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Two-Stage Methodology for Managing and Controlling Material Flow Between Multiple Construction Projects

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TWO-STAGE METHODOLOGY FOR MANAGING AND CONTROLLING MATERIAL FLOW BETWEEN MULTIPLE CONSTRUCTION PROJECTS

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ABSTRACT

There is a strong connection between managing and controlling material flow in a supply chain and its performance. While this is true in all supply chains, it is particularly true in the construction supply chain (CSC) where the total demand for parts is finite, the storage space available can be small, and the variability in consumption is high. On the other hand, effectively controlling the CSC can have a significant impact on controlling risk and buffering their impact so that projects stay on schedule and within budget. Currently, a common control of the CSC is with a push-based material ordering system based on the initial construction schedule and, then, holding a tremendous amount of inventory. Project managers even speak of the desirability to “flood the site” which means having as many of the construction materials on-site as early in the project as possible. It is not uncommon for a year-long construction project to have tens of acres dedicated to storage and for this area to be completely full early before the project begins. Further, each project is controlled completely independently from all other project even if they are for the same customer or being built by the same firm.

A new methodology for controlling the CSC that represents a paradigm shift from the current system is proposed in this dissertation. This two-stage methodology applies to products that can be used among a few construction projects being executed simultaneously. Stage 1 mirrors the current push procurement strategy but Stage 2 allows transshipments between sites. Further, the two stages collaborate in the sense that information is shared and decisions updated based on current, global knowledge. The methodology uses deterministic optimization models with objectives that minimizing the

total cost of the CSC. To illustrate how this methodology can be used in practice and the types of information that can be gleaned, it is tested on a number of cases based on the real example of multiple construction projects in Kuwait.

DEDICATION

This dissertation is dedicated to my parents for always believing in me, for instilling the love for learning, and for encouraging me to follow my dreams. To Ali, my loving husband, my rock and my best friend for giving me his heart, and for walking with me through thick and through thin in life together. And to our three beloved sons, Omar, Bader, and Barrak for bringing purpose to our lives and for giving us the reason to enjoy every day of our lives.

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CHAPTER ONE

INTRODUCTION

Managing and controlling the construction supply chain (CSC) are very important components of effective construction project execution but, until recently, have received little attention as reflected in the open literature. The goals of managing the CSC are to reduce uncertainty and optimize the performance of a construction project by improving efficiency and reducing project costs. Current notions of improving the CSC, as reflected in the literature on managing and controlling the CSC, involve focusing on one project at a time; and there is an unmistakable implication that each project has multiple supply chains (SCs) that relate to each individual component and consumable. This is actually an easily understandable consequence of the traditional approach to construction projects that pit suppliers and subcontractors against the construction firm and that focuses most, if not all, effort on negotiating contracts and payments for noncompliance. With the inherent variability in all process including construction, it is not hard to visualize how this as an environment of “adversarial relationships, unhealthy competition, purely price-based selections, incomplete contracts, numerous change orders, and improper risk-shedding tactics that can contribute directly to many cases of unsatisfactory performance, increased costs, and durations, and contract administration problems” (Palaneeswaran, Kumaraswamy, Rahman, & Ng, 2003, p. 571). The approach of viewing all supply chains as independent entities is not new. Many industries followed a very similar path from a focus on minimizing the cost of each supplier and activity individually to an integrated

SC approach as competition necessitated that they more carefully manage, control, and integrated SCs. Whether it was the US automobile industry in the 1970's or healthcare decades later, management and control of the SC were most often done by tradition, experience, and intuition with each segment of the process isolated from the others. The motivation of this research focuses on extending collaboration ideas to the CSC to improve the performance of multiple construction projects.

In the CSC, each construction project has several key input flows that are needed for successful execution of the project's tasks. These actually are analogous to the key flows in all supply chains and include information, previous work completed, human resources, physical space, availability of materials and equipment, external conditions, and funding (Koskela, 2000; Ballard & Howell, 2003). Because material costs can comprise up to 50% of the total cost of a project (Asplund & Danielson, 1991), and because having the right materials available on site when they are needed is so important in maintaining schedule in a construction project, this research focuses on investigating material flow and, in particular, when a single company has multiple projects in progress simultaneously. The opportunity that this research investigates lies in identifying and exploiting synergies in the CSC of multiple projects with the objective of minimizing the total delivered cost of materials.

The heart of much SC activity is addressing risk and the CSC is no different. The delivery and consumption of construction materials is highly variable due to the complexity of construction operations, rapidly changing demand for certain components, lead time variability from suppliers, transportation time variability, and disruptions at the job site. Organizations use a number of techniques to deal with uncertainty, variability, and risk of disruption. Thompson (1967) identifies four main methods: (1) forecasting, (2) buffering, (3) smoothing, and (4) rationing. Forecasting is useful in anticipating variability in business processes; however, forecasts have many limitations. Recently, Hopp and Spearman (2008) popularized as the "Three Laws of Forecasting" and defined them as follows (1) all forecasts are wrong, (2) the more specific a forecast is, the more the actual deviates from the forecast, (3) the farther a forecast looks into the future, the less accurate it becomes. As such, forecasts are important but their accuracy and value must be kept in perspective. The fact is that variability will enter all real processes so a thoughtful approach to buffering the impact is critical so that the cost and schedule of the construction projects are protected from the harmful consequences. There are three types of buffers: inventory, capacity, and cycle time (Hopp & Spearman, 2008). While all of these are useful to mitigate the adverse impact of variability, they can also be very costly. As such, one universal goal is to reduce variability so the buffers can be as small as possible. In production systems, smoothing demand or consumption is one of several techniques that seek to reduce variability so that less buffering is required. An example of production smoothing is leveling work load as advocated in the Toyota Production System (Liker, 2004). In construction, looking ahead at the construction schedule and delaying tasks that are not on the critical path so the total work load is better matched to the resources is one example of smoothing in construction. These ideas have been formalized to some degree with a methodology called Last Planner (Ballard, 2000). In the end, if a plan for buffering the impact of variability has not been adequately executed, there will be shortages in inventory of materials or other resources at critical times and, consequently, a slippage of schedule or costly expediting effort.

The construction industry has equivalent processes to traditional production and manufacturing that are used to coordinate activities. The literature reports anecdotal evidence that controlling the SC using push, pull, and push-pull systems have an impact on preventing and reducing the risks in both manufacturing and CSCs. On the other hand, transshipment is also a practice that is used in distribution systems to help mitigate risks by sharing common resources among entities at the same echelon of the SC. Since using transshipment between construction projects being performed in parallel has not been investigated previously, exploring a strategy that allows the possibility of transshipments to augment shipments from suppliers based on forecasts to improve the construction performance is the objective of this research. Hence, the focus of this research is developing a methodology for controlling material flow in construction projects that adds the ability to transship materials between projects. This methodology includes the framework of the current system that places orders with suppliers based on forecasts but embeds collaboration so this traditional push system actually operates differently and has different decision support tools associated with it. Once developed, a number of numerical examples are presented that are different scenarios derived from a real CSC involving three projects in Kuwait. The goal is to illustrate how this methodology can be used in practice and the types of information that can be gleaned.

A two-stage methodology is proposed that finds minimum or near minimum cost material flow strategies where the cost is restricted to transportation and shortage cost in a CSC that consists of multiple construction projects being executed simultaneously. The methodology uses deterministic optimization models to guide decisions with objectives of minimizing the total cost of the CSC that includes the costs for holding inventory, being short items necessary for construction to continue, transporting materials from suppliers to sites and between sites, and placing orders. Stage 1 focuses on the systems that order materials from suppliers based on projected consumption and uses push control. Stage 2 represents a paradigm change in practice because it allows transshipment between construction sites.

The transshipments between construction projects are really governed by a pull controller, so the proposed methodology is, in fact, an integrated push-pull control which is commonly used in non-construction applications where it has been proven to be very effective in buffering the impact of variability. It is important to note, however that there are important unique features in the construction environment. For example, with the constantly changing supplier base due to the fact that construction projects move from one part of the world to another, the impact and cost of constantly changing orders in Stage 1 is different from changing orders with at long term partner supplier.

Three versions of the methodology are presented, each adding more realism to the scenario it addresses. The first version of the methodology addresses an integrated Production and Transshipment Problem of Single supplier, Multiple projects, and Single material (PTPSMS). It assumes a single material that is commonly used in a wide variety of projects like steel rebar. The production capacity of the supplier is assumed to be limited and sufficient to satisfy the initial forecasted demand of each project site;

however, in some situations, this capacity may be insufficient to satisfy a request for additional product to accelerate a project. The number of identical trucks available to deliver products for the supplier to the sites as well as to transship between sites is assumed to be unlimited but each has limited capacity. The two-stage methodology has been applied to carefully constructed case studies to illustrate how it would work in practice and to investigate the efficacy of using transshipment in the construction environment. In addition, to explore the impact of different time periods at which each stage is executed on the total cost of the CSC and determine the combination of the time periods that provides the minimum total cost of the CSC so that these can be used in future case study examples.

The second version of the methodology is an extension of the first to a more constrained environment. Here, we include multiple products that are differentiated by their size as measured by volume. There is a single supplier with limited production capacity. The number of trucks is assumed to be limited and each has limited capacity that is reflected in the maximum allowable total volume it can transport in a single trip. The storage capacity at the project sites is also assumed to be limited. The two-stage methodology will control the flow of materials giving the storage and transportation capacity constraints to optimize the CSC performance.

The final version of the methodology focuses on the design of the CSC. Here, an additional extra storage site not associated with one of the projects has been added. By applying the proposed methodology to this new CSC, the general impact of this additional facility will be explored. As in the second version of the methodology, capacity restrictions are assumed to be relevant to the storage capacity at the project sites, the maximum number of trucks, and the maximum number of units that can be carried on the truck. The two-stage methodology with the extra storage site will be applied on different scenarios to illustrate how it would work in practice and to investigate the impact of this buffer on the material flow and the cost of CSC.

The methodology is tested on a number of cases based on the real example of multiple construction projects in Kuwait which helped motivated this research and provides a context for why the methodology is an important contribution. In this real situation, the contractor of project 1 signed the construction contract and immediately ordered the steel rebar. The decision was made to purchase the entire quantity early in the project and store the rebar as a hedge against price fluctuations. Unfortunately, while the project was still in an early stage, the owner encountered financial difficulty and had to delay the project for an unknown amount of time. The price of steel rebar increased during this time so the rebar that had been stored was sold by the contractor to another construction project contractor to use on one of their construction projects; in this case, a mutually beneficial solution presented itself by chance. Obviously, depending on unpredictable price fluctuations to rescue bad decisions is not a good long-term strategy for success; hence, the proposed methodology is used to explore questions surrounding alternate controls for the purchasing, movement, and transshipment of the rebar and meet demand and reduce risk. The specific cases have been crafted to explore a range of situations encountered in construction. Note the objective is not to statistically define superiority of any strategy; rather, the motivation is to illustrate how the methodology could be used in practice and the types of information that can be gleaned from its use.

The primary research contribution is developing a two-stage methodology for planning and controlling material flow in construction projects where Stage 1 controls the interface with the suppliers and Stage 2 provides the opportunity for transshipment between the projects. While each stage of the methodology is well known and commonly used in practice, combining them into a single, cohesive methodology is new. The second contribution is applying this methodology in a new application domain, construction. While construction and capital projects have some similarities with high volume manufacturing and distribution, some of their most pronounced unique features have a tremendous impact on material flow in the CSC. For example, in construction the following are most often true: 1) there are rarely more than a few projects within a sufficiently close proximity so that routine transshipments between sites is practical, 2) each construction project has finite total demand for a given product over its construction horizon, 3) many products are bulky and/or heavy, and 4) highly varying demand associated with expediting and delaying projects is a norm rather than in this business. The last idea suggest that holding additional inventory and/or implementing some strategy that involves risk pooling would help; however, the first three ideas make it difficult to visualize how these notions can be realized. This is why the scripted case studies are important. Although their specific outcomes are obviously dependent on how they are parameterized, the overall trends should not be immediately discounted because all the cases are based on a real scenario in Kuwait. The final contribution is that the proposed methodology can be used as an engineering design tool for the CSC even though it was developed to control material flow. Being able to identify the cost and effectiveness of adding storage capacity and/or transportation buffers in the CSC in a way that is consistent with the control strategy that will be used to move materials through it, it is important and useful application of this research.

CHAPTER TWO

LITERATURE REVIEW

An overview of the prior literature related to this research is divided into the following three categories:

- The construction supply chain
- Push and pull production systems in construction supply chain
- Transshipment and sharing inventory in construction supply chain

2.1. Construction Supply Chain for Multiple Projects

There are many similar definitions for the term *supply chain* (SC) (Bechtel & Jayaram, 1997). Chopra and Meindll (2004) operationalize this concept by nothing that a typical SC may consist of several stages that include raw material, suppliers, manufacturers, distributers, and customers. Similarly, Azambuja and O'Brien (2009) visualize the typical structure of a SC as shown in Figure 2.1.

On the other hand, supply chain management (SCM) is defined as the "coordination of independent enterprises in order to improve the performance of the whole supply chain by considering their individual needs" (Lau, Huang, & Mak, 2004). The key of success the SCM system is based on integration (Chan and Qi, 2003). In SCM, integration is described by trust, partnership, cooperation, collaboration, and, information sharing (Akkermans et al., 1999).

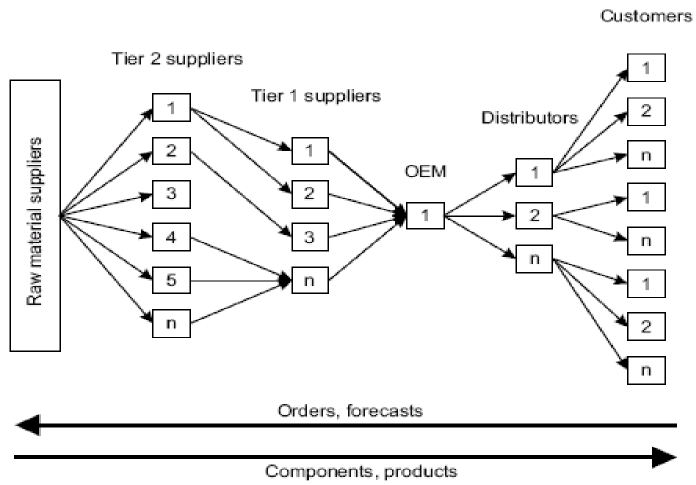


Figure 2.1: Structure of a typical SC (Azambuja and O'Brien 2009)

For construction supply chain (CSC), X. Xue et al. (2005) stated that:

"CSC consists of all construction processes, from the initial demands by the client/owner, through design and construction, to maintenance, replacement and eventual demolition of the projects. It also consists of organizations involved in the construction process, such as client/owner, designer, GC, subcontractor, and suppliers."

The implementation of SCM improved the performance of manufacturing environment by increasing the customer satisfaction with lower cost, high quality, and fast response. In recent years, construction industries are evolving and become more interested in SCM to improve project performance (O'Brien 1998; Vrijhoef and Koskela 2000). Azambuja and O'Brien (2009) summarize key differences between manufacturing SCs and CSCs, as shown in Table 2.1.

Table 2.1: The key differences between manufacturing SCs and CSCs (Azambuja & O'Brien, 2009)

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

Hence, there are obstacles that make the implementation of SCM in construction industry difficult. In order to improve the performance of CSC, significant changes are required in the type control and coordination.

Several studies (Vrijhoef & Koskela, 1999; Green, Fernie, & Weller 2005; Hopp & Spearman, 2008) described construction as highly-fragmented, complex, and inefficient industry with high variability and waste level.

Vrijhoef and Koskela (2000) analyzed four major rules of managing CSC where each rule focused on different part of the CSC: (1) on the interface between the SC and the construction site, (2) on the SC, (3) on transferring activities from the construction site to the SC, and (4) on the integrated management of the SC and the construction site. For all different rules, they indicated that the control of CSC needs to be improved in order to reduce the large waste and increase the performance.

Previous researchers have considered the conceptual view of a CSC as a single SC that is composed of multiple SCs with distinct behaviors based on the type of product or material being delivered to the construction project. A common objective in all SCs, but particularly in CSCs, is the need for increased resilience and flexibility toward variability. Thus, a new CSC paradigm is presented in this research to improve resilience while increasing SC efficiency and flexibility involves multiple independent construction projects that use the same products (e.g., reinforcing steel rebar) being executed simultaneously.

2.2. Push and Pull Production Systems in Construction Supply Chain

The effective control of the material flow in a CSC can play a significant role in a project's schedule and cost because as Asplund and Danielson (1991) noted, material costs can comprise up to 50% of the total cost of a project in some cases and increased up to 65% (Formoso & Revelo, 1999). Tserng and Li (2006) showed that the improper planning and management of materials increases the material costs. Moreover, they stated that high material costs are main reason of high variability in construction production systems. Frequently the inventory control methods of the material in construction sites depend on visual control (Halmepuro & Nyste´n, 2003). However, in some cases, Harju-

Jeanty and Jäntti (2004) stated that in some cases, managers use of spreadsheet applications to control site inventories, but it is ineffective because of inaccurate data.

Push and pull are two basic strategies for planning and controlling production. The literature reports anecdotal evidence of their impact on mitigating and reducing the risks derived from variability in both manufacturing SC and CSC.

Push Systems

Howell and Ballard (1994, 1996) and Ballard and Howell (1998) investigated the impact of adding buffers (push) and the variability of the construction project. They found that a material buffer decreases the disruption of construction projects. The common practice in the construction industry is to keep large amounts of inventory on construction sites to reduce the risks associated with production delay and the lack of flexibility in changing orders. However, this bothers the project managers because it increases the inventory cost and site congestions. Further, Tommelein and Weissenberger (1999) and Simchi-Levi et al. (2003) stated that the disadvantage of the practice of building buffers in push systems is increasing the inventory level, the waste, and decreasing the flexibility in changing the orders.

As such, several researchers showed that one requirement of buffers is to manage them carefully or else they will be ineffective and decrease the performance of the construction projects (Howell & Ballard 1996; Al-Sudairi, 2000; Alves & Tommelein, 2004; Park & Peňa-Mora, 2004; Horman & Thomas 2005). Ala-Risku and Karkkainen (2006) proposed a method to overcome the material-delivery problems in CSCs using a modified push method. The authors believed that the main problem with the traditional push method is its lack of transparency related to inventory at the project site, and they proposed a tracking-based approach in which materials are labeled with code numbers to provide more inventory transparency.

Pull Systems

Pull systems employing just-in-time (JIT) is a material management and control system with the primary goal of reducing the inventory costs by reducing the material waste. In manufacturing SC, Akintoye (1995), Pheng and Chan (1997), Pheng and Tan (1998), and Pheng and Hui (1999) showed the benefits of pull systems in reducing the inventory costs. In CSC, Chopra and Meindl (2001) stated that reducing the inventory level and site congestion at the construction site are the best ways to improve the material planning. Sobotka (2000) and Shmanske (2003) proposed controlling the materials by reducing the inventory level instead of building buffers with the rules of breaking down the orders and increasing the delivery frequency. Tserng and Li (2006) built an integrated inventory model for managing construction materials and reducing the inventory level at construction sites.

