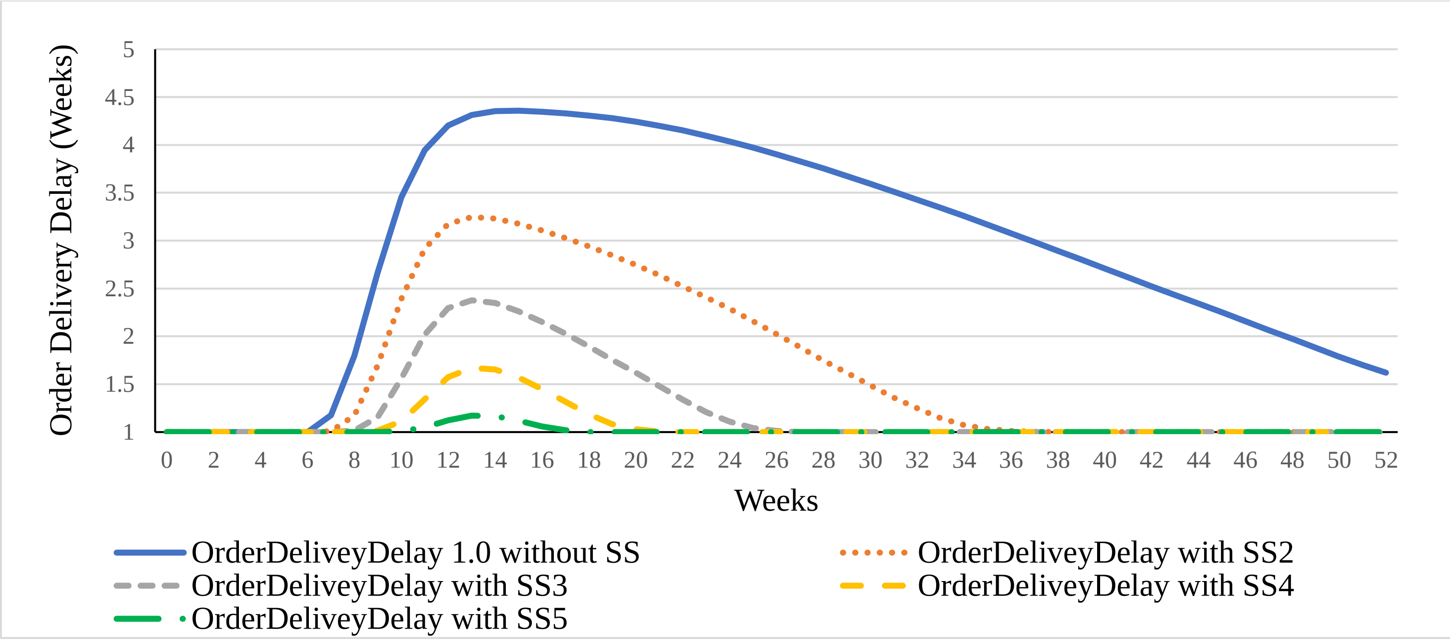


Figure 4.15e. Order delivery response to different safety stock level under 100% EPC order increase

(2) Material usage rate response to sudden EPC order change with different safety stock level: From Figures 4.16 a to 4.16e show that for the EPC contractor to keep construction rate going at the desired rate in the absence of time delay, it is recommended that the supplier increases its safety stock level with increase in order change. This shows that the supplier needs to keep high level of safety stock to absorb the unanticipated increase in the EPC order, to keep its reputation and help its contractor achieve their project goal.

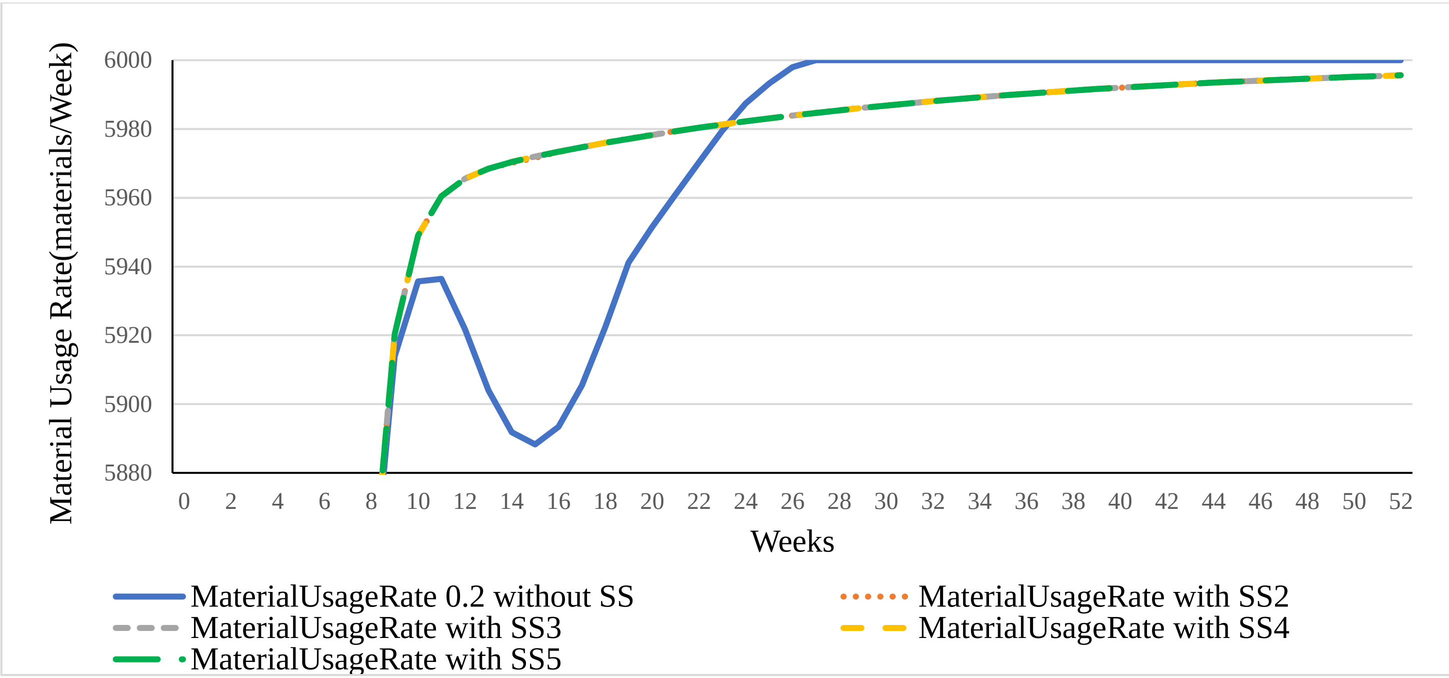


Figure 4.16a. Construction rate response to different safety stock level under 20% EPC order increase.