There are different applications of JIT based on certain material types, including perishable (e.g., ready-mix concrete), bulky heavy (e.g., pre-cast components), and unique (e.g., pipe spools) materials. Pheng and Chuan (2001) recommended using modified JIT with limited buffer. These researchers surveyed contractors in Singapore and found, that 94% of the main problems facing contractors are related to site congestion. Similarly, Naso, Surico, Turchiano, and Kaymak (2006) examined the implementation of JIT material management of ready-mix concrete using a genetic scheduling algorithm with the objective of meeting the required delivery time and minimizing delay. Tommelein (1998) investigated the benefits of the pull-driven sequencing technique for unique products (e.g., pipe spools). The author concludeds that the pull technique is appropriate for improving the performance of projects that are afflicted by uncertainties. However, implementing pull systems is not the right strategy for all production systems (Nahmias, 2009). Polat and Arditi (2005) showed that employing JIT for steel rebar is ineffective compared with the traditional high buffer case.

Previous research showed that the proper use of push and pull control systems has an impact on preventing and reducing the risks in both manufacturing SCs and CSCs for individual projects. This research proposes a new integrated planning and control system for CSCs that uses both push and pull to improve efficiency, flexibility, and resilience when multiple construction projects are being executed simultaneously. Specifically, push control is exercised throughout Stage 1, which defines the interaction between suppliers and construction projects, while pull control is used in Stage 2 to buffer the impact of variability by responding to transshipment requirements between construction sites.

2.3. Transshipment and Sharing Inventory in Construction Supply Chain

The main concept of transshipment is collaboration to help mitigate the risks of out-of-stock by sharing common resources among entities at the same echelon of the SC.

Several researches showed the effectiveness of transshipment strategy in decreasing the total cost by decreasing the inventory level and improve the performance in the SC (Hoadley & Heyman, 1977; Karmarkar & Patel, 1977; Tagaras, 1989; Herera, Tzurb, & Yucesan, 2002; Burton & Banerjee, 2005; Lee., Jung, & Jeon, 2007; Tiacci & Saetta, 2011; Chen, Hao, Li, & Yiu, 2012; Hochmuth & Köchel, 2012).

On the other hand, Lee (1987), Axsäter (1990), Alfredsson and Verrijdt (1999), Grahovac and Chakravarty (2001), Kukreja, Schmidt, and Miller (2001), Wong, Cattrysse, and Oudheusden (2005), and Wong, Houtum, Cattrysse, and Oudheusden (2006), showed the significant savings in the total cost of dealing with emergency lateral transshipment on expensive repairable items of critical machines in the manufacturing line.

Another aspect of research in this area shows the positive impact of transshipments under capacitated constraints. Özdemir, Yücesan, Herer (2006) examined transshipment and inventory sharing with capacitated transportation. In addition, Özdemir et al. (2013) extended their capacitated constraints by considering a supplier with limited production.

It is noteworthy that neither previous research nor actual practices included the opportunity for transshipment in CSCs. There are several reasons for this inapplicability. First, there is a general lack of cooperation, relationships, and information among projects. Each project is considered independent and is designed and built with this philosophy in mind (Mckenna and Wilczynski, 2005). Second, most construction projects use contractual issues or insurance as an indemnity for disruption risk. This was true until Ko, C.H. (2013) applied transshipment strategies to precast fabrication in the construction environment to reduce the total material cost. The findings of the study indicated that benefits of transshipments in construction industry are limited and based on how close the fabricators are from each other.

The key differences between this research and our research are: First, transshipment is assumed to be between precast fabricators; however, in our research the objective is to allow transshipments between the different construction projects. Second, the demand is assumed to be uncertain with normal distribution and in our case the demand is assumed to deterministic. Finally, in our research we considered different type of products (ex. steel rebar and structural steel).

Therefore, this study contributed to this line of research by integrating intra-echelon transshipment problems with multiple periods, single suppliers, and multiple construction projects.

CHAPTER THREE

A TWO-STAGE METHODOLOGY FOR SINGLE-MATERIAL FLOW CONTROL IN CONSTRUCTION SUPPLY CHAIN

3.1. Introduction

Managing unplanned and unexpected events, often referred to as risk management, is critical in all industries and it is particularly so in construction because missing scheduled deadlines frequently carry huge liquidate damage penalties. As such, construction companies most often avoid these “at all costs” which can become an operational strategy that can dramatically increase the total installed cost of a project. The underlying premise of this research is that there are opportunities to better manage the risk associated with the unplanned and unexpected and one of them is in material flow control. The current approach to construction management treats each project as standalone and approaches that have been introduced to reduce this risk or buffer its impact focus on managing and controlling each construction project independently. This strategy, along with the long lead times required for many materials to arrive at the site from the suppliers, often leads to inefficient inventory control resulting in excess inventory, shortages, or both.

To quantify and explore the opportunities associated with a paradigm shift that allows transshipments between construction projects, a new methodology is proposed based on an integrated Production and Transshipment Problem (PTP) of the CSC. This methodology addresses control of the material flow between multiple construction projects at different sites that are being executed simultaneously and it explicitly includes costs associated with shortages, excess inventory, and transportation.

The methodology consists of two distinct stages. The first coordinates shipments from suppliers based on forecasts and information about consumption of materials while the second determines transshipments between sites. Each stage uses a mixed integer optimization model that is solved at different frequencies to determine material flow decisions. The stages pass information at predetermined times so decisions are based on the best data available at the time. Although each element of the methodology is well known, combining them into a unique methodology for this application domain is the contribution. The methodology addresses an integrated Production and Transshipment Problem of Single supplier, Multiple projects, and Single material and henceforth, will be referred to as PTPSMS.

The proposed methodology is based on a two-stage strategy that includes the current order fulfillment process used in project sites plus a new idea in which transshipment can occur between sites. Control is decentralized meaning each stage has its own control and information is passed at predetermined times during the horizon. The time horizon is divided into discrete periods and each project is assumed to start and end within this horizon. Stage 1 is controlled using a push strategy that mirrors the existing practices. Quantities of needed components and commodities are forecasted from the project design drawings, bill of material, and estimated construction schedule. Orders are placed with the supplier and shipped directly to the construction sites without keeping intermediate inventory at the supplier. An unlimited number of trucks, each with equal but limited capacity, deliver materials to each construction site. The received materials are held in a warehouse on the project site until they are needed to be installed or consumed. Stage 2 offers the opportunity to redeploy the materials based on actual demand. When there are no disruptions and the forecasted demand actually occurs, no transshipment takes place. Materials are transported from the supplier to each project site based on their initial scheduled delivery dates and Stage 2 will provide information to Stage 1 that the actual demand and forecasted demand agreed. In the case of a disruption at one or more of the project sites or at supplier, the Stage 2 optimization model will accommodate it by adjusting inventory using a deterministic optimization model. Stage 2 will determine if transshipments between the construction projects will reduce the supply chain cost and provide Stage 1 with information on any repositioning of inventory and updated forecasted demand and actual demand. Note that to preserve realism between the methodology and the practice, the updated forecast of demand during the Stage 2 to Stage 1 information sharing is made by the project manager based on the current situation and expectations for his or her project in the next few periods. It is not part of the Stage 2 model. It has to be noted that the updated information from Stage 2 to Stage 1 occurs at a predetermined "updating Period "called τ.

An example of the basic flow of materials and information in the PTPSMS methodology is illustrated in Figure 3.1. The construction planning horizon is from time *t* up to time T. First, Pre-Stage work occurs before construction is begun at the project sites. Then, Stage 1 is executed based on the original plan for each project site from the pre-Stage. Stage 1 is subsequently executed at predetermined updating periods (τ) but these updates are based on updates to the forecasted demands and the actual material consumption reported by Stage 2.

Stage 2 is also executed at predetermined intervals (*f*) until the updating time of Stage 1, where information on the actual inventory status at the sites is combined with updates to the forecast and another Stage 1 update is performed. Transshipments in Stage 2 are performed from the project site with excess inventory level (+) to the one with shortage (-) to balance supply and demand (=) under the assumption that transshipment cost are cost optimal. In this figure, we postulate that Project 1 has been delayed so it has extra inventory while both Project 2 and Project 3 have been accelerated and need more product so they are short product. Assume the cost optimal solution is to transship product from Project 1 to Project 2 and leave a shortage at Project 3. Then this information is passed to Stage 1 at the updating period τ along with any updates to the forecast. Further, if the supplier has limited capacity, it is quite possible that the request for an increase in the amount of product at Project 3 cannot be met and Project 3 will remain in a shortage condition even after the Stage 1 update. The cycle will be repeated until the end of the time horizon.

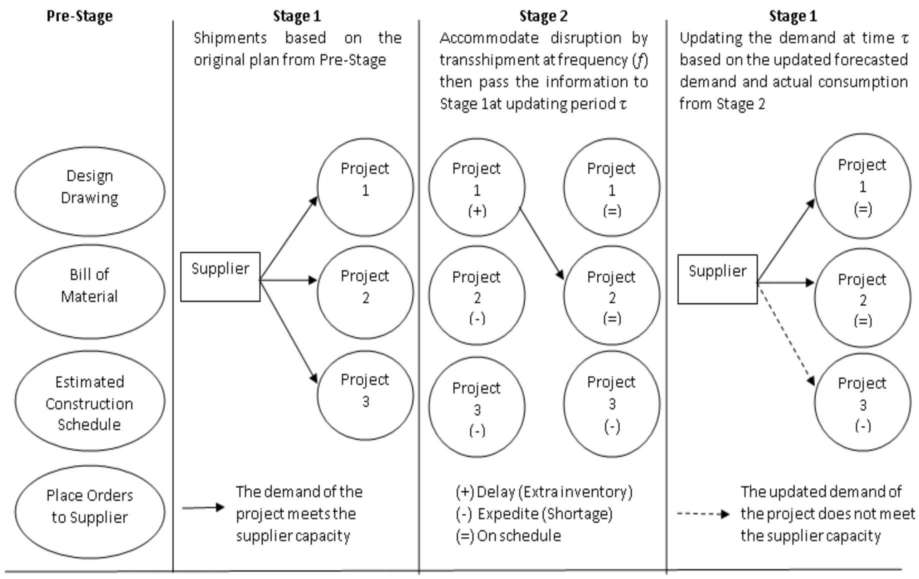


Figure 3.1: The integrated Production and Transshipment Problem (PTPSMS)

In this chapter, a two-stage methodology is proposed that will be applied it to carefully constructed case studies to illustrate how it would work in practice. We will numerically explore the impact of different time periods at which each stage is executed. Specifically, the goals are: (1) to assess the effect of different "updating periods" (τ) when Stage 1 is executed, and "transshipment periods" (f) when Stage 2 is executed on the total cost of the CSC and (2) to determine the combination of the time periods (τ, f) that provides the minimum total cost of the CSC so that these can be used in future case study examples.

3.2. Mixed Integer Programming Model for the PTPSMS

The methodology proposed in this research considers two types of material flow control: 1) between a single supplier and multiple project sites and 2) between project sites. The methodology consists of two-stages with each stage containing a mathematical model that minimizes the total cost of transportation, inventory, ordering, and shortage in the CSC.

The Stage 1 optimization model reflects a centralized push control that defines communication between project sites and the supplier. It serves a function similar to traditional Materials Requirements Planning (MRP) or Materials Management in the sense that it uses forecasted or predicted demand of an item at a project site along with deterministic and known lead times to place orders. The Stage 2 optimization model determines if transshipments among the project sites are needed to minimize the cost due to imbalances between demand and supply.

The methodology reflects some key constraints at the project sites with an important one being that central planning (Stage 1) and site coordinator (Stage 2) operate independently. The only cooperation between them is passing data at predefined times. This proposed interactive methodology operates as follows: 1) The Stage 1 model is solved at the beginning of period 1 and then updated every τ periods thereafter. 2) The Stage 2 model is periodically solved to determine possible transshipments. This occurs every f periods beginning when Stage 1 information is passed and ending τ periods later when information is shared with Stage 1 on inventory levels and an update to Stage 1 occurs.

3.2.1. Mathematical Model of Stage 1

This model considers a single product that is used at all project sites (e.g., steel rebar). Based on the initial deterministic forecasted demand at each project site for the entire planning horizon, the Stage 1 model determines shipments to each site in each period. X_{ijt} is the number of units to be transported from the supplier *i* to site *j* at time *t*. At each update that occur every τ time periods, Stage 1 receives updated forecasted demand from the project sites. In practice, the updated quantities can come from several sources including the project manager based on the actual status of the project site or, upper management based on overall priorities; regardless, it is assumed this information is accurate and available when needed. Since these requests could result in expediting or delaying an existing order, a penalty cost is imposed that is based on when the existing order was to be delivered. That is, the penalty cost for updating an order to be delivered in the next period is higher than one that is scheduled for delivery two or three periods in the future.

The model assumes that the suppliers have finite production capacity and there are no inventory charges associated with any stock held at it. Transit times from the suppliers to sites as well as the times to load and unload are not considered. Several additional assumptions are made related to the delivery trucks: 1) A fleet of identical trucks is used to ship the products to the project sites. 2) Shipping is assumed to be performed by a TL (truckload) carrier and there is a maximum capacity associated with each load. 3) Multiple routes and multi-stop routes are not permitted; that is, each truck delivers to only one construction project site during a single trip. The objective of Stage 1 is to minimize ordering costs, transportation costs, costs associated with expediting or delaying orders already placed with suppliers, costs of shortages at the sites, and the costs of holding inventory. The following notation is used in the Stage 1optimization model:

Indices

$i \in S = \{1, 2, ..., \mathrm{S}\}$	the set of suppliers
$j \in N = \{1, 2, ..., \mathrm{N}\}$	the set of project sites
$t \in T = \{1, 2, ..., \mathrm{T}\}$	time periods up to the end of the planning horizon, T

Input Parameters

C_{ijt}^{1}	ordering cost for a unit procured from supplier *i* to be delivered to site *j* at time *t*, *i*∈*S*, *j*∈*N*, *t*∈*T* ($/unit)
UTC_{ijt}^{1}	transportation cost associated with each truck used to transport items from supplier *i* to site *j* at time *t*, *i*∈S, *j*∈*N*, *t*∈*T* ($/mile)
PC_t	penalty cost to expedite or delay each unit scheduled for delivery at time *t*, *t*∈*T* ($/unit)
Q_{jt}^{1}	per unit cost of shortage at site *j* during time *t*, *j*∈*N*, *t*∈*T* ($/unit)
Q_{jt}^{2}	per unit cost of holding inventory at site *j* during time *t*, *j*∈*N*, *t*∈*T* ($/unit)
D_{jt}	forecasted demand at site *j* at time *t*, *j*∈*N*, *t*∈*T* (units)
Cap_{it}	the production capacity at supplier *i* at time *t*, *i*∈*S*, *t*∈*T* (units)
$Invcap_{jt}$	the storage capacity at site *j* at time *t*, *j*∈*N*, *t*∈*T* (units)
H	the maximum capacity per truck (units)
F_{ijt}	number of units scheduled to ship from supplier *i* to site *j* at time *t* from the previous Stage 1 update, *i*∈*S*, *j*∈*N*, *t*∈*T* (units)

Computed variables

U_{jt} total number of expedited and delayed units requested by site *j* at time *t* (units)

S_{jt} number of units that are short at site *j* at time *t* (units)

I_{jt} end of period on-hand inventory at site *j* at time *t* (units)

M^1_{ijt} number of trucks used to ship the units from supplier *i* to site *j* at time *t*, $i \in S, j \in N, t \in T$

Decision variables

X_{ijt} number of units transported from supplier *i* to site *j* at time *t* (units)With these variables, the following Stage1 model is proposed for the PTPSMS problem:

$$Min\ \ z = \sum_{i \in S} \sum_{j \in N} \sum_{t \in T} \left(C^1_{ijt} X_{ijt} + UT^1_{ijt} M^1_{ijt} \right) + \sum_{j \in N} \sum_{t \in T} \left(PC_t U_{jt} \right) + \sum_{j \in N} \sum_{t \in T} \left(Q^1_{jt} S_{jt} \right) + \sum_{j \in N} \sum_{t \in T} \left(Q^2_{jt} I_{jt} \right)$$

Subject to:

$$U^+_{jt} = \sum_{i \in S} \left(X_{ijt} - F_{ijt} \right) \qquad \forall j \in N, t \in T \tag{1}$$

$$U^-_{jt} = \sum_{i \in S} \left(F_{ijt} - X_{ijt} \right) \qquad \forall j \in N, t \in T \tag{2}$$

$$U_{jt} = U^+_{jt} + U^-_{jt} \qquad \forall j \in N, t \in T \tag{3}$$

$$I_{jt} = I_{j,t-1} + \sum_{i \in S} X_{ijt} - D_{jt} + S_{jt} \qquad \forall j \in N, t \in T \tag{4}$$

$$I_{j,t-1} = a \qquad \forall j \in N, t \in T, \text{ where } a\text{=0 at } t\text{=1} \tag{5}$$

$$\sum_{j \in N} X_{ijt} \leq Cap_{it} \qquad \forall i \in S, t \in T \tag{6}$$

$$\sum_{i \in S} X_{ijt} \leq Invcap_{jt} \qquad \forall j \in N, t \in T \tag{7}$$

$$X_{ijt} / H \leq M^{1}_{ijt} \qquad \forall\ i \in S, j \in N, t \in T \tag{8}$$

$$X_{ijt} \geq 0 \tag{9}$$

Constraints (1), (2), and (3) determine the number of units to be expedited, delayed, and total changes, respectively. Constraint (4) balances the number on-hand at each site that that can be used to satisfy the demand. This is where the shortage term is forced positive if there is insufficient on-hand inventory after shipments to meet demand. Constraint (5) defines the inventory from the previous period and it is assumed that the planning horizon begins with zero at each site. Constraints (6) and (7) enforce the supplier production capacity and the project site storage capacity restrictions, respectively. Constraint (8) fixes the minimum number of trucks required. Finally, non-negativity constraint is included in (9).

3.2.2. Mathematical Model of Stage 2

Attention is now turned to Stage 2 where materials can be transshipped to better match actual demand and supply at each site. These decisions are made at predetermined intervals called fixed transshipment intervals that are *f* periods in length. The Stage 2 model is assumed to have perfect information regarding inventory levels because each site knows exactly how much product was consumed in previous periods (I_{jt-1}). It also has the scheduled shipments from the suppliers that were determined from the latest Stage 1 update (F_{ijt}). Stage 2 focuses on determining if lateral transshipment among the project sites is cost effective to accommodate the actual situations which could have been altered due to a disruption. The objective is to minimize the transshipment, inventory, and shortage costs. Each project site *j* is assumed to have unlimited storage capacity. It is assumed that the ordering cost for a unit transshipped from site *d* to site *j* is always less than the cost to ship from the supplier to site *j*. The transportation cost UT^2_{djt} to ship from any site *d* to site *j* is equal to the transportation cost from any supplier to site *j*.

Stage 2 uses the same assumptions related to the trucks as in Stage 1. Stage 2 also assumes that time to transport, load, and unload are not consequential. Stage 2 calculates the transshipment quantity through a network flow formulation to minimize the overall costs.

Stage 2 is executed at a predetermined transshipment intervals *f* until reaching the updating time τ to pass the information on inventory level to Stage 1. The model is provided with the actual demand for each site *j* in each time period t Δ_{jt} for all previous periods and the forecasted demand for all future periods D_{jt}. This forecast is the most recent one used for Stage 1 calculations. The following notation is used in the Stage 2 optimization model:

Indices

$i \in S = \{1, 2, ..., \mathrm{S}\}$	the set of suppliers
$j \in N = \{1, 2, ..., \mathrm{N}\}$	the set of project sites
$t \in T = \{1, 2, ..., \mathrm{T}\}$	time periods up to the end of the planning horizon, T

Input Parameters

C^2_{djt}	ordering cost for a unit procured from site *d* by site *j* at time *t*, $d,j \in N$, $t \in T$ ($/unit)
UT^2_{djt}	transportation cost from site *d* to site *j* at time *t*, $d,j \in N$, $t \in T$ ($/mile)
Q^1_{jt}	per unit cost of shortage at site *j* during *t*, $j \in N$, $t \in T$ ($/unit)
Q^2_{jt}	per units cost of holding at site *j* during time *t*, $j \in N$, $t \in T$ ($/unit)
Δ_{jt}	actual demand at site *j* at time *t*, $j \in N$, $t \in T$ (units)
H	the maximum capacity per truck type (units)
$Invcap_{jt}$	the inventory storage capacity at site *j* at *t*, $j \in N$, $t \in T$ (ft^3)

Input Parameters from Stage 1

F_{ijt}	number of units scheduled to be shipped from supplier *i* to site *j* at *t* according tolatest update of Stage 1, $i \in S$, $j \in N$, $t \in T$ (units)
D_{jt}	forecasted demand at site *j* at time *t*, $j \in N$, $t \in T$, (units)

Computed variables

I_{jt}	end of period on-hand inventory at site *j* at time *t*, $j \in N$, $t \in T$ (units)
S_{jt}	projected number of units that will be short at site *j* at time *t*, $j \in N$, $t \in T$ (units)
M^2_{djt}	number of trucks used to ship the units from site *d* to site *j* at time *t*, $d, j \in N$, $t \in T$

Decision variables

Y_{djt}	number of units transshipped from site *d* to site *j* at time *t*, $d, j \in N$, $t \in T$

(units)

With these variables, the following Stage 2 model is proposed for the PTPSMS problem:

$$Min\ \ z = \sum_{d\in N}\sum_{j\in N}\sum_{t\in T}\left(C_{djt}^{2}Y_{djt} + UT_{djt}^{2}M_{djt}^{2}\right) + \sum_{j\in N}\sum_{t\in T}\left(Q_{jt}^{1}S_{jt}\right) + \sum_{j\in N}\sum_{t\in T}\left(Q_{jt}^{2}I_{jt}\right)$$

Subject to:

$$I_{jt} = I_{j,t-1} + \sum_{i\in s}F_{ijt} + \sum_{d\in N}Y_{djt} - \sum_{b\in N}Y_{jbt} + D_{jt} + S_{jt} \quad \forall j\in N, t\in T \tag{1}$$

$$I_{jt} = I_{j,t-1} + \sum_{i\in S}F_{ijt} + \sum_{d\in N}Y_{djt} - \sum_{b\in N}Y_{jbt} + D_{j,t-1} - \Delta_{j,t-1} - D_{jt} + S_{jt} \quad \forall j\in N, t\in T \tag{2}$$

$$\sum_{b\in N}Y_{bjt} \le I_{j,t-1} + D_{j,t-1} - \Delta_{j,t-1} \quad \forall j\in N, t\in T \tag{3}$$

$$\sum_{d\in N}Y_{djt} \le Invcap_{jt} \qquad \forall j\in N, t\in T \tag{4}$$

$$Y_{djt}/H \ \le\ M^{2}_{djt} \qquad \forall\ d,j\in N, t\in T \tag{5}$$

$$I_{j,t-1} = a \qquad \forall j\in N, t\in T,\ \text{where } a=0 \text{ at } t=1 \tag{6}$$

$$Y_{djt} \ge 0 \tag{7}$$

Constraint (1) forces a material balance at time period t that corresponds to the first time in the updating planning horizon. Constraint (2) forces material balance for all periods that ranges from the time period after the first on in each updated planning horizon to the last one in the updated planning horizon by using the actual demand. Constraint (3) limits the number of units available for transshipment to the physical units on hand. Constraint (4) enforces the project site inventory capacity. Constraint (5) determines the number of trucks required based on the assumptions of full truck loads. Constraint (6) defines the inventory from the previous period and it is assumed that the planning horizon begins with zero at each site. Finally, non-negativity constraint is included in (6). Figure 3.2 is an illustration of the order events of PTPSMS at time *t.*

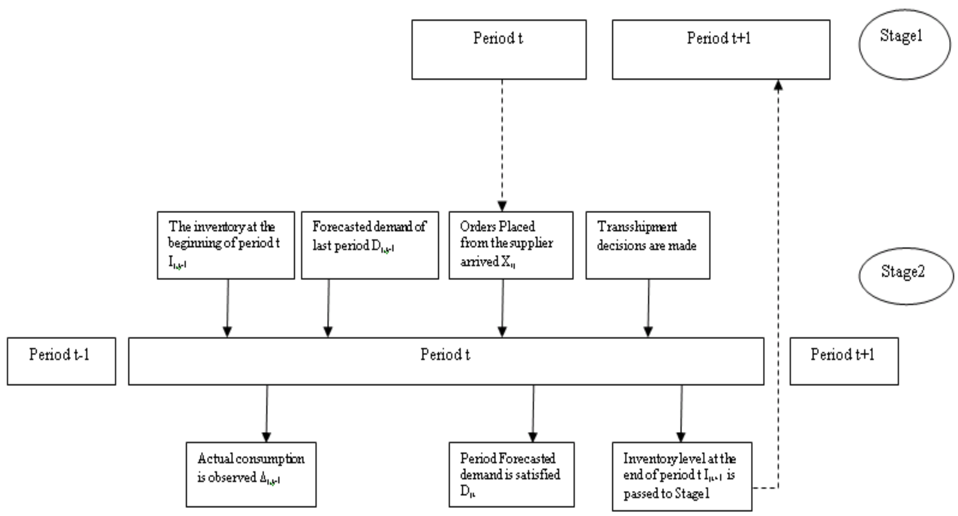


Figure 3.2: Order of events in PTPSMS

The PTPSMS problem that consists of Stage 1 and Stage 2 is a version of the generalized assignment problem which has been shown to be an NP-hard problem (Shmoys & Tardos, 1993). PTPSMS inherits the complexity of the generalized assignment problem and it is also NP-hard problem. In this research, only small problem instances are considered; however, as the number of suppliers and project sites grows, the time required to find an optimal solution will grow in a nonpolynomial fashion.

3.3. Case Study Examples

3.3.1. Experimental Design

Consider a PTPSMS problem with a single supplier producing one product type and supplying three different construction projects during a planning horizon of T=13 periods. The problem will be applied under three different scenarios that focus on exploring the impact of different time factors on the CSC. The first factor of interest is the updating period at which Stage 1 is executed and it is set at three different levels τ = (2, 4, and 6 periods). Recall, these are the time periods when information from Stage 2 is passed to Stage 1 for an update and Stage 1 updates the scheduled shipments from the supplier to the sites. The second time factor is the "transshipment period" at which Stage 2 is performed with four different control levels as summarized in Table 3.1. The "Base Control" allows no transshipments which are designated as a transshipment period (f =zero). Although no transshipment is allowed at any time between the project sites, the actual inventory levels are still passed to Stage 1 at the predetermined updating period τ. There are three "Proposed Controls," each representing different transshipment periods f: Proposed Control 1 determines if transshipments should occur every period (f=1), Proposed Control 2 every other period (f=2), and Proposed Control 3 every three periods (f=3).

Table 3.1: The control levels of the "transshipment period" factor

Controls	Transshipment Periods(*f*)
Base Control	0
Proposed Control 1	1
Proposed Control 2	2
Proposed Control 3	3

The series of interaction and combination examples between the two factors (τ, *f*) are represented in Table 3.2 to explore different aspects of the two-stage methodology. The combination factors are divided into three scenarios according to the value of the updating period τ. Each scenario includes four different combination examples as follows: (1) (τ, *f=0*), (2) (τ, *f=1*), (3) (τ, *f=2*), and (4) (τ, *f=3*).

Table 3.2: The Combination examples between the two time factors (τ, *f*)

Scenario 1(τ=2, *f*)	Scenario 2 (τ=4, *f*)	Scenario 3 (τ=6, *f*)
(2,1)	(4,1)	(6,1)
(2,2)	(4,2)	(6,2)
(2,3)	(4,3)	(6,3)
(2,0)	(4,0)	(6,0)

The following Figures 3.3 through 3.5 explain the difference between the three scenarios. Figure 3.3 represents Scenario 1 with updating period τ=2. As such, the updating of Stage 1 occurred at *t*=1, 3, 5, 7, 9, and 11. Figure 3.4 illustrates Scenario 2 with updating period τ=4 that occurred at *t*= 1, 5, and 9. Finally, Figure 3.5 shows the updating period τ=6 considered in Scenario 3 that occurred at *t*=1 and 6. In each scenario, three different transshipment frequencies can be performed. In *f*=1, transshipments can be performed every period between the updating periods. *f*=2, transshipments are only allowed to be performed at *t*=1, 3, 5, 7,9,11, and 13. And in *f*=3, transshipment occurred at *t*=1, 4, 7, 10, 13.

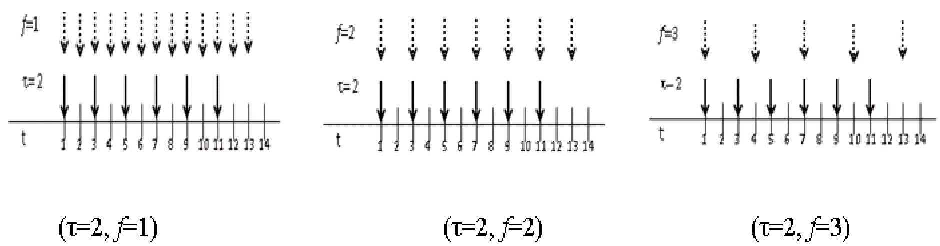


Figure 3.3: The interaction between τ=2 and different transshipment periods *f*

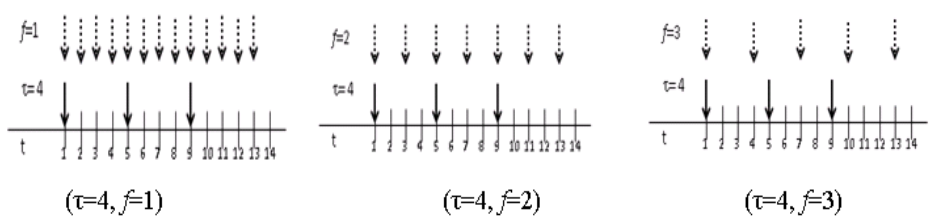


Figure 3.4: The interaction between τ=4 and different transshipment periods *f*

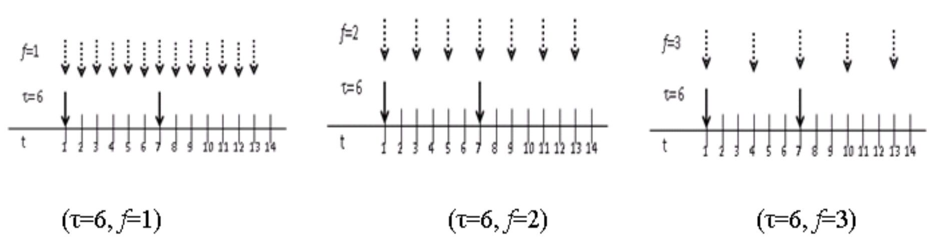


Figure 3.5: The interaction between τ=6 and different transshipment periods *f*

For all the scenarios and combination examples, the following assumptions are made:

1) The product is shipped by a fleet of identical trucks with capacity *H*=100 units/truck.

2) The number of trucks available is unlimited in both Stage 1 and Stage 2.

3) The transportation cost from the supplier to each site *j* is fixed UT_{ijt} =$1/mile. And it is the same between the project sites.

4) The cost of shortage at site *j* during time *t* is assumed to be Q^1_{jt} = $100, $50, and $75/unit for Project 1, 2, and 3, respectively.

5) The holding cost is identical for all sites *j* during all times *t* and is =$25/unit.

6) The ordering cost for a unit procured from the supplier to site *j* in Stage 1 at time *t* (C^1_{ijt} = $150/unit)

7) The ordering cost for a unit procured from site *d* to site *j* in Stage 2 at time *t* (C^2_{djt} =$100/unit).

8) During the Stage 1 updating period τ, each construction project coordinator will submit new updated demands for the coming *t* periods. That is the cost to expedite or delay an order scheduled for delivery in the next period is PC_t $100/unit, $75/unit for scheduled delivery two periods in the future, $50/unit for three periods in the future, and $25/unit for four periods in the future. The update cost is assumed to be zero for any period more than 4 periods.

9) The supplier's total capacity in each time period is reflected in Table 3.3.

Table 3.3: The capacity of the supplier in each period of time

Capacity	1	2	3	4	5	6	7	8	9	10	11	12	13
Supplier	300	600	600	600	300	300	300	300	600	600	600	300	300

10) In all of the scenarios in this case study, the initial forecasted demand of the single product is assumed to be equal to 100 units for each project over each time period (t=1 to t=12) and zero at t=13.

12) The actual demands presented in Table 3.4 reflect the fact that actual demand changes as follows:

- A request is made to accelerate Project 1 by 30% during two different intervals (t=4 to t=7) and (t=12).
- There is a delay at Project 2 by 50% for five periods (t=6 to t=10).
- Project 3 is completely stopped from period (t= 6) until the end of the planning horizon (t=13).

Table 3.4: The actual demand of each project site over the planning time horizon

	1	2	3	4	5	6	7	8	9	10	11	12	13
Project 1	90	90	90	150	150	150	150	90	90	100	100	150	0
Project 2	90	90	90	90	90	50	50	50	50	50	100	100	0
Project 3	90	90	90	90	90	0	0	0	0	0	0	0	0

To illustrate the flow of information in all the scenarios associated with this case study, consider Figure 3.6. This figure depicts the flow of information between Stage 1 and Stage 2 for a situation in which Stage 1 is updated every 4 periods (τ = 4) and transshipment period is one (f=1).

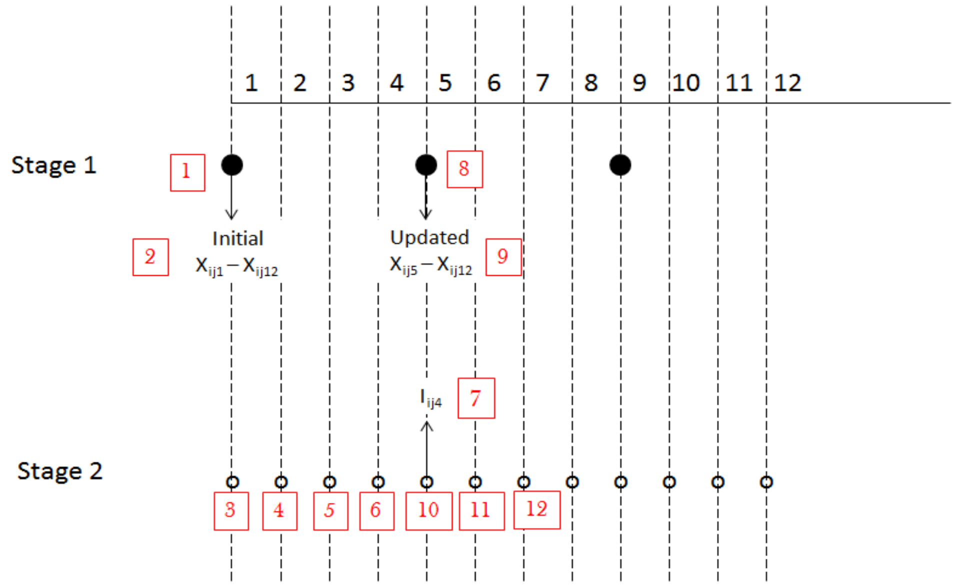


Figure 3.6: The basic steps of solving PTPSMS

The numbers in the figure denote actions that are described below:

1) Execute Stage 1 model with the Initial planning demand and set $I_{j0}=0$ for all j. After the optimal solution (X_{ijt}) is found for the entire time horizon (t=1 to 13). Set $F_{ijt}=X_{ijt}$ for all i, j, and t for use during the next update of Stage 1.
2) Pass all X's to Stage 2.
3) Execute Stage 2 model with forecasts for all future demands.
4) Execute Stage 2 model with actual demand from period 1 and forecasts for future.
5) Execute Stage 2 model with actual demand from periods 1 and 2, forecasts for future.
6) Execute Stage 2 model with actual demand from periods 1, 2, and 3, forecasts for future.
7) Update the inventory at the end of period 4 for all sites and pass to Stage 1.
8) Execute Stage 1 model with all constraints and inventories from Stage 2.

9) Pass all X’s to Stage 2.

10) Execute Stage 2 model with forecasts for all future demands.

11) Execute Stage 2 model with actual demand for period 5 and forecasts for future.

12) Execute Stage 2 model with actual demand for periods 5 and 6 and forecasts for future.

This process repeats for the entire planning horizon.

The results of the case study examples over the different scenarios will be discussed in the next section; however, it should be pointed out that the case studies are used to illustrate how the methodology can be applied and the types of results that can be generated to better control the material flow of the CSC. As such, the results of the case study are not applicable across all construction projects because the exact results in these cases are an artifact of the numbers used for costs and distance and these will certainly vary from project to project. On the other hand, the numbers in the case studies are realistic so the information is not necessarily without merit or value. For example, the general trends found in these results might well point a decision maker towards good ideas that should be explored more closely for a particular project to improve the CSC. This would allow him or her to avoid the time-consuming effort trying to find a few promising areas for closer investigation.