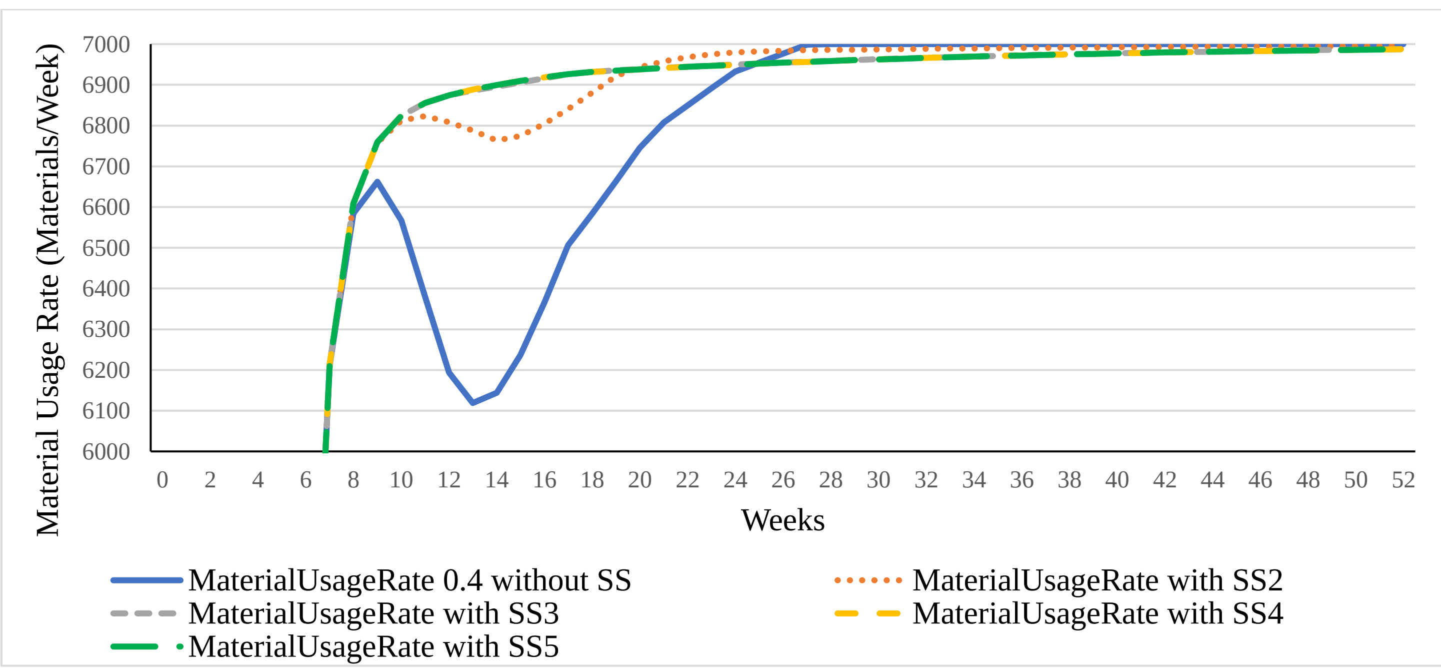


Figure 4.16b. Construction rate response to different safety stock level 40% EPC order increase

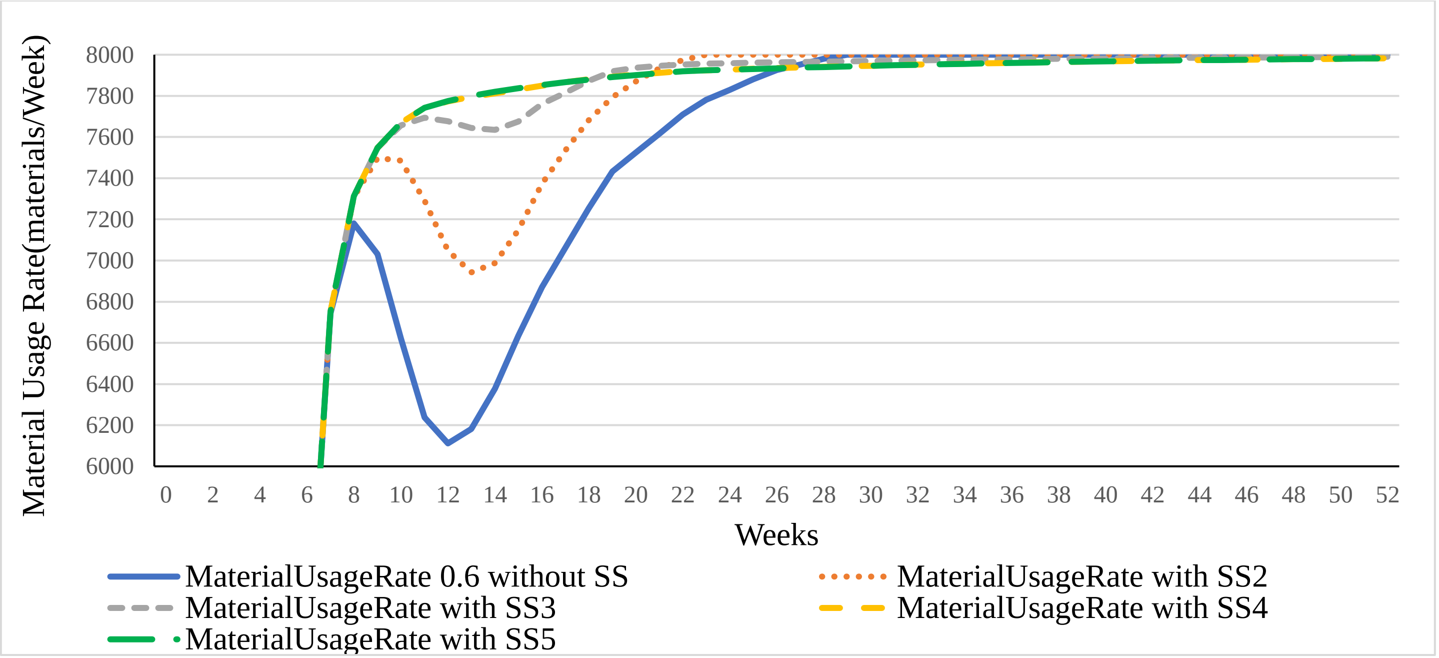


Figure 4.16c. Construction rate response to different safety stock level under 60% EPC order increase

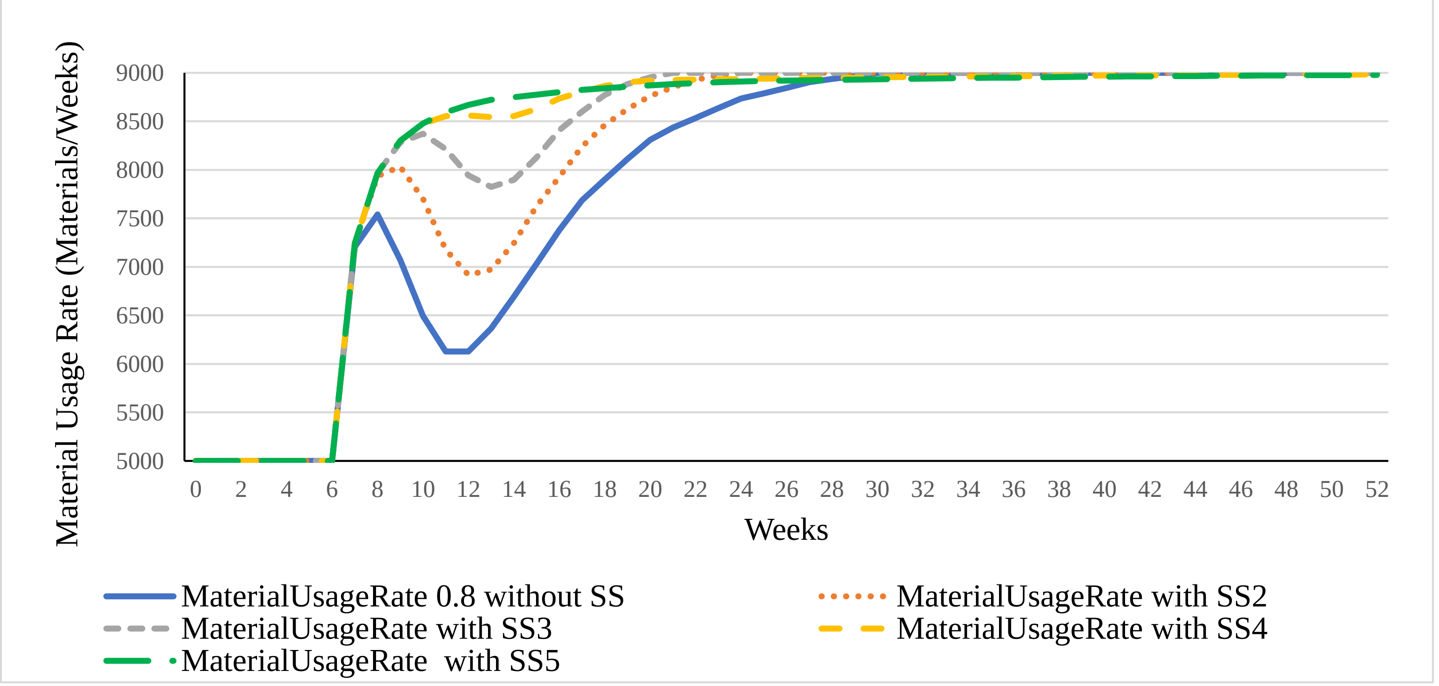


Figure 4.16d. Construction rate response to different safety stock level under 80% EPC order increase

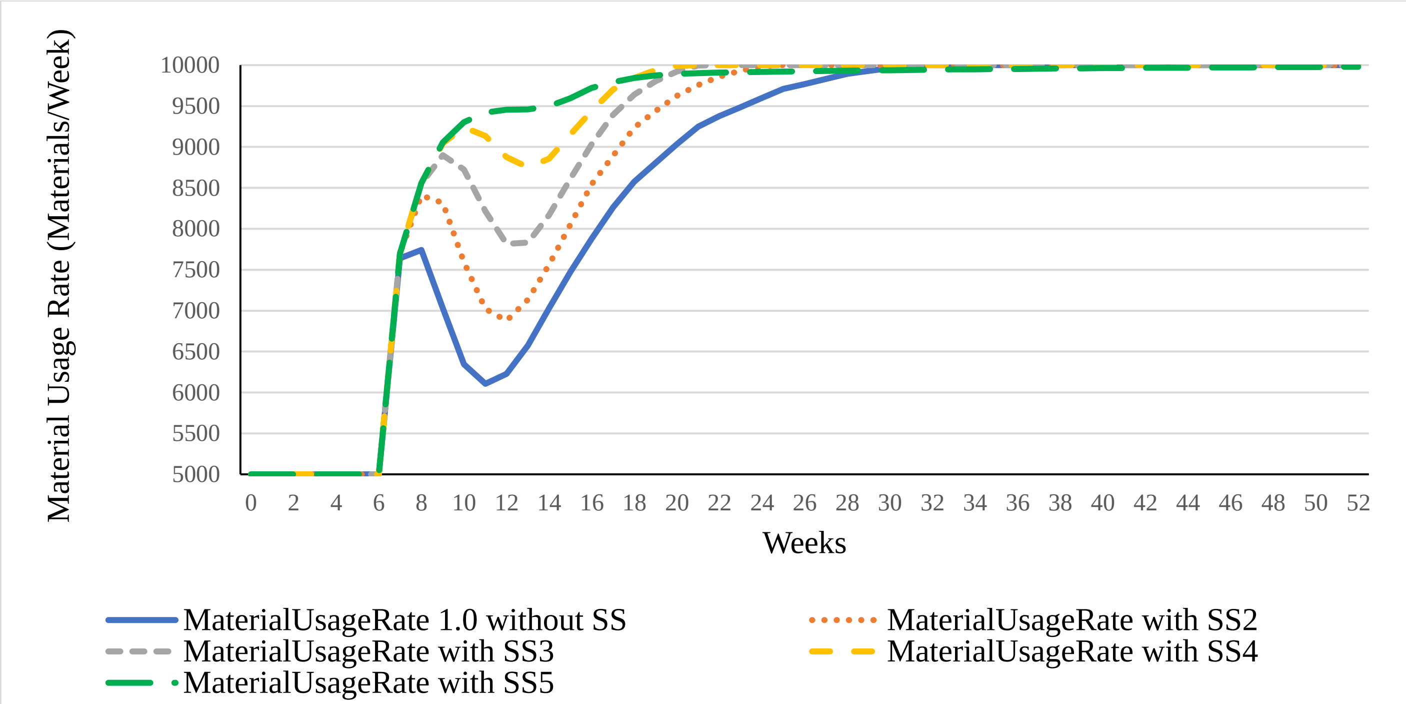


Figure 4.16e. Construction rate response to different safety stock level under 100% EPC order increase

(3) Supplier's Service level: Supplier's inventory coverage refers to the numbers of weeks a firm can ship at the current rate considering its present invent. Figures 4.17a to 4.17e show that for supplier to maintain satisfactory delivery reliability level, it is recommended that the supplier increases its safety stock level with increase in order change. For the supplier to maintain a satisfactory service level and keep its reputation, there is need to keep adequate safety stock to minimize the undesired effect of the unanticipated increase in the EPC order.