3.3.2. Results of the Case Study Examples

The proposed methodology is now solved for the scenarios indicated previously in Table 3.2 using ILOG OPL Development Studio version 5.5 and tested on a single core of a SONY OptiPlex 980 computer running the Windows 7 Enterprise 64 bit operating system with an Intel(R) Core(TM) i5 CPU860@ 2.80GHz, and 8GB RAM. The results are analyzed and discussed below:

Scenario 1: This scenario considers a two updating period, where Stage 1 decisions are made based on an updated forecast every two periods. That is, feedback from Stage 2 on the actual demand, the updated forecast, and the inventory level of each project site is provided to Stage 1 every two periods (*t*=1,3,5,7,9, and 11). We will study the impact of different Stage 2 control levels represented by how frequent the transshipment process is allowed among the construction projects. The results of the four examples with transshipment frequencies (*f*= 1, 2, 3, 0) are represented in Table 3.5. To facilitate discussing and analyzing the control examples, figures are constructed to show the material flow represented by the initial inventory (carried from the previous period), the transportation from the supplier to the project sites, and the transshipments between the project sites.

Table 3.5: Comparison between the results of the four control examples for (τ=2)

Controls	Total Cost ($)	Total Inventory level (units)	Total Number of Shortage (units)	Total Number of transshipment (units)
(τ=2,*f*=1)	2,199,549	870	20	30
(τ=2,*f*=2)	2,206,043	890	40	10
(τ=2,*f*=3)	2,210,290	900	50	0
(τ=2,*f*=0)	2,210,290	900	50	0

We observe that the savings increased as the transshipment frequency increased Table 3.6 represents the savings associated with adding transshipment frequency.

Table 3.6: The Savings in the total cost of adding transshipment frequency in Scenario 1

	f=1	*f*=2	*f*=3
f=2	0.3%	-	-
f=3	0.5%	0.2%	-
f=0	0.5%	0.2%	0%

Based on the results of our case study, we observe that there is no savings of adding transshipment frequency from *f*=0 to *f*=3. This happened here because there were no transshipments during the time periods where transshipments are allowed in *f*=3 which make it responds as *f*=0. This is obvious upon reflection. When the transshipment frequency exceeds the updating period, no transshipments would be considered in at least some of the intervals between Stage 1 updates. Even when transshipment would be possible, it would quite possibly not be needed because the Stage 1 update would have adjusted shipments from the supplier. This is only important to note because, in practice, Stage 1 and 2 decisions are often made independently and this situation can occur. Because there is no saving in *f*=3, the consideration will be either *f*=1 or *f*=2 according to their savings.

There is a saving in the total cost from *f*=0 to *f*=2 by 0.2%. The reason of this is because the total inventory level and the total number of shortages decreased as the transshipment frequency increased from *f*=0 to *f*=2.

To facilitate discussing the savings of different updating and transshipment periods, the following material inflow figures will be illustrated to show the site inventory at the beginning of each time period that is equal to:

Site inventory of project *j* = Initial inventory of Project *j* from the previous period + Shipments from supplier + Shipments from project *d*

Figures 3.7 through 3.10 show the material flow of Project 1 in Scenario 1 under the four transshipment frequencies. Recall that in *f*=0, transshipments are not allowed to be performed, and in *f*=2, transshipments are allowed to be performed six times during the planning horizon at *t*=3, 5, 7,9,11, and 13. Notice in Figure 3.8, for example, at *t*=5, transshipment are allowed to be performed when *f*=2, with 10 units from Project 2 to Project 1. However, in Figure 3.10, at *t*=5, transshipments are forbidden for *f*=0, this results to increase the number of shortage in Project 1 by 10 units because of no transshipments and decrease the inventory level at the end of planning horizon from 900 units in Figure 3.10 to 890 units in Figured 3.8.Thus, the total cost at *t*=5 decreased from $1500 in *f*=0 to $1253 in *f*=2.

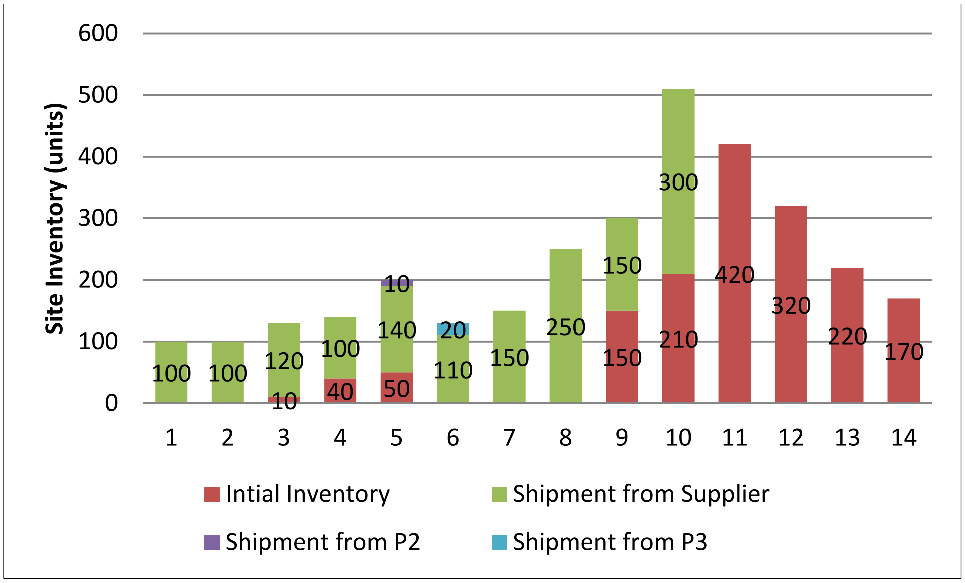


Figure 3.7: Material flow for Project 1 with (τ=2, *f*=1)

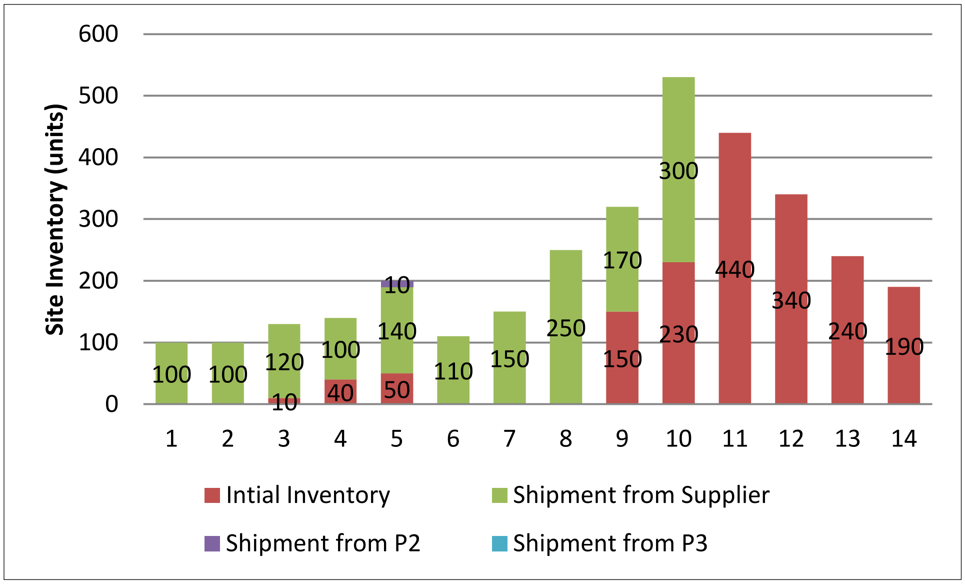


Figure 3.8: Material inflow for Project 1 with (τ=2, *f*=2)

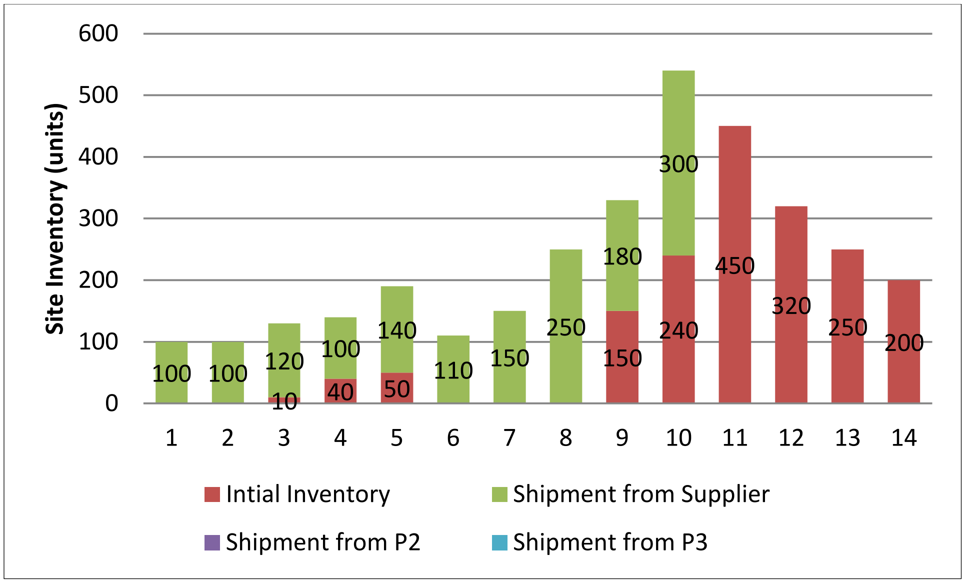


Figure 3.9: Material inflow for Project 1 with (τ=2, *f*=3)

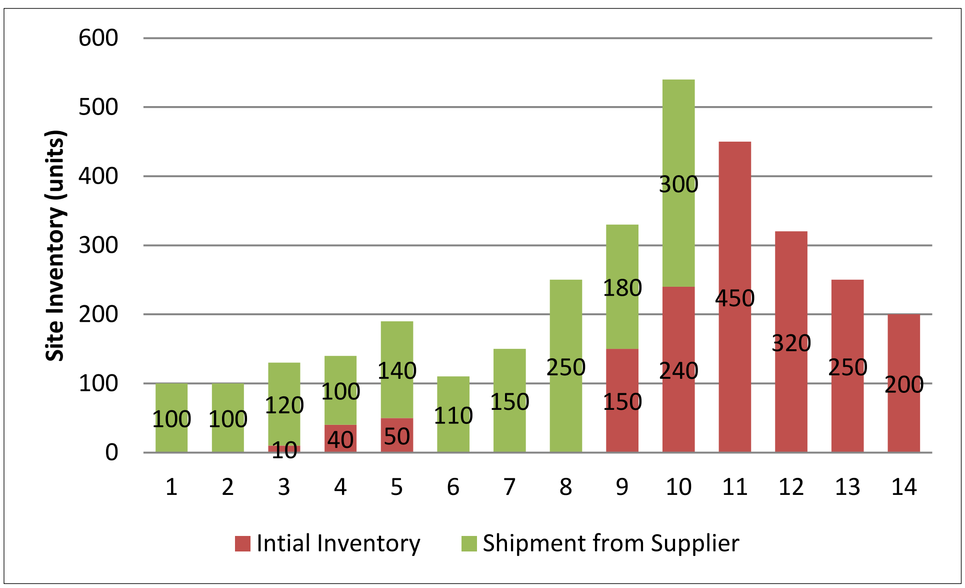


Figure 3.10: Material inflow for Project 1 with (τ=2, *f*=0)

The savings from no transshipment *f*=0 to *f*=1 that occurs every period is 0 .5% which is more than from *f*=0 to *f*=2 with 0.2%. The reason of this is, by increasing the transshipment frequency the amount of units being transshipped will increase and will positively affect the inventory level and the number of shortages. In Figure 3.7 transshipments occurred at *t*=5 with 10 units from Project 2 to Project 1 and at *t*=6 with 20 units from Project 3 to Project 2 which reduced the number of shortage at t=5 from 10 units to zero and at *t*=6 from 40 units to 20 units.

Finally, The savings from *f*=2 to *f*=1 is 0.3% because in *f*=2, as shown in Figure 3.8, transshipments occurred only at *t*=5 with 10 units from Project 2 to Project 1. However in *f*=1, as shown in Figure 3.7, transshipments occurred at *t*=5 with 10 units from Project 2 and at *t*=6 with 20 units from Project 3 to Project 1. The transshipments in *f*=1 reduced the shortage of Project 1 at *t*=6 from 40 units to 20 units. As such, the total cost at *t*=6 decreased from $4500 in *f*=2 to $4006 in *f*=1.

Based on the previous analysis of the four different combination examples based on their savings in total cost, *f*=1 is the optimal transshipment frequency with the minimum total cost and maximum reduction in the total cost compared with base example (*f*=0). Figure 3.11 compares the total cost of the four transshipment frequencies.

Figures 3.12 compares the total inventory level at the end of the planning horizon and the total number of shortages during the entire planning horizon. It shows that *f*=1 has the lowest total inventory level with a reduction from 900 units to 870 units by 3% compared with *f*=0. Moreover, *f*=1 has the minimum total number of shortages and the most reduction by 60 %. The reason for this is because by increasing the transshipment practices, the ability of matching the supply and demand increases which will balance the inventory and the shortage.

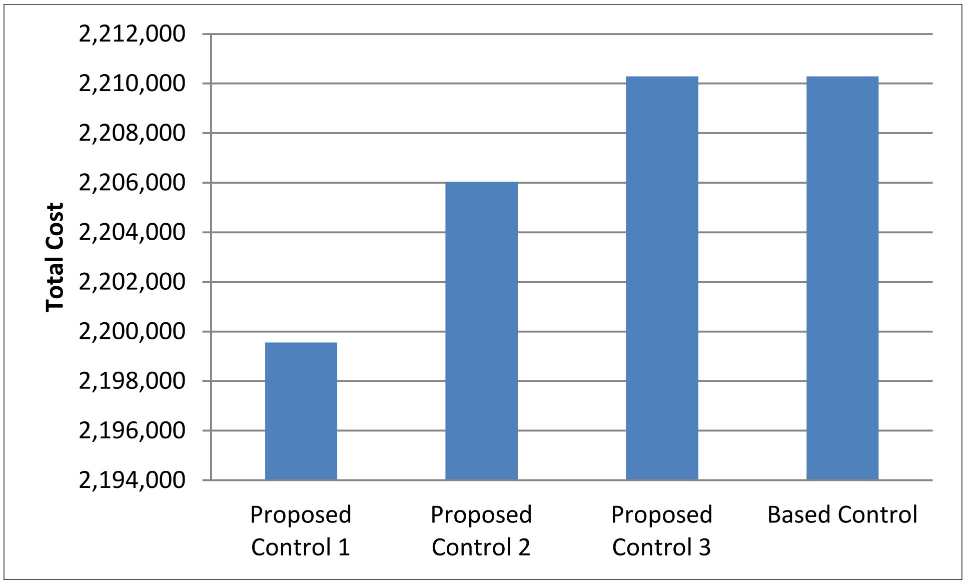


Figure 3.11: Total cost of Scenario 1 under the four control examples

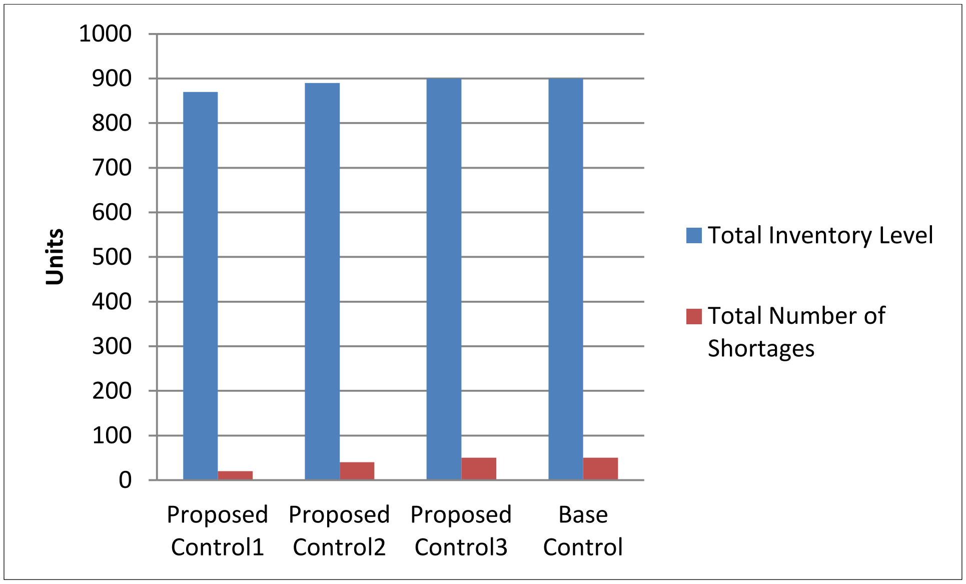
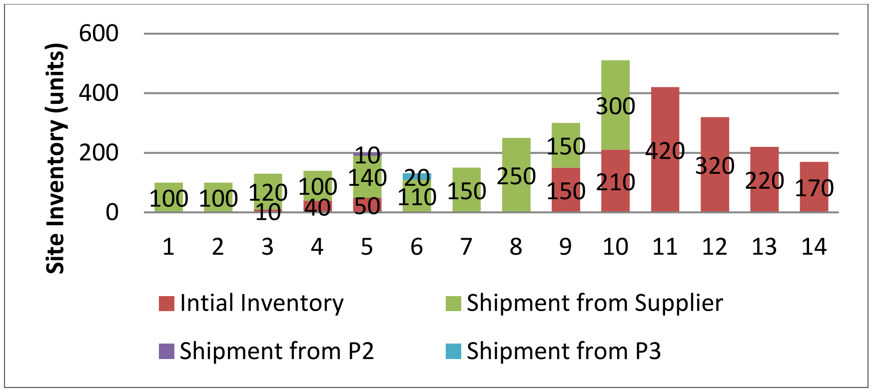


Figure 3.12: Total inventory level and number of shortage of Scenario 1 under the four control examples

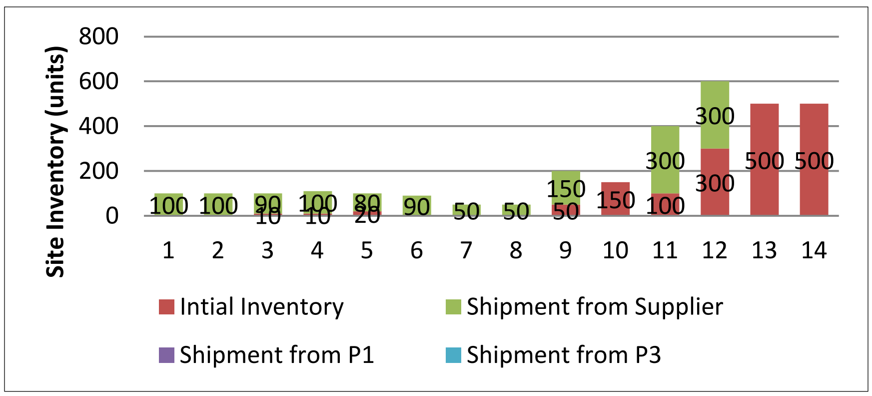
Recall that the main concept of the two-stage methodology is that each stage is operating and acting independently. The only cooperation between them is passing the information among each other. So, in order to have the most adequate information, it is important to have the best combination at which each stage is run which will lead to the best interacting between the two stages and to the most reduction in the total cost of the CSC.