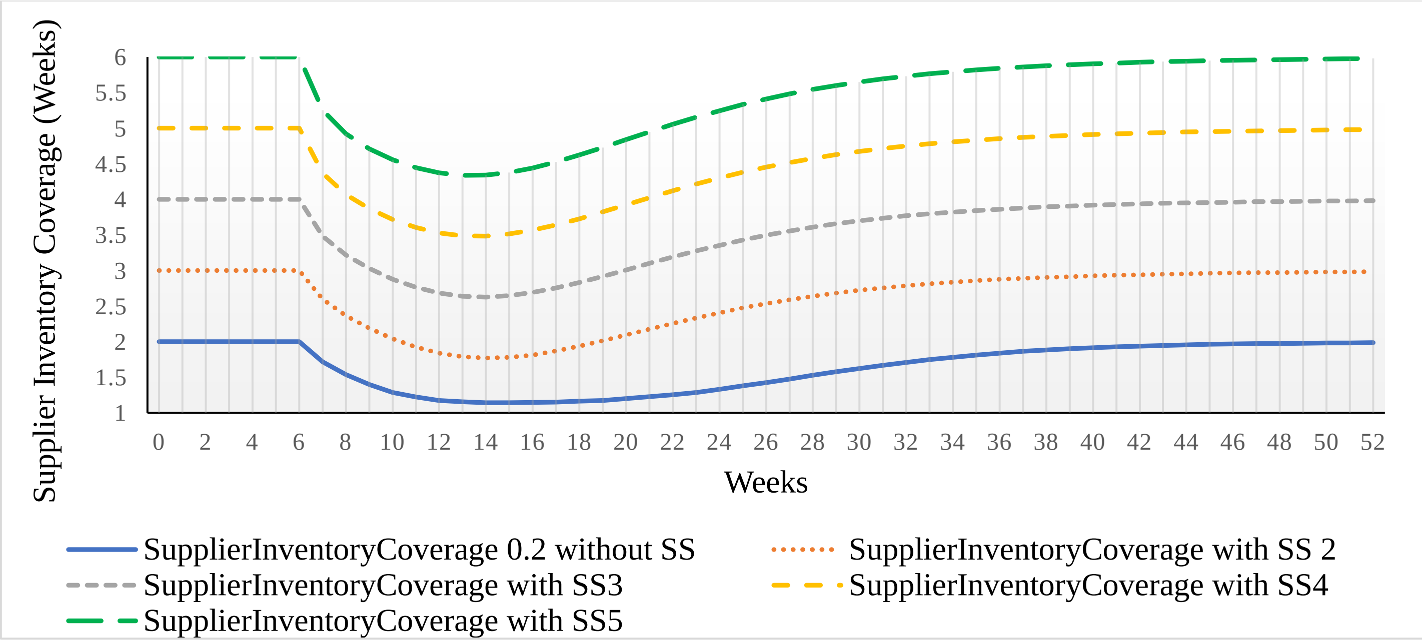


Figure 4.17a. Supplier's service level response to different safety stock level 20% EPC order increase

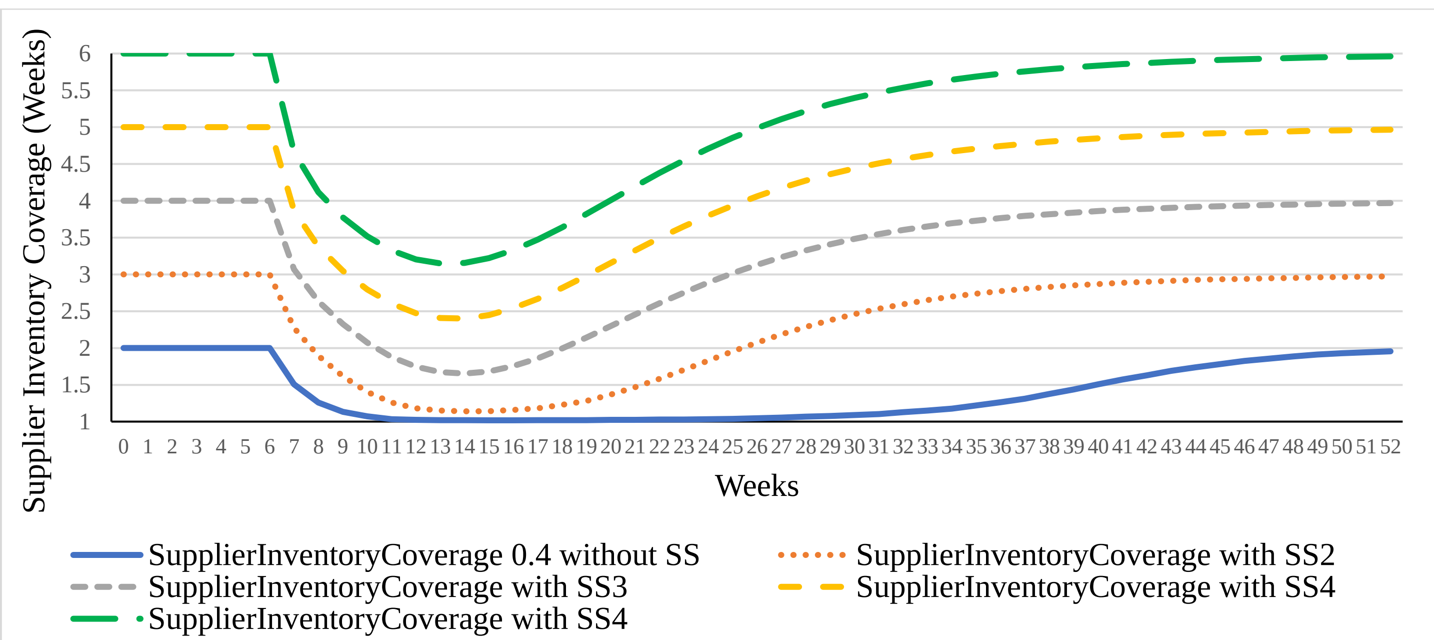


Figure 4.17b. Supplier's service level response to different safety stock level 40% EPC order increase

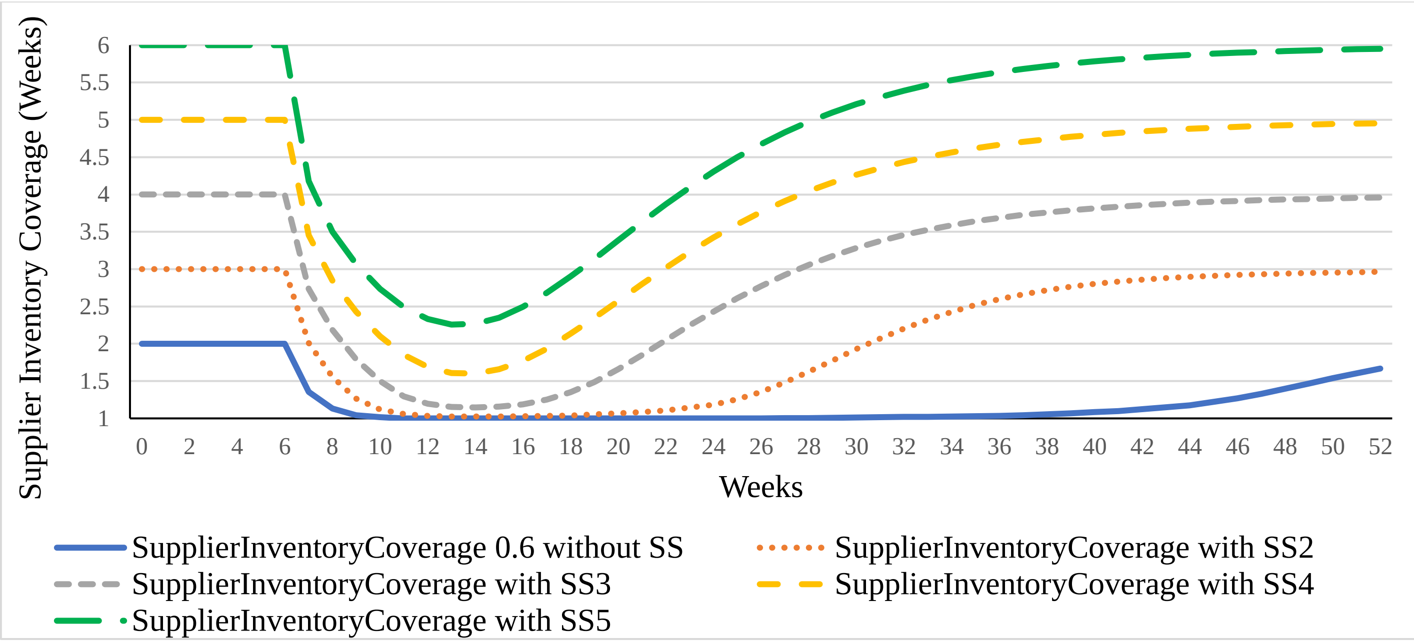


Figure 4.17c. Supplier's service level response to different safety stock level 60% EPC order increase

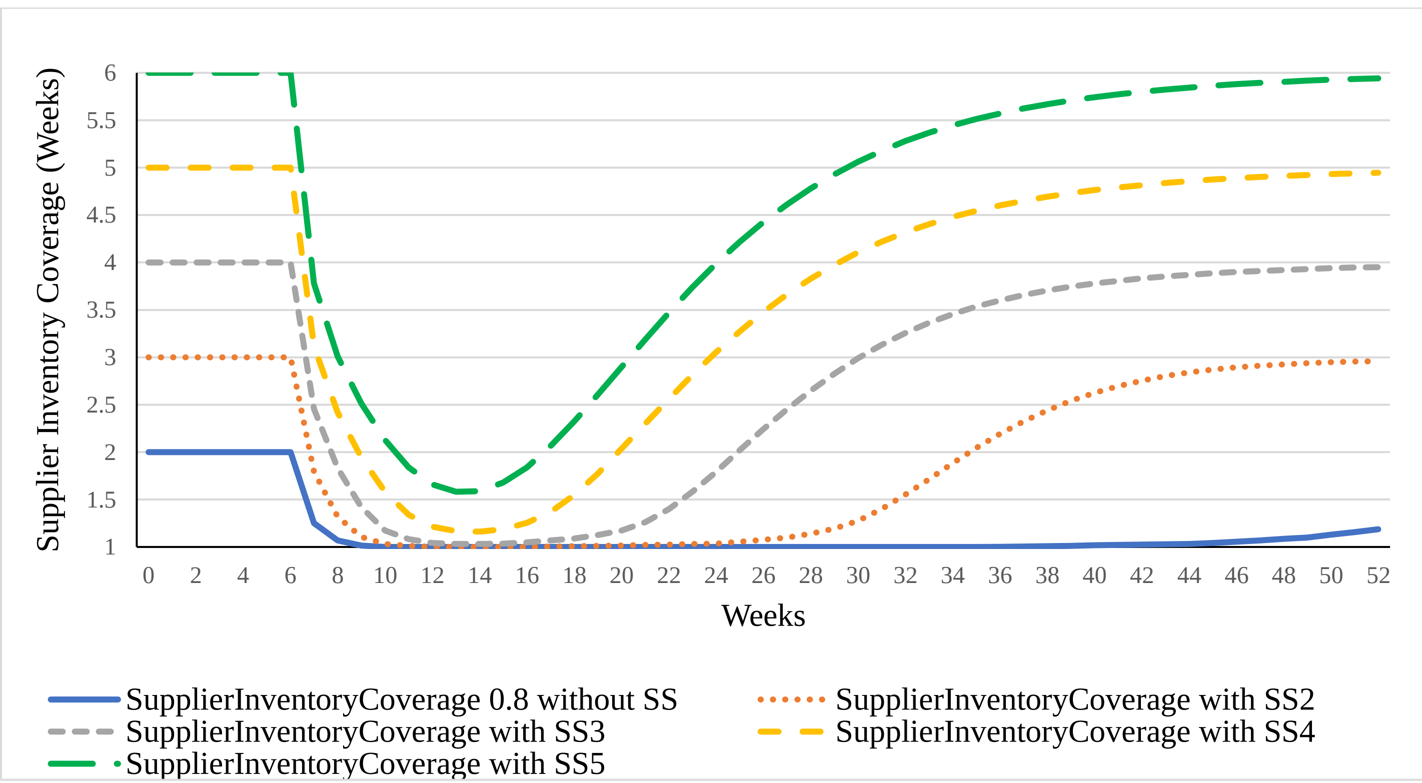


Figure 4.17d. Supplier's service level response to different safety stock level 80% EPC order increase