At this point it is noted that the frequency period of transshipment can be shorter than, longer than, or equal to the updating period of Stage 1 (i.e., $f < \tau$ or $f \geq \tau$). For example (τ=2, f=3), means Stage 2 has to pass the information to Stage 1 every other period, however; transshipments are only allowed every third period. Hence, for example, transshipments are only allowed after the first Stage 1 update. More comprehensively, in this example Stage 1 will update at periods 1, 3, 5, 7, 9, and 11 while transshipments can occur at periods 1, 4, 7, 10, and 13. So, at time period t=3, Stage 2 passes information to Stage 1 about inventory levels carried from the previous period t=2 and the updated forecasted demand, This can be actually counterproductive since it does not provide an adequate picture of the CSC status because no transshipments were allowed between the project sites at time periods t=1 and t=2 but one is possible before the next update. As a result, the updated forecast demand may be lead to changes in future orders that would not need to occur if better coordination were present. The lack of coordination may increase the (1) shortage cost when the supplier limited production capacity could not satisfy the update (2) the updating cost (expedite or delay) by increasing the forecasted demand of a project under shortage and decrease the other one with extra inventory, where these extra costs can be avoided by transshipment. However, this strategy might be helpful if the lead time from supplier to site is long but might be detrimental when lead time is short as in our case study. These consequences of the lack of coordination as a result of long frequency transshipment period can be reduced by increasing transshipping between Stage 1 updates even if the amount and the number of transshipments are small. For example, the difference between f=2 and f=3 is that f=2 allows transshipment just once at t=5 with only 10 units, even though, this has a nice impact on decreasing the total cost by 0.2%.

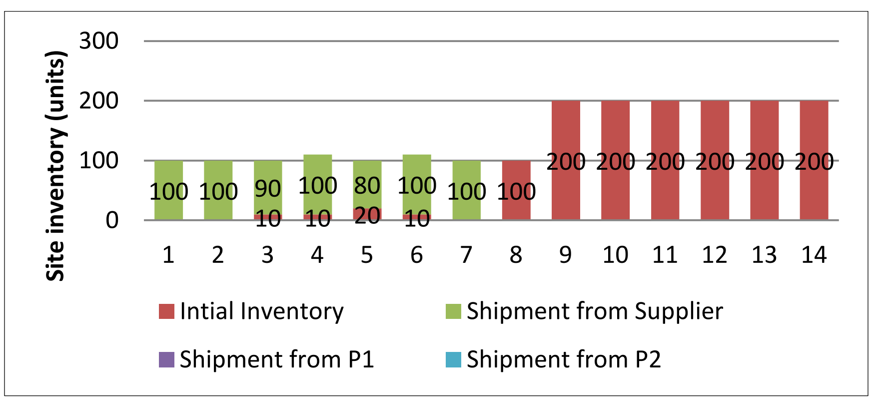
For a better understating of the material flow associated with the optimal control example (τ=2, f=1), Figure 3.13 depicted the material inflow of each project graphically throughout the time horizon. The material inflow of each project consists of three parts: (1) the initial inventory at each project that is the inventory carried from the last period, (2) the input from the supplier (from Stage 1) that is the scheduled shipments received by each project at the beginning of the time period, and (3) the transshipments received from any of the other two projects. Note that the scheduled shipments from the supplier are allowed to be updated in Stage 1 in the time periods (t=3, 5, 7, 9, 11). In those periods, Stage 2 passes information about the actual inventory level to Stage 1 and along with the requested forecasted demand for the next periods.



Project 1



Project 2



Project 3

Figure 3.13: Material flow for each Project under (τ=2, f=1)

At *t*=3, *t*=5, *t*=7, *t*=9 and *t*=11 are the updating time periods in Stage 1. The initial inventory carried from the previous period and the updated forecasted demand (this is the changing in the forecasted demand either expedite or delay that is requested by the project managers based on the transshipment practices in Stage 2 and on their decisions) entered Stage 1 for the update. The optimal solution of the demand allocation is at each updating period is:

- At *t*=3, the initial inventory at all the project sites is 10 units. Although there is no any update in the forecasted demand , the inventory at both project 2 and project 3 will be transferred and stored at Project 1 as a preventive strategy against demand variation because it has the highest shortage cost. The optimal solution increased the scheduled demand of Project 1 at t=3 from 100 units to 120 units, and decreased the one of Project 2 and Project 3 from 100 units to 90 units.
- At *t*=5, the initial inventory level is (50, 20, 20) for Project 1, Project 2, and Project 3 respectively. The updated forecasted demand requested to expedite Project 1 from 100 units to 150 units. The optimal solution transferred a total of 40 units from Project 2 and Project 3 equally because both of them have inventory at their site and they do not request any update.
- At *t*=7, the initial inventory at all the project sites is zero and the updated forecasted demand requests to expedite only Project 1 from 100 units to 150 units. We observe that the optimal solution transferred these 50 units from Project 2 (because it has the lowest shortage cost) to fill up the expediting of Project 1.

- At *t*=9, the initial inventory is (150, 50, 200) for Project 1, Project 2, and Project 3 respectively. The updated forecasted demand requested to delay Project 2 from 100 units to 50 units and Project 3 is shut down. The optimal solution did not consider these delay units and transferred them to both Project 1 and Project 2 to build a buffer at both of them.
- At *t*=11, the initial inventory is (420, 100, 200) for Project 1, Project 2, and Project 3 respectively. The updated forecasted demand requested to keep Project 3 shut down. The delayed units are transferred to Project 2 as a hedge because the inventory level at Project 1 is already high.

The transshipment frequency in this Proposed Control 1 is (*f*=1). This means the transshipment can occur at any time when it's required. We observe that Project 1 receives the most benefits from transshipments because it experienced expedited demand. Transshipments are received from either Project 2 or Project 3 based on their inventory, shortage cost, and forecasted demand. Notice that transshipments occurred at *t*=5 and *t*=6. At *t*=5, the initial inventory of both Project 2 and Project 3 is the same, so units are transshipped from Project 2 because it has lower shortage cost. At *t*=6, because the initial inventory of Project 2 is zero and units are transshipped from Project 3. Table 3.7 provides the precise material flows for Proposed Control 1.

Table 3.7: The material flow for (τ=2, *f*=1)

Time	STAGE 1			STAGE 2							
	Scheduled Shipment			Trans. Trip Route	NO. of Trans.	Inv.Level			Short. Level		
	P1	P2	P3			P1	P2	P3	P1	P2	P3
1	100	100	100	___	___	0	0	0	0	0	0
2	100	100	100	___	___	10	10	10	0	0	0
3	120	90	90	___	___	40	10	10	0	0	0
4	100	100	100	___	___	50	20	20	0	0	0
5	150	70	80	P2 to P1	10	0	0	10	0	0	0
6	150^{+}	50^{-}	100	P3 to P1	20	0	0	0	20	0	0
7	150^{+}	50^{-}	100	___	___	0	10	100	0	0	0
8	100	200^{+}	0	___	___	150	50	200	0	0	0
9	100	0	200	___	___	210	150	200	0	0	0
10	0	300	0	___	___	420	100	200	0	0	0
11	200^{+}	100^{+}	0	___	___	330	300	200	0	0	0
12	0	300	0	___	___	220	500	200	0	0	0
13	0	0	0	___	___	170	500	200	0	0	0

t=1 Stage 1: All the shipments are based on the original plan demand that is equal to 100.

t=1 Stage 2: The scheduled shipments from Stage 1 at *t*=1(100) is compared with the forecasted demand at *t*=1 (100) and the actual demand at *t*=0 (zero), which results in inventory of zero in all the project sites by the end of *t*=1.

t=2	Stage 2:	The scheduled shipments from Stage 1 at *t*=2 (100) is compared with the forecasted demand at *t*=2 (100). The forecasted demand at *t*=1 (100) is compared with actual demand at *t*=1 (90), which results in inventory of 10 in all the project sites by the end of *t*=2.
**t*=3	Stage 1:	Stage 2 passes actual inventory level of the end of t=2 (10) and the updated forecasted demand requested by the project manager to Stage 1. There is no update at any of the project sites. However, the inventory at both project 2 and project 3 will be transferred and stored at project 1 as a preventive strategy against demand variation because it has the highest shortage cost.
t=3	Stage2:	By comparing the input with the output, the scheduled shipments from Stage 1 at *t*=3and the inventory from *t*=2 are compared with the forecasted demand at *t*=3 (100). Also, the forecasted demand at *t*=2 (100) is compared with the actual demand at t=2 that is (90, 90, 90) for project 1, 2, and 3 respectively. This results in inventory of (40, 10, 10) in projects 1,2, and3.
t=4	Stage2:	The scheduled shipments from Stage 1 at *t*=4(100) and the from *t*=3 compared with the forecasted demand at *t*=4 (100). The forecasted demand at *t*=3 (100) is compared with the actual demand at *t*=3 that is (90, 90, 90) for project 1, 2, and 3 respectively. This results in inventory (50, 20, 20).
**t*=5	Stage1:	Stage 2 passes actual inventory of *t*=4 and the updated forecasted

demand requested by the

project manager to Stage 1. The updated forecasted demand of Project 1 shows expediting at *t*=5 and *t*=6 with 50 units. At time period 5, both projects 2 and 3 will transfer their inventory to project 1(20 units). However, this will not fill up the required update requested from project 1, the optimal solution keeps project 1 with the highest shortage cost to be under shortage instead of transferring more units from project 2 or three where they have lower shortage cost, that is because their forecasted demands show that everything will be on schedule. At *t*=6, the on hand inventory at project 2 and 3 is assumed to be zero, project 2 is the one that will transfer only 10 units to project 1 even this is not enough to fill up the shortages because the forecasted demand is on schedule.

t=5 Stage 2: The scheduled shipments from Stage 1 at *t*=5 (140, 80, 80) for project1, 2, and 3 respectively and the inventory of all projects from *t*=4 (50, 20, 20) are compared with the forecasted demand at t=5(150, 100,100). The forecasted demand at *t*=4 (100) is compared with the actual demand at *t*=4 that is (90, 90, 90) for project 1, 2, and 3 respectively. This results in shortage of 10 units in project 1 and inventory of 10 in projects2 and 3. Transshipment will occur from project 2 to project1 because it has lower shortage cost.

t=6 Stage 2: The scheduled shipments from Stage 1 at *t*=6 (110, 90,100) for project1, 2, and 3 respectively and the inventory of all projects from *t*=5 (0) are compared with the forecasted demand at *t*=6(150, 100,100). The forecasted demand at *t*=5 (150, 100, 100) for project 1, 2, and 3 is compared with the actual demand at *t*=5 that is (150, 90, 90) for project 1, 2, and 3 respectively. This results in shortage of 40 units in project 1 and inventory of 20 in projects3. Transshipment will occur from project 3 to project1.

**t*=7 Stage 1: Stage 2 passes actual inventory of *t*=7 and the updated forecasted demand requested by the project manager to Stage 1. The updated forecasted demand of Project 2 shows to expedite by 50 units at *t*=7 and delay at *t*=8 with 50 units. Project 3 shows a delay with 100 units for *t*=8 because of shutdown. The optimal solution transfer the expedited units totally from project 2 because of its lowest shortage cost used both project 1 as a buffer against unexpected demand variability.

t=7 Stage 2: The scheduled shipments from Stage 1 at *t*=7(150, 50,100) for project 1, 2, and 3 respectively and the inventory of project 3 from *t*=6 (10) are compared with the forecasted demand at *t*=7 (150, 100,100). The forecasted demand at *t*=6 (150,100,100) for project 1, 2, and 3 is compared with the actual demand at *t*=6 that is (150, 50, 0) for project 1, 2, and 3 respectively. This results in inventory of 100 units in project 3 because of the delay.

This process will repeat for the entire time horizon.

Scenario 2: In this scenario, the updating period of Stage 1 is every 4 periods and Stage 2 is allowed to direct transshipments at different transshipment periods. From Table 3.8, we observe a decrease in total cost, inventory level, and number of shortages as the transshipment frequency increased. Table 3.9 represents the savings in the total cost associated with adding transshipment frequency. According to the results of our case study, we noticed that considering the transshipment period (f=3) has the same result as in (f=0) based on the results of our case study. This happened because there were no transshipments during the time periods where transshipments are allowed in f=3 which make is respond as f=0.

Table 3.8: Comparison between the results of the four control examples for (τ=4)

Controls	Total Cost ($)	Total Inventory Level (units)	Total Number of Shortage (units)	Total Number of transshipment (units)
(τ=4,f=1)	1,325,139	870	20	30
(τ=4,f=2)	1,331,633	890	40	10
(τ=4,f=3)	1,334,880	900	50	0
(τ=4,f=0)	1,334,880	900	50	0

Table 3.9: The Savings in the total cost of adding transshipment frequency in Scenario 2

	f=1	*f*=2	*f*=3
f=2	0.5%	-	-
f=3	0.73%	0.24%	-
f=0	0.73%	0.24%	0%

We observe that the savings from *f*=0 to *f*=2 is 0.24% because the transshipment practices in *f*=2 matches the supply-demand of the CSC which decreased the total inventory level and the total number of shortages. Figures 3.14 through 3.17 show the material flow of each project site in Scenario 2 under different transshipment frequencies. It is noticed from Figure 3.14 at *t*=5, Project 1 received 10 units from Project 2 that fulfills its expediting demand and overcomes shortage. This reduced the total cost at *t*=5 from $1500 to $1253 or by 16% compared with *f*=0.

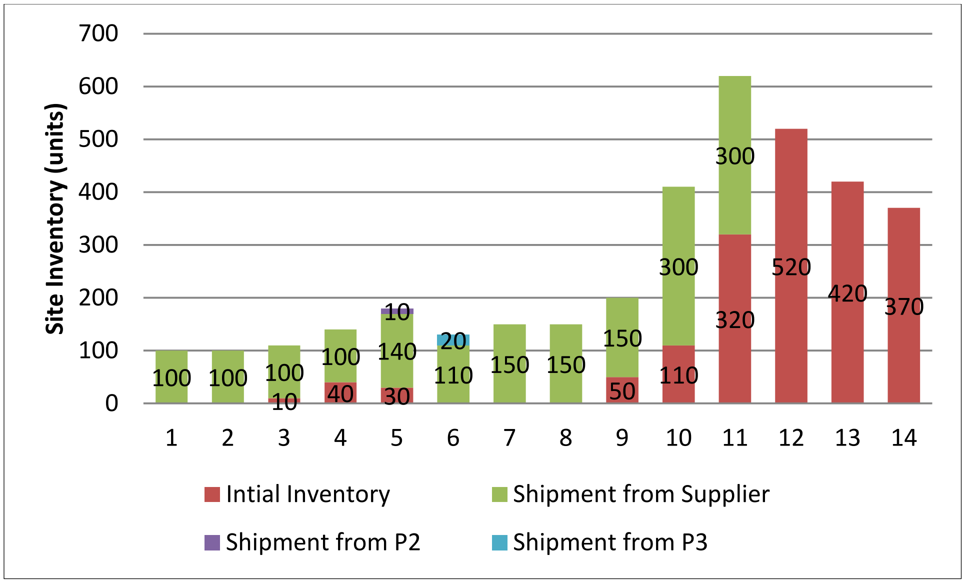


Figure 3.14: Material inflow for Project 1 with (τ=4, *f*=1)

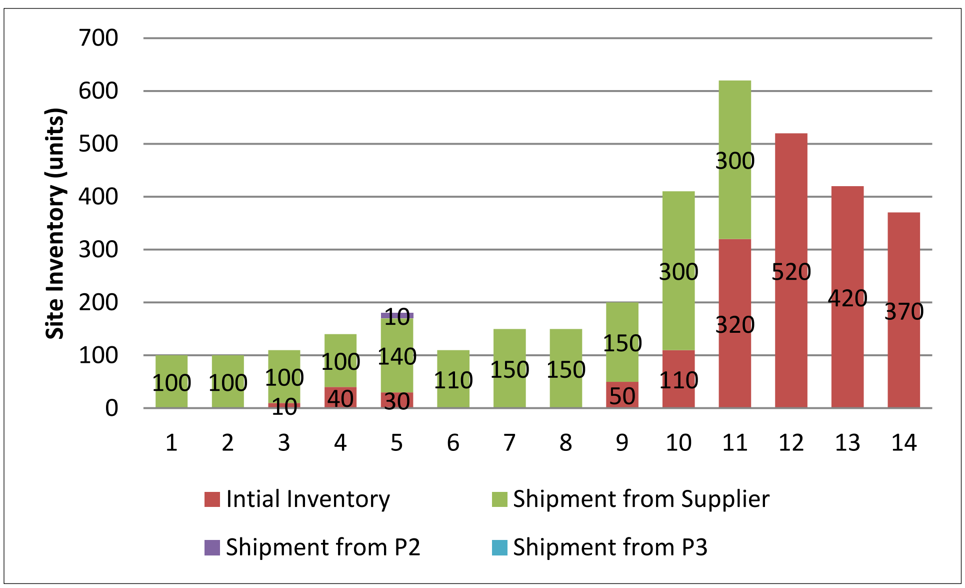


Figure 3.15: Material inflow for Project 1 with (τ=4, *f*=2)

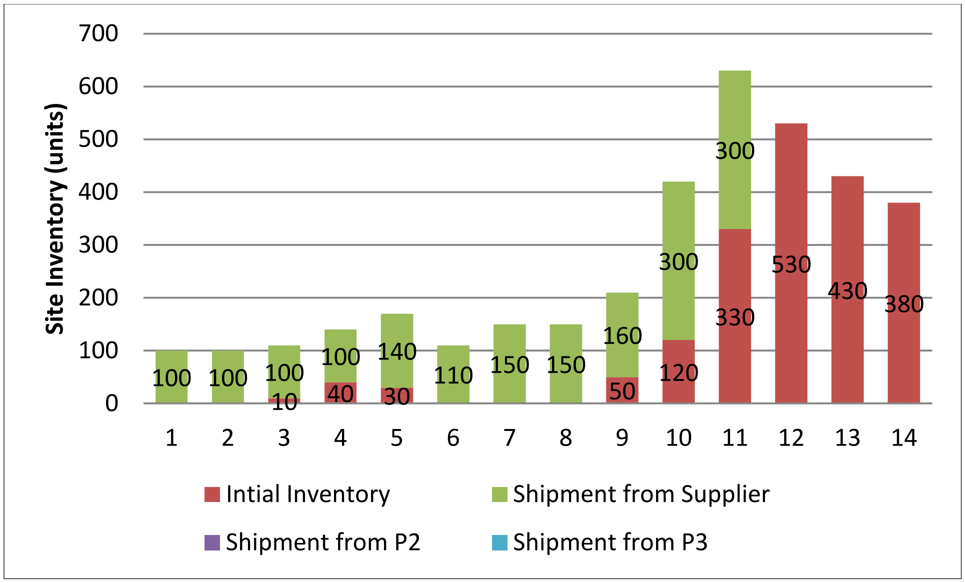


Figure 3.16: Material inflow for Project 1 with (τ=4, *f*=3)

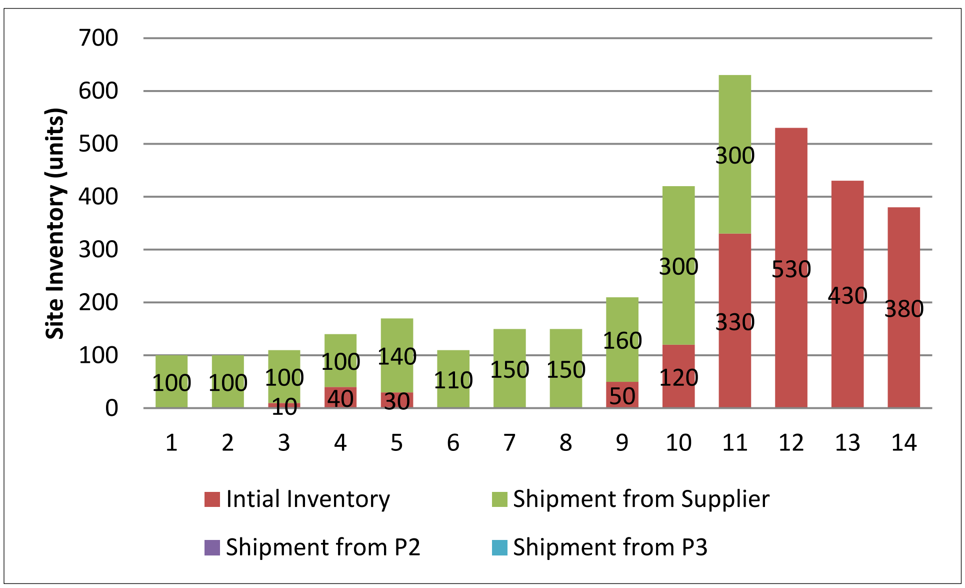


Figure 3.17: Material inflow for Project 1 with (τ=4, *f*=0)

The savings from *f*=2 to *f*=1 is 0.5%. By Comparing Figure 3.14 and Figure 3.15, we observe that both of them have transshipments from Project 2 at t=5. However, in Figure 3.14 with *f*=1, additional 20 units transshipped from Project 3 to Project 1 at *t*=6. This reduced the total cost at *t*=6 from $4750 in *f*=2 to $4500 in *f*=1or by 5%. The increasing in the total cost at *t*=6 when *f*=2 is because transshipments at this time period are forbidden, the shortages in Project 1 are not satisfied.