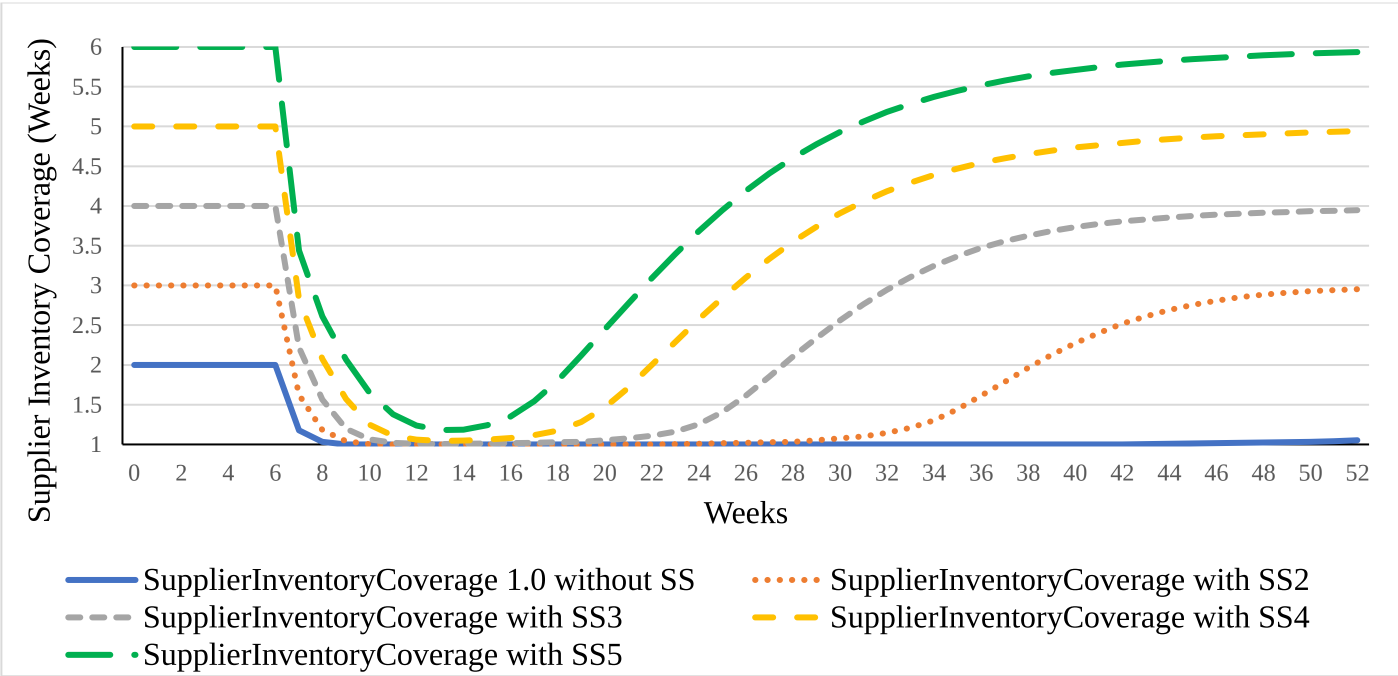


Figure 4.17e. Supplier's service level to different safety stock level under 100% EPC order increase

From the intervention analysis, it is observed that for adequate service level fulfilment, increase in safety stock is needed to cover the order change increase, to mitigate material shortage. This aligns with a work done on how buffer size depends on variability by Korponai, Tóth, and Illés, (2017). This shows that the supplier needs to keep high level of safety stock to absorb the unanticipated increase in the EPC order, so as keep its reputation and help its EPC contractor achieve its project goal. Comparing the results from various levels of interventions, decision makers will be able to understand better how safety stock can mitigate in the effect of order change and use them to make necessary adjustments to policy in the construction industry.

Also, an understanding of the holding cost incurred by the supplier on large safety stock to satisfy its customers, will make the EPC contractor see reasons why it needs to give timely and adequate information to the supplier so that it can help meet EPC target construction rate to finish the project on time and avoid cost overrun. Safety stock is to help improve performance but excess of it leads to wastage and impedes performance. This conclusion agrees to how the keeping of safety stock can improve performance by Horman and Thomas (2005).

4.6 Discussion

It has been established that the project success of the EPC firm is dependent on the supplier's delivery performance. In addition, the decision taken by the EPC firm on material quantity ordered per period has effect on the supplier and the EPC firm itself. Complex supply system cannot be managed by just one member of the supply network (Choi, Dooley, and Rungtusanatham, 2001).Previous work has shown that order change is inevitable in construction industry and therefore there is need for members of construction material supply chain to have insight into the behaviour of the system, how the order change affects the performance of the system and how performance can be enhanced. Studies have shown that supply chain can be improved by promoting collaboration and communication among entities in a supply network. Long term relationship and commitment between supply chains entities will help improve the service level of supplier and EPC contractor. It is easier for supplier to deliver on time and in right quantity when order is certain and steady. Timely material demand information from the EPC firm will help the supplier plan its material processing schedule to ensure it is able to fulfil order when it comes. With effective information sharing, EPC firm can mitigate project disruption. The information that must be shared in the material supply system are inventory management decisions, delivery delay, lead time, shipment, and contractor's orders. Factors to be considered for optimum performance include timely and accurate information sharing, working closely with supplier to overcome challenges, arranging preference based on effect of material shortage on performance, and backup plan to accommodate contingencies. EPC firm should avoid order change in short notice, being uninformed on the impact of its decisions on itself and other entities in the network, not paying suppliers on time, to enhance supplier relationship and improve performance.

The results shown in chapter four are useful for EPC firm and its supplier. The EPC firms, whose performance is tied to delivery performance of the supplier to make the construction materials available, can use safety lead time or premium freight to expedite instead of safety stock because the construction site is a temporary storage room and there is not so much space often times on the construction site and that is the reason JIT delivery method is embraced in the construction industry for off-the-shelf materials. On the other hand, for the supplier, it is recommended they keep safety stock to maintain high delivery performance for an off-the-shelve construction material which is constantly used for a period.

Modelling aims at understanding the behavioural pattern to design policies to improve the system. Supply system enhancement tests if the modelling process helped improve the system. Analyses shown in chapter four have shown that the higher the EPC order increases, the more the order backlog and material delivery delay, the lesser the material usage rate by the EPC contractor and supplier's delivery reliability level. To study the supplier's intervention policy for the material supply coordination, experimental scenarios were devised by varying the order change of EPC contractor, and supplier's safety stock level. The order change ranges from 10% increase to 100% increase while the supplier's inventory coverage ranges from 2 weeks to 5 weeks. An increase in the supplier's inventory coverage (safety stock level) to absorb the order changes from the EPC contractors implies that the supplier invests more on guaranteeing construction materials for the EPC contractor. Model suggests that when there was order change, the construction performance reduced in the absence of the supplier's safety stock but, the construction performance was enhanced in the presence of safety stock. Therefore, parameters such as the safety stock, desired inventory and current inventory were examined during the experiment implementing ordering policy. The decision support model developed in this work is useful to the construction industry, specifically Engineering, Procurement and Construction (EPC) firms, who tilt towards lean principles. It is a tool that can be used to enhance the service level of the EPC firm and its supplier.

Decision support SD model developed in this work will help understand the material supply chain dynamics between the EPC firm and its supplier, which often emanates into material shortage on site and how this risk can be mitigated to enhance project performance. In conclusion, the proposed research in terms of the research objectives may make some meaningful contribution to the construction management in general and EPC management specifically.

4.6.1 Supplier's safety stock planning

The safety stock policy was examined under the assumption that no information is between the EPC contractor and its supplier. Therefore, the supplier must anticipate the material shortage based on experience and judgement, thus, deal with the uncertainty of deciding what safety stock level should be kept guaranteeing high service and at the same time not to have excess stock. When EPC order increases slightly and the material shortage is not serious, incurring extra holding cost of high safety stock level might not be needed and can be minimized. On the other hand, if the order change cause great material shortage, both the EPC contract and the supplier will bear the consequences, i.e. the supply chain risk which may cause more damage than spending extra holding cost on more safety stock. The result presented in section 4.5 shows the EPC contractor's construction performance (material usage) and the supplier's service level (supplier's inventory coverage) under various order change and safety stock level. The supply chain performance differs under different scenarios. When the EPC contractor shares the information on material needed with the supplier on time, the supplier will know what level of safety stock is needed to maintain high supply chain performance, as safety stock level should increase with increase in EPC order. For a bulky, off the shelve construction material, the supplier has developed a solid processing capacity and can accomplish the material supply. Supplier often measures its performance by delivering in full and on time. When the supplier has no information about the material needed on time, it is unable to plan very well and might keep low or excess safety stock. Five scenarios were studied with safety stock level ranging from 2 to 5 weeks of demand. These results are required in decision making by the supplier to help give insight to the safety stock level to be maintained in response to EPC order increase. Suppliers must also have good relationship with the producer which is shown in section 4.4.2.1 where delayed processing reduces the service level of both the supplier and the EPC contractor.

4.6.2 EPC material management planning

To study the role of the EPC contractor in the material coordination, experimental scenarios were carried out by varying the order change of the EPC firm which from 20% increase to 100% increase of its initial order. The order increase means that there is high material usage in the construction process and the EPC contractor needs more materials. The order rate decision has impact on material availability which eventually affects the project performance. Depending on the contract made with the supplier and safety lead time kept by the EPC firm, the material delivery rate can be managed by the decision makers by allowing premium freight i.e. to expedite the construction material to meet the project goal and avoid schedule and cost overrun. When the EPC firm shares accurate and timely information with the supplier, the supplier will not have to worry about material shortage and can keep the safety stock level required for each order change by increasing its order with the producer. EPC firm must also have good relationship with the supplier which is shown in section 4.4.1.1 where construction rate reduced because of material shortage and section 4.4.2.2 where delayed shipping time reduced the service level of the EPC contractor.

CHAPTER 5

RECOMMENDATION AND CONCLUSION

5.1 Suggested policies

Based on the results and analyses in chapter 4, this model shows the capability to generate policy, therefore the following inventory management policies are suggested:

1. Effective information sharing should be foremost to support the EPC contractor and supplier in developing inventory management policies. From section 4.4.1.1, the effect of sudden order change was observed on the accumulated order backlog, increased delivery delay, fall in inventory coverage, instability in material usage, which are all important factors to timely delivery of material on site and project success.
2. For EPC contractors to make effective alternative plan (such as diverting to other project aspect) to meet its project goal, there must be accurate and timely information on the shipping and order processing status. From the analysis in 4.4.2.1 and 4.4.2.2, it was observed that instability in construction project progress increased as time delay encountered increased.
3. Supplier should keep satisfactory safety stock level corresponding to the order change to enhance its service level and project performance. From result obtained in section 5.4.3, a 5x% increase in initial order can help maintain service level of supplier in the presence of x% sudden increase in order change. The results also suggest that the safety stock as intervention in the construction material supply chain improves demand and inventory variability, reduces order backlog and delivery delay of construction materials, improves the project performance, and the supplier's service level. Therefore, inventory buffer beyond certain levels does not enhance project performance or service level, which is the main purpose of its usage, instead it impedes it.
4. Contingency plans, such us freight premium, must be made in the binding contract for shipping time delay because of the adverse effect it has on the project performance.

Furthermore, it was observed that the sudden order change has more effect on the EPC contractor, than on its supplier, in term of the recovery rate as seen in Figure 4.1 and 4.2. These propositions also apply to each entity in the material supply chain, as the success of entire supply network depend on the success of each entity (Wang, Dou, Muddada, and Zhang, 2017). With effective information sharing, the supplier can use optimal safety stock level to enhance its service level and the project performance, therefore excess holding cost can be avoided.

For this model to used by firms, there is need to be aware of the cost associated with it and what is needed to utilize the model effectively. This model can be used as a stand-alone, which is run with data obtained from the existing ERP software of a firm. There is need for the firm to buy AnyLogic software, which is the environment where the model was simulated. In addition, the cost of obtaining the model, training and hiring the staff that will be responsible for the software management should also be considered.

5.2 Concluding Remarks

In today's timeline performance environment, it is very important for decision makers to have access to decision tools in order to make effective, correct and quick decision. For a successful supply chain, each firm in an interconnected network should consider themselves as an integral member of the network and not only focus on its own interest. Holistic supply network is a proactive measure towards resilience which improves project performance for the sustainability of the EPC, in the face of supply disruption that can arise in this ever-changing market. Supply chain collaboration gives platform for organisation to have a better performance in terms of supplier's service level and project performance. Application of SD to this work make it an effective tool for decision makers by giving insights to various possible outcome of a material supply chain reaction under different policies and parameters. The developed decision systems dynamics simulation model in this work will provide potential opportunity for firms that seek better project performance by understanding the dynamic behavior of the complex material supply coordinating system. This model also enhances visibility in the material supply chain, which positions the EPC contractor and its supplier to make informed-based decision and policy. Therefore, the EPC firm sees the importance of timely and accurate information sharing and how its supplier can make adequate plans to meet its demand, even in the face of order changes. This effective process improvement method is suitable because of its capability to model and simulate the time-variant behavior to get a decision support system on chain reactions when firms collaborates and share information. Resilience is not a static goal; continual improvement is needed and crucial to the success of any firm.

Insufficient and untimely delivery of construction materials would reduce the construction rate which in turn lead to schedule and cost overrun. The optimal planning of the supplier will not only reduce holding cost but improve the material delivery performance and the project performance. This work also focuses of the synergy of the supplier's inventory management and EPC order and material coordination, which developed a SD model to generate optimal strategy for inventory management in the CMSC. To improve the material supply chain performance, the material safety stock policy should be made based of the EPC's order. This study focuses on the bulk off the shelve construction material supply coordination between EPC contractor's and its supplier. As the thesis topic suggests, the goal of the study is to design a decision simulation model for the construction material supply. The model can be used to project the response of a policy or decision, but the results are based on assumptions. It can be used to as a support tool to assist decision makers understand the basic causes of material delay in the material supply dynamics and test potential intervention policies. This study introduced some supply chain performance metrics such us supplier's inventory coverage, material usage rate, order backlog and order delay, among others. These metrics have been linked and the decision simulation model had been developed based on them. This decision support simulation model backs studies on how material shortage reduces construction progress and how safety stock can help achieve higher service level in the presence of demand variation and inventory variability. This SD model helped study the behaviour of construction materials supply chain and evaluate the impact of safety stock intervention and sharing information. This study contributes to the literature by developing a SD decision support system to help understand the material supply chain dynamics between the EPC firm and its supplier, which often emanates into material shortage on site and how this risk can be mitigated to enhance project performance. In conclusion, the proposed research in terms of the research objectives made some meaningful contribution to the construction management in general and EPC management specifically.

5.3 Limitation and Future Work

For future research, the result and suggested policies can be further validated using empirical data. In addition, the findings are limited to construction industry supply chain setting. Further work can be done on cost of material shortage on the EPC firm in the supply network and incorporation of capacity expansion model for the construction material to have a better insight to the cost associated to premium freight taking into consideration the time delay in the capacity expansion decision making. More studies can also be conducted on the safety stock level required in the presence of shipping time delay and processing time delay.