Also we observe that the savings from *f*=0 to *f*=1 is 0 .73% that is more than the savings from *f*=0 to *f*=2 which is 0.24% because the higher is the transshipment frequency (*f*=1), the more units are allowed to be transshipped in CSC. In *f*=1, the total number of transshipment units is 30 units and in *f*=2, the total number of transshipment units is 10 units. As the number of transshipment increased, the total inventory cost at the end of the planning horizon is 870 units lower the total inventory units of 900 units in *f*=2. So, the extra aggravation of transshipping every period is worth compared with every other period.

Figure 3.18 shows the total cost of the updating period τ=4 over different transshipment periods where (τ=4, *f*=1) is the optimal solution with the minimum total cost. Moreover, Figures 3.19 shows the reduction in the inventory level and the number of shortage units by 3.3% and 60% respectively from (τ=4, *f*=0) to (τ=4, *f*=1).

In the closing of this discussion about Scenario 2, we conclude that when the transshipment frequency or the number of time periods at which transshipment could occur is low and very close to the updating period, transshipments would quite possibly not be needed because the Stage 1 update would have adjusted shipments from the supplier. However, in practice this situation can occur because Stage 1 and 2 decisions are often made independently. In other words, if the updating period in Stage 1 and the transshipment period of Stage 2 have similar durations, the effectiveness of transshipments is reduced. For example, in (τ=4, *f*=3), information is passed from Stage 2 to Stage 1 every four periods (*t*= 5 and 9) while transshipments are allowed in *t*= 4, 7, 10, and 13. In this example, there is only one time period, *t*=7, that allows transshipments to occur between the updating periods *t*=5 and *t*=9. Hence, if no transshipments occur at *t*=7, there is no other chance for the CSC to balance the supply and demand in any other period from Stage 2.

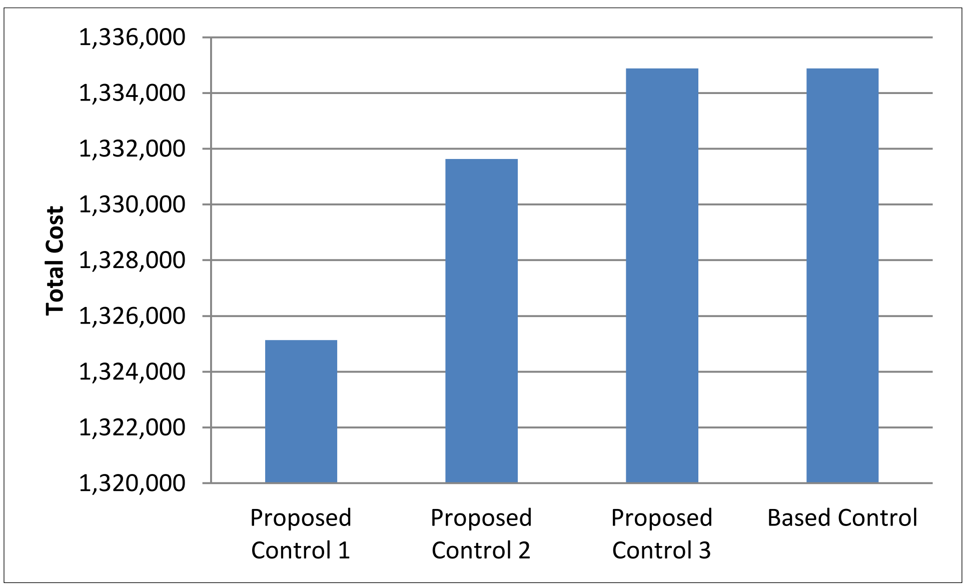


Figure 3.18: Total cost of τ=4 for 4 control examples with different transshipment periods

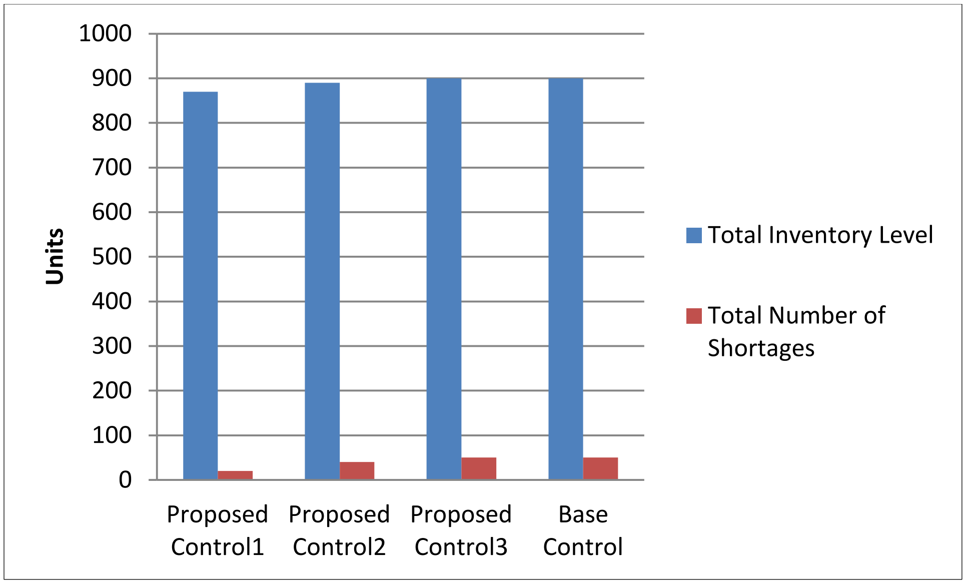


Figure 3.19: Total inventory level and number of shortage of τ=4 for 4 control examples

Scenario 3: This scenario extends the updating period to six periods. Table 3.10 shows the impact of the different transshipment period examples (*f*= 1,2,3,0) at Stage 2 on total cost and the other criteria - total inventory level at the end of the planning horizon, total number of units that are short, and the total number of units transshipped during the entire planning horizon. We observe that the savings increased as the transshipment frequency increased. Table 3.11 represents the savings associated with adding transshipment frequency.

Table 3.10: Comparison between the results of the four control examples for (τ=6)

Controls	Total Cost ($)	Total Inventory level (units)	Total Number of Shortage (units)	Total Number of transshipment (units)
(τ=6,*f*=1)	1,010,943	870	20	110
(τ=6,*f*=2)	1,015,434	900	50	80
(τ=6,*f*=3)	1,027,169	920	100	30
(τ=6,*f*=0)	1,027,910	950	130	0

Table 3.11: The savings in the total cost of adding transshipment frequency for (τ=6)

	f=1	*f*=2	*f*=3
f=2	0.44%	-	-
f=3	1.6%	1.14%	-
f=0	1.7%	1.2%	0.1%

The saving from *f*=0 to *f*=3 is 0.1%, very low compared with the savings from *f*=0 to *f*=2 that is 1.2% and the savings from *f*=0 to *f*=11.7% because the number of periods where transshipment is allowed becomes fewer and this will affect the amount of the units being transshipped, the total inventory level, and the number of shortage units. According to actual and forecasted demand in our case study example, when there is no transshipment (*f*=0), shortages occurred in Project 1 with 50 units at the end of *t*=5, *t*=6, and 30 units at the end of the planning horizon (*t*=13). In *f*=3, transshipments are only allowed at *t*=4, *t*=7, *t*=10, and *t*=13. Notice from Figure 3.22 at *t*=13, a transshipment with 30 units occurred from Project 3 to Project 1. This reduced total cost at *t*=13 from

$26,750 to $26,009 or by 3% because the number of shortage decreased from 30 units to zero and the inventory level from 950 units to 920 units. In *f*=2, transshipments are allowed at *t*=3, *t*=5, *t*=7, *t*=9, *t*=11, and *t*=13. So, from Figure 3.21 we observe that in addition to the transshipment at *t*=13, transshipments will be performed at *t*=5 from Project 2 to Project 1 with 20 units and from Project 3 to Project 1 with 30 units. This reduced the shortage in Project 1 at *t*=5 from 50 units to zero, the inventory level from 60 units to 10 units, and the total cost at *t*=5 reduced from $6500 to $5265 or by 19%. Finally, in *f*=1, transshipments are allowed at every period of the planning horizon. As such, notice from Figure 3.20 that in addition to the transshipments that occurred in *f*=3 at *t*=13 and in *f*=2 at *t*=5 and *t*=13, there are transshipments at *t*=6 from Project 2 to Project 1 with 20 units and from Project 3 to Project 1 by 10 units. This reduced the shortage at *t*=6 from 50 units to 20 units, the inventory level from 80 units to zero, and the total cost at *t*=6 reduced from $7000 in *f*=0 to $5009 in *f*=3or by 28.4%.

The savings of adding transshipments from *f*=3 to *f*=1 is 1.6% which is more than the savings from *f*=3 to *f*=2 that is 1.14%. The reason of this is in *f*=3 there are shortages of 50 units at both *t*=5 and *t*=6 because transshipments are not allowed in these time periods. With *f*=2, transshipments can only be performed at *t*=5 and the total cost reduced from $6500 in *f*=3 to $5265 in *f*=2or by 19%. However, with *f*=1, transshipment occurred at both *t*=5 and *t*=6 and the total cost at these two periods reduced from $13,500 to $10,274 or by 24%.

Finally, there is saving of adding transshipment frequency from *f*=2 to *f*=1 by 0.44%. This reduction is a result of having transshipment at *t*=5, t=6, and *t*=13 in *f*=1 with a total of 110 units instead of being only at t=5 and t=13 in f=2 with a total of 80 units. The total inventory level at the end of the planning horizon reduced from 900 units to 870 units and the total number of shortages reduced from 100 units to 50 units.

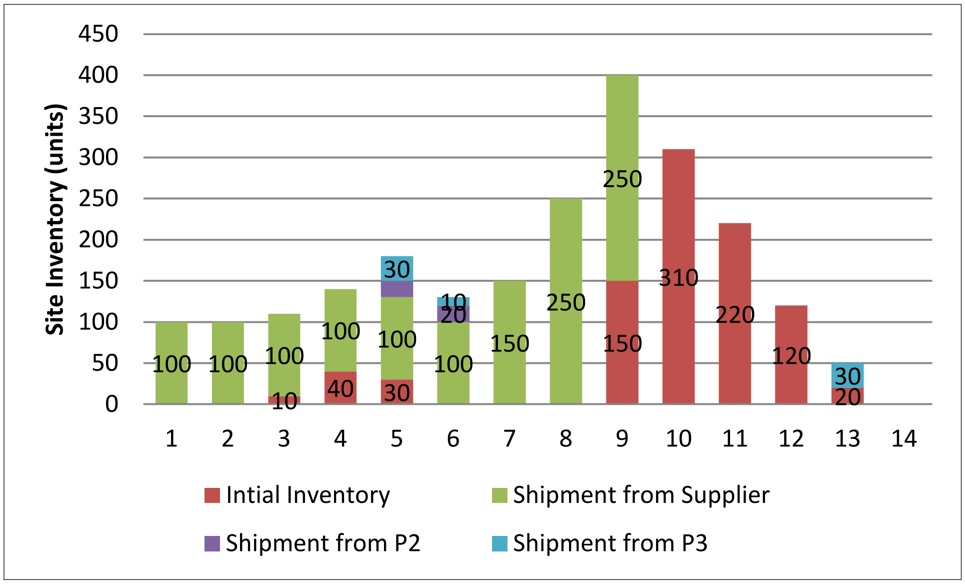


Figure 3.20: Material inflow for Project 1 with (τ=6, f=1)

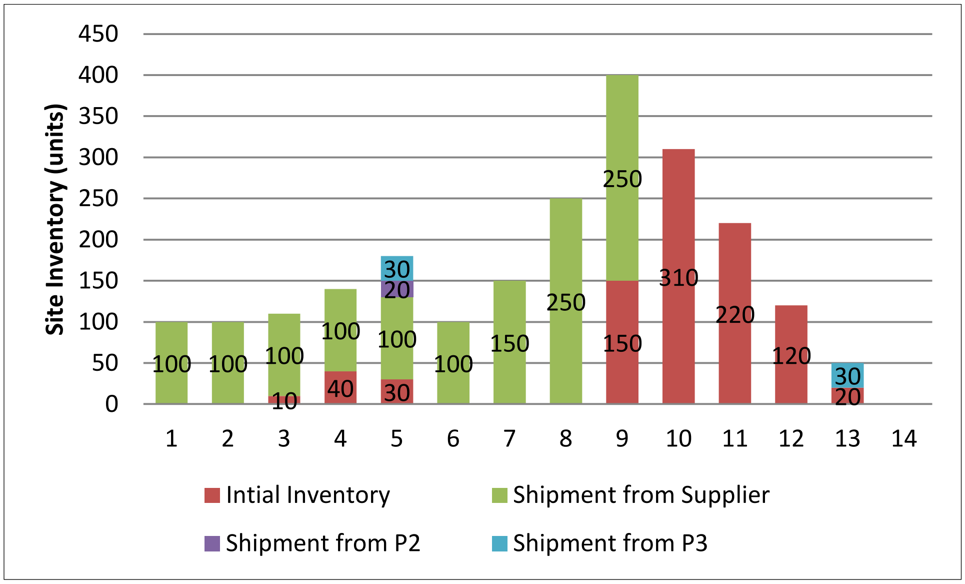


Figure 3.21: Material inflow for Project 1 with (τ=6, f=2)

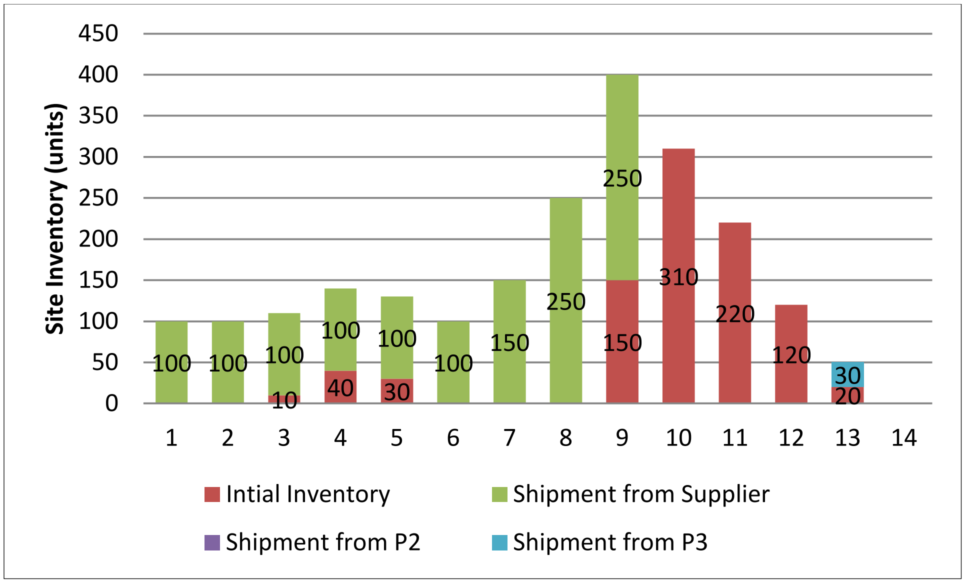


Figure 3.22: Material inflow for Project 1 with (τ=6, *f*=3)

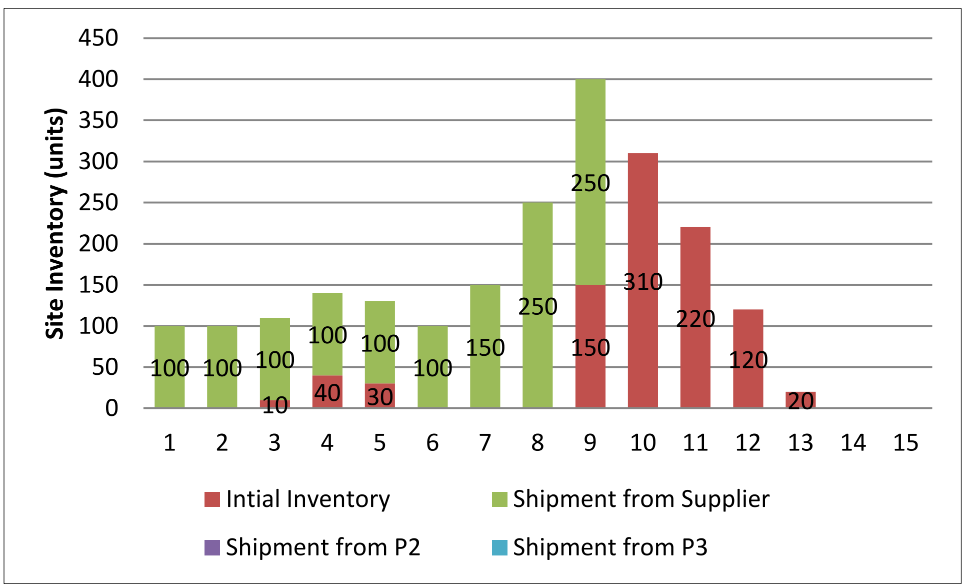


Figure 3.23: Material inflow for Project 1 with (τ=6, *f*=0)

Figure 3.24 shows the reduction in total cost as the transshipment frequency increased at which f=1 is the optimal transshipment frequency with the minimum total cost under the updating period τ=6. Moreover, Figure 3.25 shows the reduction in the total inventory level and the number of shortages as the transshipment frequency increased at which f=1 is the optimal transshipment frequency with the minimum total inventory level and total number of shortages. As stated earlier, increasing the transshipment frequency will increase the opportunity of Stage 2 in matching the supply and demand of the CSC which reduced the total inventory level and the total number of shortages.