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APPENDIX A

SYSTEMS DYNAMICS MODEL EQUATIONS

Order Fulfilment

The CMSC model starts with an incoming EPC Order rate (*OR*). *OR* provokes *OB. OB* increases the unfulfilled orders by reason of the EPC order cannot be delivered immediately. To provide model's equilibrium

$$OB = OR \times DD = 0 \quad \text{(A.1)}$$

where *DD* can be any value decided on by the EPC firm

$$OB = (OR \times DD) + OR - OFR \quad \text{(A.2)}$$

OB affects the behaviour of the desired shipment *DSR. DRS* is calculated as the ratio of *OB* and *DD*

$$DSR = OB / TDD \quad \text{(A.3)}$$

OB also affect the actual average delay, A*DD. DD* is obtained as the ratio *OB* and O*FR*

$$DD = OB/OFR \quad \text{(A.4)}$$

where $OFR = SR \quad \text{(A.5)}$

Shipment Rate, is calculated as follows:

$$SR = DSR \times [TF(MSR/DSR)] \quad \text{(A.6)}$$

Where TF indicate to the Table of Order Fulfilment. [TF *(MSR/DSR)*] shows a function of *MSR* to *DSR* that indicates the fraction of the orders given DSR which is called *FR*

MSR is the supplier maximum rate of shipments that can occurs given the current *SI* level regulated by *ST*

MSR = SI/ST ………………………………………………………………………………………..(A.7)

where minimum shipping time, *ST* is given

<u>Inventory Control</u>

SI, the level of ready supplier inventory in stock which is computed as

SI =DSI ………………………………………………………………………………………...(B.1)

SI accumulates the discrepancy between the processing rate *PR* ad the shipment rate *SR*

***SI = (PR – SR)* ×dt** ………………………………………………………………………...(B.2)

Where, ***MDR = SR***…………………………………………………………………………(B.3)

SIC shows the numbers of weeks supplier could ship at the current *SR* given their *SI* level. Supplier seeks to maintain adequate *SIC* to enhance adequate service level to the EPC. To maintain *SIC,* the supplier tries to keep *SI* level adequate at the *DSI* by protecting the *EOR.*

SIC= SI / SR ……………………………………………………………………………(B.4)

Therefore, *DSI* is determined by:

DSI = (ST+SS)* × *E0R …………………………………………………………………(B.5)

where *ST* and *SS* are given predetermined values.

***EOR*, initialized when the *t* = 0 as follows: *EOR* = *EO*, *t* = 0** ……………………………..………(B.6)

EOR was determined by first order exponential smoothing technique as follow:

EOR = EO+ CEO ……………………………………….…………………………….….…(B.7)

where *CEO*, change in expected order, is determined between *EO* and *EOR* adjusted by the given *AT*, time to average order rate:

CEO = (EO – EOR)/AT …………………………………….…………………………………(B.8)

When there is not enough supplier inventory coverage, there is discrepancy between *DSI* and *SI*, which is referred as *SID*, supplier inventory gap which is adjusted by *SDT:*

SID = (DSI-SI)/SDT ………………...……………………………………………………….(B.9)

To reduce *SID*, and take the *SI* level to desired level, supplier desired processing rate *DP* is determined as follows:

***DP* = (*EOR*+*SID*)** ………………………………….……………………...…………….……(B.10)

SR = MDR …………………………….……………………………...…………………(B.11)

<u>Order Processing</u>

DP alters *PS*, processing start rate, which is regulated by *DP* as:

PS =DP + WD ……………………...……………………………………………………..…(C.1)

WD work in process discrepancy, adjust *PS*, to reduce the difference between desired work in process, *DW*, and supplier work in process inventory, *WIP*

$$WD = (DW - WIP)/WDT \qquad (C.2)$$

where *WDT* value is given.

WIP accumulates the difference between processing start rate *PS and processing rate, P. WIP is calculated as*

$$WIP = DW,\ t = 0 \qquad (C.3)$$

$$WIP = DW + PS - PR \qquad (C.4)$$

DW enhances a level of *WIP*, adequate to provide the *DP*, given processing time *PT:*

$$DW = PT \times DP \qquad (C.5)$$

Processing rate *PR* is calculated by the third order delay of the processing start rate (delay 3) δ_3 with the delay time determined by the *PT*:

$$PR = \delta_3 (PS, PT) \qquad (C.6)$$

<u>Material Management</u>

Recall from equation 18, *SR = MDR*

EI, the level of ready EPC inventory in stock which is computed as

$$EI = DEI \qquad (D.1)$$

EI accumulates the discrepancy between the material delivery rate *MDR* and the material usage rate *MUR*

$$EI = (MDR - MUR) * dt \qquad (D.2)$$

EIC shows the numbers of weeks EPC contractors could construct (use) at the current *MUR* given their *EI* level. *MUR* is the rate at which construction materials are consumed depending on its availability in the store.

***MUR = DUR*× [TU(*MU/DUR*)]** ……………………………………………………….………... (D.3)

where TU indicate to the Table of Material Usage. [TU *(MU/DUR)*] shows a function of *MU* to *DUR* that indicates the fraction of the material used given *DUR* which is called *UR.*

MU is the EPC maximum rate of material usage that can occurs given the current *EI* level regulated by *MIC*

MU = EI/MIC …………………………………………………………………….……… (D.4)

where minimum material inventory coverage, *MIC* is given.

DUR is the construction rate EPC firm seeks determined the expected material delivery rate, *EMD*

DUR = EMD……………………………………………………………………….….……… (D.5)

***EMD*, initialized when the *t*=0 as follows: *EMD =EO at t*=0** …………………………….…...….. (D.6)

EMD was determined by first order exponential smoothing technique as follow:

EMD = EO+ CMD ……………………..……………………………...…….……….…... (D.7)

where *CMD*, change in expected material delivery, is determined between *EO* and *EMD* adjusted by the given *AD*, time to average delivery rate:

CMD = (EO – EMD)/AD ……………………………………….………….……………… (D.8)

When there is not enough supplier inventory coverage, there is discrepancy between *DEI* and *EI*, which is referred as *EID*, EPC inventory gap which is adjusted by *EDT:*

EID = (DEI-EI)/EDT …………………………………………….……….……………… (D.9)

EIC shows the number of weeks the EPC can carry out construction at the current *MUR* given *EI*.

EIC = EI/MUR…………………………………………………………….……..………………. (D.10)

EPC contractor tries to maintain enough inventory *EIC* to give adequate service in term of the construction rate. To maintain *EIC*, the EPC contractor tries to keep *EI* level adequate at the *DEI* by protecting the *EMD* which affects the *DUR*

Therefore, *DEI* is determined by:

DEI = (MIC+ESS) ×DUR ………………………………………….…………………….. (D.11)

where *MIC* and E*SS* are given predetermined values.

APPENDIX B

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