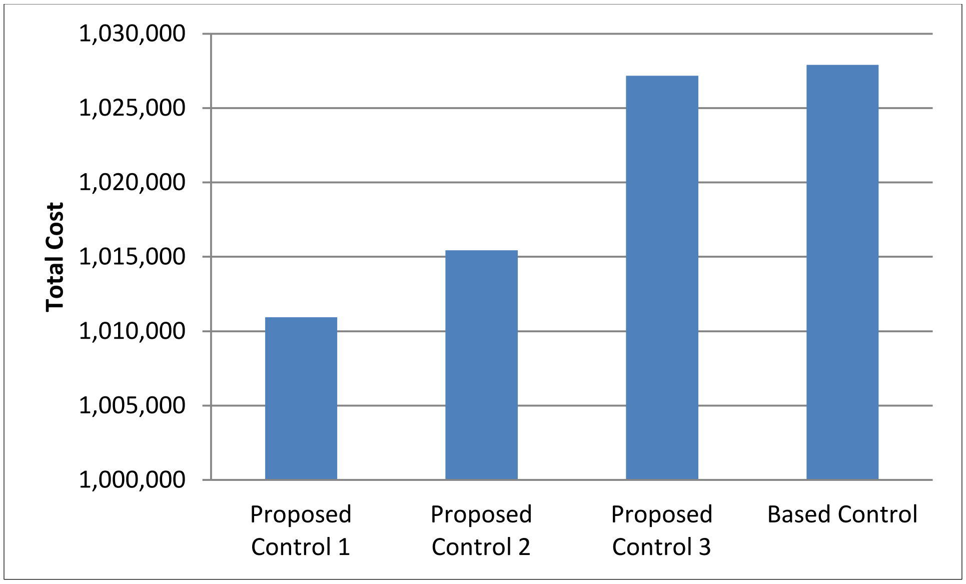


Figure 3.24: Total cost of τ=6 for 4 control examples with different transshipment periods

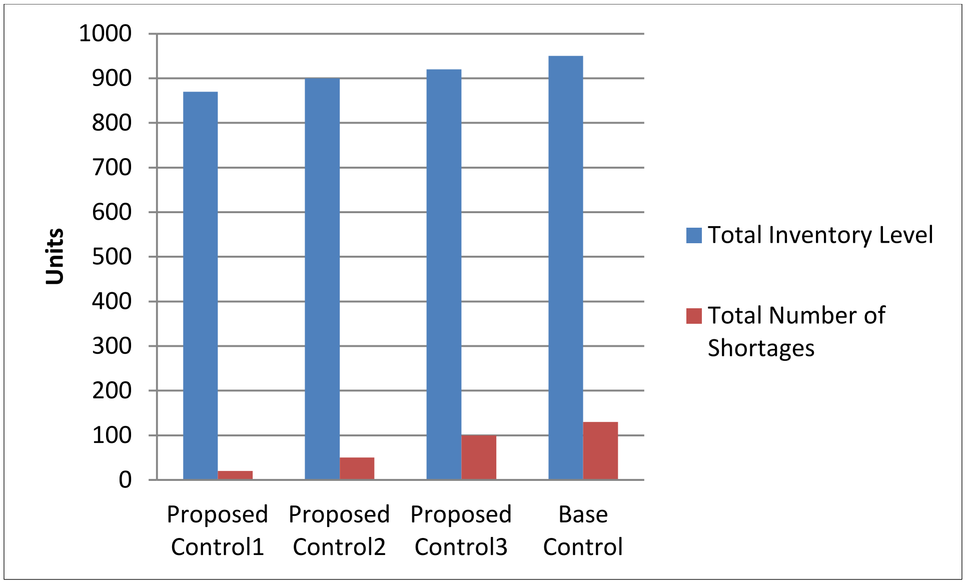


Figure 3.25: Total inventory level and Total Number of Shortages of τ=6 for 4 control examples

<u>3.3.3. Summary</u>

In all the three scenarios, we observe that the corporation of transshipment between the project sites (Proposed Controls) regardless of the transshipment period reduced the total cost of the CSC compared with the no transshipment in the Base Case by reducing the total inventory level and number of shortage units. Sharing the inventory between the CSC's projects by transship the excess inventory of one project to the other under shortage will not only reduce their inventory level and the number of shortage units, however, reducing the additional cost of updating the forecasted demand of the project sites from the supplier in Stage 1 when the data is passed by the site coordinator either expediting or delaying.

Based on the results of our case study example, we observe that the optimal transshipment frequency period in all the scenarios is the one that allows transshipment to occur more frequent (*f*=1). Table 3.12 compares the optimal transshipment period (*f* =1) under the three updating periods (τ=2, τ=4, τ=6) to determine the optimal combination of the time periods (τ, *f*=1) that provides the minimum total cost of the CSC. We observe that as the updating period decreased (gets longer), the total cost decreased.

Table 3.12: Comparison of the optimal transshipment period under different scenarios

Scenario	Total Cost ($)	Total Inventory level (units)	Total Number of Shortage (units)	Total Number of transshipment (units)
(τ=2, *f*=1)	2,199,549	870	20	30
(τ=4, *f*=1)	1,332,136	870	20	30
(τ=6, *f*=1)	1,010,943	870	20	110

The optimal updating period with the minimum total cost is τ=6. The reason for this is with a longer updating period, the opportunity of the site coordinator in Stage 2 using the extra inventory of the construction projects for matching supply with demand in the whole CSC will increase and the total cost will decrease. Based on our case study example, transshipments are required at *t*=5, *t*=6, and *t*=13. So, with τ=6, Stage 2 transshipped more units to Project 1 at *t*=5 and t=6 compared with τ=2 and τ=4. From Figures 3.26 through 3.28 where the material flow of Project 1 at each updating period is represented, we notice that at *t*=5, Project 1 receives 10 units from Project 2 in τ=2 and τ=4 and 50 units from both Project 2 and Project 3 in τ=6. At t=6, Project 1 receives 20 units from Project 3 in τ=2 and τ=4 and 40 units from both Project 2 and Project 3 in τ=6.

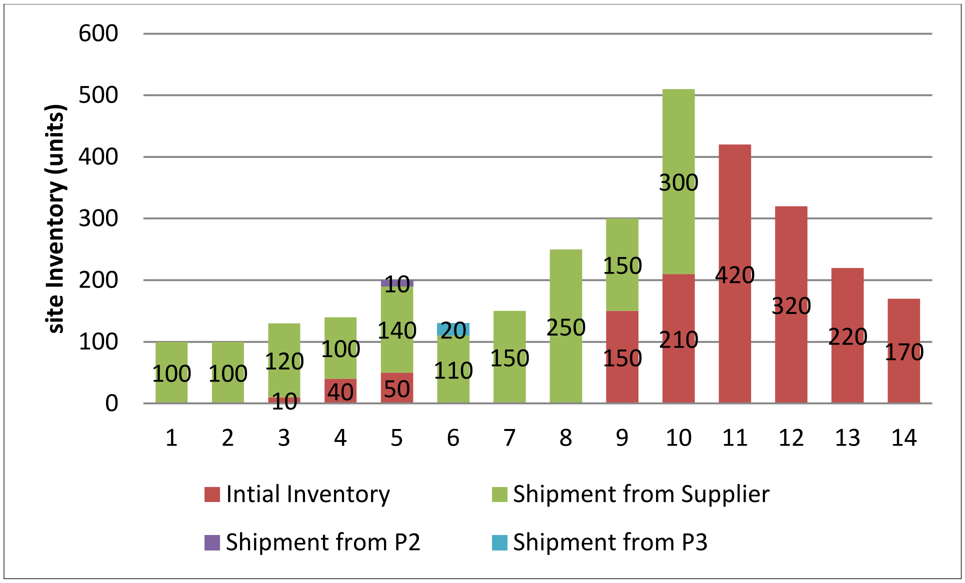


Figure 3.26: Material flow for Project 1 with (τ=2, *f*=1)

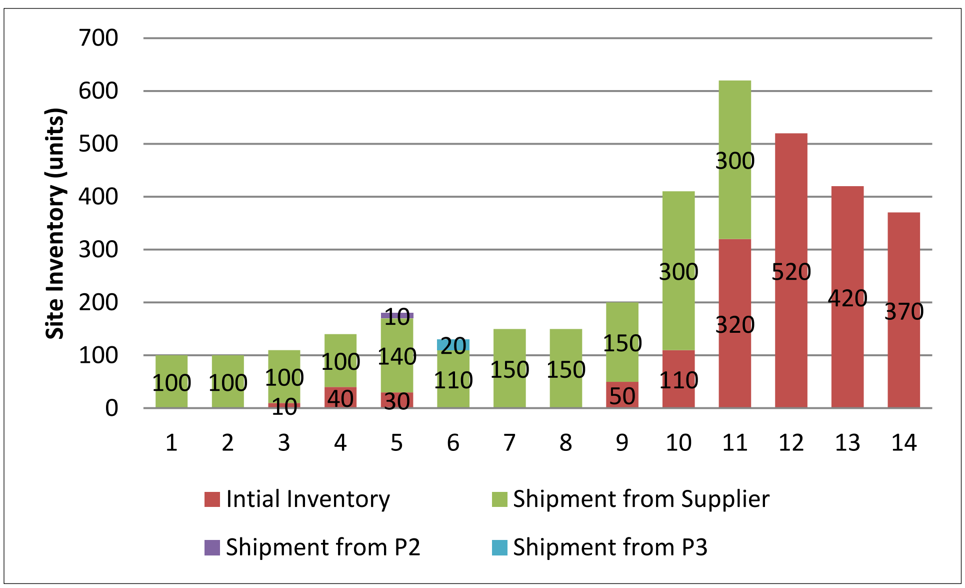


Figure 3.27: Material flow for Project 1 with (τ=4, *f*=1)

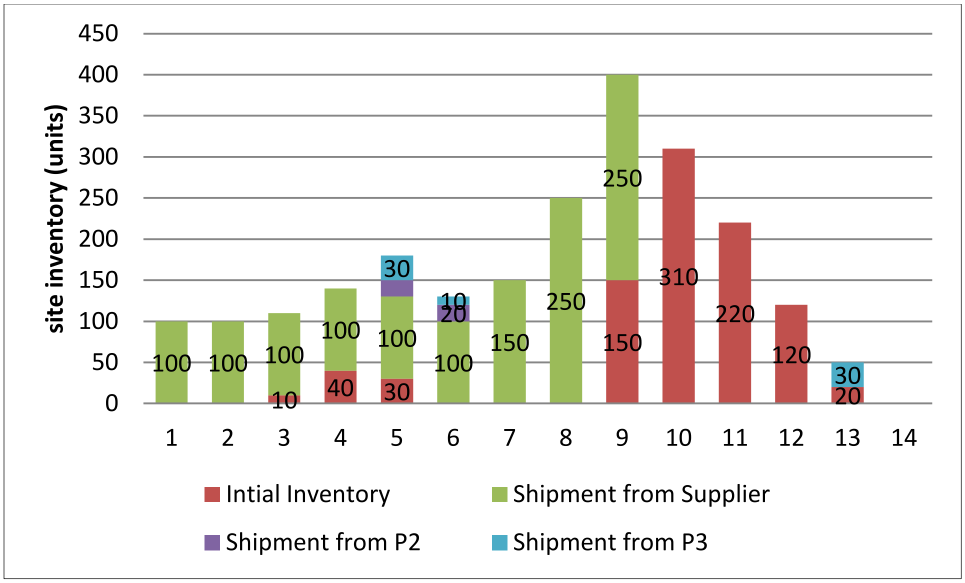


Figure 3.28: Material flow for Project 1 with (τ=6, *f*=1)

On the other hand, the total inventory level and the total number of shortages are the same through the three updating periods. The reason of this is because the transshipment practices (*f*=1) in Stage 2 will balance the supply-demand between the project sites and end up with the same total inventory level and number of shortages. It can be noticed that the different updating periods change the way the inventory is distributed among the project sites. For example, the inventory of Project 1 at the end of the planning horizon is 170, 370, and zero for the updating periods τ=2, 4, and 6 respectively. However, because the inventory cost is assumed to be same over the project sites, there is no impact in the total cost of CSC. So, there is no need for updating Stage 1 very frequently in the presence of transshipment with high frequency (*f*=1) between the projects in Stage 2 because at the end the same total inventory level and same total number of shortages will be reached.

As such, by decreasing the updating period in Stage 1, the total cost of Stage 1 decreased because the number of time periods at which updates are occurred will decrease. In τ=2, the updates in Stage 1 are allowed to occurred at *t*=1, 3,5,7,9, and 11with a total cost of $2,080,050. In τ=4, the updates in Stage 1 reduced and are allowed to be at t=1, 5, and 9 with a total cost of $1,205,630. And in τ=6, the updates in Stage 1 decreased to be only at two time period *t*=1 and 7 with a total cost of $883,410.

This is only one case study with one set of parameters and any generalizations must be studied much more carefully. With that said, it seems clear that increasing transshipments capability in Stage 2 by allowing it to occur every period (*f*=1) and decrease the updating periods from the supplier in Stage 1 (τ=6) has the most impact on the performance of the CSC.

3.4. Conclusions and Future Research

This chapter describes a new methodology for controlling material flow in the CSC. The methodology involves a paradigm shift of allowing transshipments between the construction project sites that are being executed simultaneously and a new integrated material flow control to take advantage of opportunities transshipment affords in terms of reduced cost, better adherence to schedule, improved supply chain resilience, and improved efficiency. The methodology is implemented using two deterministic optimization models that were developed to minimize total cost. Stage 1 is a CSC adaptation of MPR that specifies the communication between construction projects and suppliers. Stage 2 focused on possible transshipment opportunities and defines those that can improve the current situation relative to total cost. It is proposed that these models be solved iteratively and executed with different time periods. Stage 1 is executed with "updating periods" (τ), and Stage 2 is executed with "transshipment periods" (f). The impact of different combination of time periods at which each stage is executed on total cost of the CSC is explored.

The methodology is applied to a case study that is composed of three construction projects and one supplier of steel rebar in Kuwait. The models were solved using OPL and subsequently validated through experimentation and comparison with spreadsheet calculations. When applied to the to the case study, the methodology showed promise to increase the effectiveness of the CSC's performance by reducing the total cost in both Stage 1 and Stage 2 when compared with no transshipment.

Moreover, based on the results of the case study, the optimal transshipment frequency time period in which Stage 2 is executed is f=1. So, the incorporation of transshipment and enhance its applicability by increasing the frequency shows an alternative way to mitigate the impact of the disruptions and changes in CSC by increasing the opportunity in matching the supply and demand of the CSC which reduced the total inventory level, the total number of shortages, and the additional penalty cost of updating the forecasted demand (to expedite or delay) of the project sites from the supplier in Stage 1. As such, the optimal time period at which Stage 1 is updated based on the actual results of Stage 2 is τ=6. That is the longer the updating period in Stage 1 and the shorter the transshipment period in Stage 2 exhibited the best performance with the minimum total cost compared with the other combinations.

Further research will be adding more constraints and real world complexity by extending PTPSMS to multiple product types. In addition, investigate the impact of restricting the storage and the transportation capacity on the CSC.

CHAPTER FOUR

A TWO-STAGE METHODOLOGY FOR MULTIPLE-MATERIAL FLOW CONTROL IN CONSTRUCTION SUPPLY CHAIN

4.1. Introduction

In Chapter 3, PTPSMS methodology was proposed that represented a new concept for the control of construction projects. It involves a two-stage process that coordinates the feed-forward control (Stage1) of advanced order placement with a supplier to a feedback local control (Stage2) in the form of adding the ability to transship materials between project sites to improve efficiency and reduce costs. The previous methodology focused on the single supplier integrated production and transshipment problem with a single product.

In this chapter, the methodology is expanded to include multiple products from a single supplier in a much more highly constrained environment. This integrated Production and Transshipment Problem of a Single supplier, Multiple projects, and Multiple material, will be referred to as PTPSMM. The consumption of the products is assumed to be independent; that is, a higher consumption of one product does not imply a higher consumption of the others. It is assumed that the different types of products have different sizes that are measured by their volume. All types of products can be used in all construction projects but all types are not necessarily used in all projects in each period. If a product type is not used, the demand is zero for that product in a given period. Considering different products is an important extension from a practical viewpoint because it adds realism and the associated complexity to the project's planning and scheduling. It also forces the methodology to be extended to accommodate the situation where a single site has a shortage of one product and a surplus of another.

The difference in this chapter is that the methodology will be extended to a significantly more constrained environment. It is assumed that the trucks used to transport materials from the supplier to the project sites and the trucks used to transshipment between sites have limited capacity which will be reflected as a maximum allowable total volume. All trucks will be capable of carrying all product types simultaneously. As in the previous chapter, the production capacity of the supplier is assumed to be limited. Finally, the storage capacity at the project sites is assumed to be limited.

The contribution of this chapter lies in including multiple products with different volumes and adding significant capacity constraints to both site storage and transportation. The primary goal is to analyze and compare the impact of the storage and transportation capacity constraints on CSC behavior and on construction projects' performance under the case of limited production capacity at the supplier. The underlying mathematical models have been modified to include these features and a number of case study examples are provided to investigate the types of controls that are best.

4.2. Mixed Integer Programming Model for the PTPSMM

The CSC network here consists of a single supplier that must deliver k product types to N project sites. Future deliveries from the supplier can be adjusted periodically based on updated forecasts and materials can be transshipped between project sites. The two-stage methodology outlined in Chapter 3 is extended here for the PTPSMM situation with a goal of minimizing the total cost of transportation, inventory, ordering, and shortage in the CSC.

4.2.1. Mathematical Model of Stage 1

Stage 1 of the methodology uses a deterministic model to determine the shipments of each product *k* to each site *j* respecting all of the capacity restrictions. The material flow is determined at the beginning of period *t*=1 and then at predetermined updated periods τ thereafter. The events of Stage 1 occur in the following order:

(1) At period 1, the initial forecasted demand for each product *k* at each project site *j* at each time period *t* (D_{jkt}) is used to determine the number of units to be shipped in all future periods, X_{ijkt} .

(2) There is an update to the Stage 1 orders every τ time periods. This involves an information update in which Stage 2 provides information to Stage 1 regarding the actual inventory level of each product at each project site from the prior period $I_{j,k,t-1}$.

(3) Using this information, Stage 1 will find the cost of optimal flows from the supplier to project sites for all future periods. This completes the updated feed forward part of the controller, Statge1.

(4) Stage 1 then provides updates of the orders and forecasts to Stage 2 for use in determining any required transshipments in the time interval before the next update.

It should be noted that the updated information used in Stage 1 (i.e., the updated forecast of consumption) is assumed to be given by an external entity like the project manager or an owner's central organization. These updates are not necessarily gleaned from historical data and may not be reasonable or thoughtful; they reflect expectations are made independently with no attempted coordination regarding feasibility. It is possible, for example, for each site to request expedited shipments that greatly exceed the supplier capacity; or all projects might request future shipments be delayed. The model includes actions associated with expediting and delaying order but assigns penalty costs based on the time that the order was scheduled for shipment. That is, the penalty cost for updating an order that was to be shipped in the next period is higher than the one scheduled further in the future. When the requested demand cannot be satisfied, it is referred to as being short and the number of product *k* items that are short at site *j* in time period *t* is denoted S_{jkt}. From a practical perspective, this can have a significantly detrimental impact on the project. In the model, this can happen for three reasons: (1) there is insufficient supplier capacity (2) the storage capacity at the construction site is insufficient to accept a shipment (3) the replenishment and/or the transshipment quantities required to meet demand exceed the capacity of the trucks. In real situations, a significant shortage of any product is likely to demand additional actions beyond the scope of this model like purchasing items on the open market if possible or paying a premium to acquire items with a short lead time. The optimization model to be used in Stage 1 is now presented.

<u>Indices</u>

$i \in S = \{1, 2, ..., \mathrm{S}\}$ the set of suppliers

$j \in N = \{1, 2, ..., \mathrm{N}\}$ the set of project sites

$t \in T = \{1, 2, ..., \mathrm{T}\}$ time periods up to the end of the planning horizon, T

$k \in K = \{1, 2, ..., \mathrm{K}\}$ the set of types of unique products

Input Parameters

C^1_{ijkt} ordering cost for a unit of product k procured from supplier i by site j at time t, $i \in$S, $j \in N$, $k \in K$, $t \in T$ ($/unit)

UT^1_{ijkt} transportation cost associated with each truck used to transport product type k from supplier i to site j at time t, , $i \in$S, $j \in N$, $k \in K$, $t \in T$ ($/mile)

PC_{kt} penalty cost to expedite or delay unit of product k at time t , $k \in K$, $t \in T$ ($/unit)

Q^1_{jkt} cost of shortage of product k at site j during time t, $j \in N$, $k \in K$, $t \in T$ ($/unit)

Q^2_{jkt} cost of inventory of product k at site j during time t, $j \in N$, $k \in K$, $t \in T$ ($/unit)

D_{jkt} forecasted demand of product k at site j at time t ,$j \in N$, $k \in K$, $t \in T$ (units)

F_{ijkt} number of units scheduled to ship from supplier i to site j at t from the previous Stage 1 update, $i \in$S, $j \in N$, $k \in K$, $t \in T$ (units)

Cap_{it} production capacity of supplier i at time period t, $i \in$S, $t \in T$ (units)

$Invcap_{jt}$ the storage capacity of site j at t, $j \in N$, $t \in T$ (ft^3)

ν_k the volume of product k, $k \in K$ (ft^3/unit)

V the maximum volume a truck can carry (ft^3)

L_1 the maximum number of trucks available in Stage 1

Computed variables

U_{jkt} total number of updated units of product *k* ordered by site *j* at time *t* (units)

S_{jkt} number of units of product *k* that are short at site *j* at time *t* (units)

I_{jkt} end of period on-hand inventory of product *k* at site *j* at time *t* (units)

M^1_{ijkt} number of trucks used to ship the units of product type *k* from supplier *i* to site *j* at time *t*, $i \in S$, $j \in N$, $k \in K$, $t \in T$

Decision variables

X_{ijkt} number of units of product *k* transported from supplier *i* to site *j* at time *t* (units)

With these variables, the following Stage1 model is proposed for the PTPSMM problem:

$$Min\ \ Z = \sum_{i \in S}\sum_{j \in N}\sum_{k \in K}\sum_{t \in T}\left(C^1_{ijkt}X_{ijkt} + UT^1_{ijkt}M^1_{ijkt}\right) + \sum_{j \in N}\sum_{k \in K}\sum_{t \in T}PC_{kt}U_{jkt} + \sum_{j \in N}\sum_{k \in K}\sum_{t \in T}Q^1_{jkt}S_{jkt} + \sum_{j \in N}\sum_{k \in K}\sum_{t \in T}Q^2_{jkt}I_{jkt}$$

Subject to:

$$U^+_{jkt} = \sum_{i \in S}\left(X_{ijkt} - F_{ijkt}\right) \qquad \forall j \in N, k \in K, t \in T \qquad (1)$$

$$U^-_{jkt} = \sum_{i \in S}\left(F_{ijkt} - X_{ijkt}\right) \qquad \forall j \in N, k \in K, t \in T \qquad (2)$$

$$U_{jkt} = U^+_{jkt} + U^-_{jkt} \qquad \forall j \in N, k \in K, t \in T \qquad (3)$$

$$I_{jkt} = I_{j,k,t-1} + \sum_{i \in S}X_{ijkt} - D_{jkt} + S_{jkt} \qquad \forall j \in N, k \in K, t \in T \qquad (4)$$

$$I_{j,t-1} = a \qquad \forall j \in N, t \in T, \text{ where } a\text{=0 at } t\text{=1} \tag{5}$$

$$\sum_{j \in N} X_{ijkt} \leq Cap_{ikt} \qquad \forall i \in S, k \in K, t \in T \tag{6}$$

$$v_k \sum_{i \in S} X_{ijkt} \leq Invcap_{jt} \qquad \forall j \in N, k \in K, t \in T \tag{7}$$

$$\sum_{k \in K} X_{ijkt} / V = M^1_{ijkt} \qquad \forall\ i \in S, j \in N, t \in T \tag{8}$$

$$\sum_{j \in N} \sum_{k \in K} M^1_{ijkt} \leq \mathrm{L}_1 \qquad \forall\ i \in S, t \in T \tag{9}$$

$$X_{ijkt} \geq 0 \tag{10}$$

The objective function consists of five terms. The first represents the cost of the number of units of product *k* procured from the i^{th} supplier to the j^{th} site at time period *t*. The second term represents the cost associated with the number of trucks used for shipments between the supplier and sites. The third term determines the variable cost associated with updating an order that will be delivered to the j^{th} site. The fourth and fifth terms calculate the shortage and inventory costs respectively.

Constraints (1), (2), and (3) determine the number of units of each product to be expedited, delayed, and the total units changed at *t*. Constraint (4) is the inventory balance for each product type *k* in each time period. This is where the shortage term is forced positive if not enough are to be shipped to have sufficient items on hand to meet the demand. Constraint (5) defines the inventory from the previous period and it is assumed that the planning horizon begins with zero at each site. Constraints (6) and (7) enforce the supplier and site capacity restriction. Constraint (8) determines the number of trucks required. Constraint (9) ensures that the total required number of trucks not exceeds the maximum number of available trucks. Finally, non-negativity constraint is included in (10).

4.2.2. Mathematical Model of Stage 2

Stage 2 of the methodology utilizes a deterministic model as a feedback-type controller based on actual consumption and the forecasted deliveries from the supplier in the future. This model determines the transshipments between the project sites respecting the limited number of trucks available for shipping. Recall that a given project site can have both a shortage of one product and excess inventory of another at the same time. The model includes the costs for shortage and holding inventory as part of the optimization. The overall strategy is that the Stage 2 model is executed multiple times between the Stage 1 updates. This can be every period but it can be less frequent as well. The idea is that the Stage 2 feedback loop makes adjustments to accommodate disruptions. The objective of the model that dictates Stage 2 actions is to minimize the costs of transshipping, inventory, and shortages. Each construction site has limited storage to accommodate all of the products. It is further assumed that each product can have a unique volume and they can share the same truck during transshipment according to the available space in order to minimize the transshipment cost. The following notation is used in the Stage 2 optimization model.

Indices

$i \in S = \{1, 2, ..., \mathrm{S}\}$ the set of suppliers

$j \in N = \{1, 2, ..., \mathrm{N}\}$ the set of project sites

$t \in T = \{1, 2, ..., \mathrm{T}\}$ time periods up to the end of the planning horizon, T

$k \in K = \{1, 2, ..., \mathrm{K}\}$ the set of types of unique products

<u>Input Parameters</u>

C^2_{djkt} the ordering cost for a unit of product *k* procured from site *d* by site *j* at time *t* , *d*,*j* ∈ *N*, *k* ∈ *K*, *t* ∈*T*($/unit)

$UT^2{}_{djkt}$ transportation cost of product *k* from site *i* to site *j* at time *t*, *d*,*j* ∈ *N*, *k* ∈ *K*, *t* ∈*T* ($/mile)

Q^1_{jkt} shortage cost of product *k* at site *j* during *t* ,*j* ∈ *N*, *k* ∈ *K*, *t* ∈*T* ($/unit)

Q^2_{jkt} holding cost of product *k* at site *j* during time *t*, *j* ∈ *N*, *k* ∈ *K*, *t* ∈*T* ($/unit)

Δ_{jkt} actual demand of product *k* at site *j* at time *t*, *j* ∈ *N*, *k* ∈ *K*, t ∈*T* (units)

v_k the volume of product *k*, *k* ∈ *K* (ft^3/unit)

V the maximum volume a truck can carry (ft^3)

$Invcap_{jt}$ the storage capacity of site *j* at *t*, *j* ∈ *N*, t ∈*T* (ft^3)

L_2 the maximum number of trucks available in Stage 2

<u>Input Parameters from Stage 1</u>

F_{ijkt} number of units of product type *k* scheduled to ship from supplier *i* to site *j* at *t* according to latest update of Stage 1, *i*∈ *S*, *j* ∈*N*, *k* ∈ *K*, *t* ∈*T* (units)

D_{jkt} forecasted demand of product type *k* at site *j* at time *t* – default is from Stage 1, can be updated at site, *j* ∈*N*, *k* ∈ *K*, *t* ∈*T* (units)

Computed variables

I_{jkt} end of period on-hand inventory of product *k* at site *j* at time *t*, $j \in N$, $t \in T$, $k \in K$ (units)

S_{jkt} projected number of units of product *k* that will be short at site *j* at time *t*, $j \in N$, $t \in T$ (units)

M^2_{djkt} number of trucks used to ship the units of product type *k* from site *d* to site *j* at time *t*, $d, j \in N$, , $k \in K$, $t \in T$

Decision variables

Y_{djt} number of units of product *k* transported from site *d* to site *j* at time *t*, $d, j \in N$, $t \in T$ (units)

With these variables, the following Stage 2 model is proposed for the PTPSMM problem:

$$Min\ \ Z = \sum_{d \in N} \sum_{j \in N} \sum_{k \in K} \sum_{t \in T} \left(C^2_{djkt} Y_{djkt} + UT_{djt} M^2_{djt} \right) + \sum_{j \in N} \sum_{k \in K} \sum_{t \in T} Q^1_{jkt} I_{jkt} + \sum_{j \in N} \sum_{k \in K} \sum_{t \in T} Q^2_{jkt} S_{jkt}$$

Subject to:

$$I_{jkt} = I_{j,k,t-1} + \sum_{i \in S} F_{ijkt} + \sum_{d \in N} Y_{djkt} - \sum_{b \in N} Y_{jbkt} + D_{jkt} + S_{jkt} \quad \forall j \in N, k \in K, t \in T \tag{1}$$

$$I_{jkt} = I_{j,k,t-1} + \sum_{i \in S} F_{ijkt} + \sum_{d \in N} Y_{djkt} - \sum_{b \in N} Y_{jbkt} + D_{j,k,t-1} - \Delta_{j,k,t-1} - D_{jkt} + S_{jkt} \quad \forall j \in N, k \in K, t \in T \tag{2}$$

$$\sum_{b \in N} Y_{jbkt} \le I_{j,k,t-1} + D_{j,k,t-1} - \Delta_{j,k,t-1} \quad \forall j \in N, k \in K, t \in T \tag{3}$$

$$v_k * \sum_{d \in N} Y_{djkt} \le Invcap_{jt} \qquad \forall j \in N, k \in K, t \in T \tag{4}$$

$$v_k * \sum_{j \in N} Y_{djkt} / V = M^2{}_{djkt} \qquad \forall\ d \in N, k \in K, t \in T \tag{5}$$

$$M^2{}_{ijkt} \ \leq \ \mathrm{L}_2 \qquad \forall\ i \in S, j \in N, k \in K, t \in T \tag{6}$$

$$I_{j,t-1} = a \qquad \forall j \in N, t \in T, \text{ where } a\text{=0 at } t\text{=1} \tag{7}$$

$$Y_{djkt} \geq 0 \tag{8}$$

Constraint (1) is the material balance in the first period after Stage 1 update of the material flow from the suppliers to the sites and it is based on the forecasted demand. Constraint (2) is the material balance in the periods after the first one after a Stage 1 update and using actual demand. Constraint (3) limits the number of units that can be transshipped to the on-hand inventory. Constraint (4) ensures that volume of the total number of transshipped units does not exceed the inventory volume capacity of the project site. Constraint (5) calculates the total number trucks required for transshipment. Constraint (6) ensures that the required number of trucks not exceeds the maximum number of available trucks. Constraint (7) defines the inventory from the previous period and it is assumed that the planning horizon begins with zero at each site. Finally, non-negativity and integer constraints are included in (8).

4.3. Case Study Examples

To analyze the impact of storage and transportation capacities on the total cost of CSC under PTPSMM problem, two different cases have been developed and examined with a range of scenarios. The first case investigates the impact of limiting the storage capacity of the CSC by limiting the inventory at one of the project sites. The second example will study the impact of restricting the capacity of transportation on the performance of the CSC by varying the number of trucks available in Stage1 and Stage 2. All of these cases are solved using ILOG OPL Development Studio version 5.5 on a single core of a SONY OptiPlex 980 computer running the Windows 7 Enterprise 64 bit operating system with an Intel(R) Core(TM) i5 CPU860@ 2.80GHz, and 8GB RAM. For all cases, the following assumptions are made:

1) There are three project sites (1, 2 and 3) which can consume two Products (A and B). A 13 period planning horizon (T=13) is considered.

2) The updating period (τ) of Stage 1 and the transshipment period (*f*) of Stage 2 are the same as the optimal findings in PTPSMS in Chapter 3. The findings indicate that, the longer the updating period (τ=6) which reflects how frequent is the communication between the central planning in Stage 1 and the site coordinator in Stage 2 and the shorter the transshipment period (*f=1*) that allows transshipment to occur every period during the time horizon, the minimum the total cost of the whole CSC.

3) A single supplier produces two different products (Product A and Product B) with limited production capacity to each of them. Hence, *i*=1 always.

4) In Stage 1, the cost for site *j* to order one unit of Product A (Product B) from the supplier at time *t* is \$150/unit (\$200/unit). That is, C^{1}_{1jAt} = \$150/unit and C^{1}_{1jBt} = \$200/unit.

5) In Stage 1 and Stage 2, the transportation cost to deliver one unit of Product A (Product B) from the supplier to each project site and between the sites is fixed at $1/mile. That is, both UT^1_{ijkt} and UT^2_{djkt} are $1/mile.

6) All the project sites are assumed to have limited storage capacity $Invcap_{jt}$ = 400 ft^3, which can hold both Product A and Product B.

7) The cost of shortage of both Product A and Product B at site *j* during time *t* is assumed to be Q^1_{jt} = $80, $90, and $100/unit for *j*=1, 2, and 3 respectively.

8) The holding cost of both Product A and Product B at project site *j* is assumed to be Q^2_{jkt} =$45, $35, and $25/unit for *j*=1, 2, and 3 respectively.

9) The maximum number of units that can be in each shipment is limited according to the truck volume capacity restriction (V=100 ft^3/truck).

10) In Stage 2, the cost for site *j* to order one unit of Product A (Product B) from the site *d* at time *t* is $100/unit ($100/unit). That is, C^2_{djAt} = $100/unit and C^2_{djBt} = $100/unit.

11) During the Stage 1 updating period, the forecasted demand for Product A and Product B are revised and used in the model. It is assumed the changing an order schedule for delivery sooner is more expensive than one scheduled for later. If the updating period is *t*, this is modeled by setting PC_{t+1} =$100/unit, PC_{t+2} =$50/unit, and PC_{t+3} =$25/unit.$100/unit. The update cost is assumed to be zero for any period more than 4 months in the future. This cost is assumed to be the same for both Product A and Product B.

12) The initial demand forecast used by Stage 1 in period 1 is for Product A to be consumed at a rate of 100 units/period in each of the 12 periods (*t*=1,2, …, 12) and for Product B to be consumed at a rate of 50 units per period for each of the 12 periods. At *t*=13 the demand is zero.

13) It is assumed that the needed demand (called actual demand henceforth) of Product A is presented in Table 4.1. This reflects several realistic situations that can occur in practice.

   a. Project 1 expedites the work by 30% during two different intervals: between *t*=3 and *t*=7 and beginning at *t*=9.

   b. Project 2 slows the work by 50% during two different intervals: between *t*=6 and *t*=8 and then *t*=10. Also, there is an expediting by 30% at *t*=9.

   c. Project 3 is completely stopped at period *t*=6 and remains in that condition until *t*=10.

14) The actual demands presented in Table 4.2 reflect the fact that actual demand of Product B changes as follows:

   a. Project 1 expedites the work by 50% during two different intervals: between *t*=3 and *t*=5 and then *t*=11 and *t*=12.

   b. Project 2 expedites by 50 % at *t*=6 and by 25% at *t*=8.

   c. Project 3 is completely stopped between *t*= 5 and *t*=7 and then expedites by 50% from *t*=8 to *t*=10.

Table 4.1: The actual demand of Product A at each project site over the time horizon

	1	2	3	4	5	6	7	8	9	10	11	12	13
Project 1	90	90	150	150	150	150	150	90	150	100	100	100	0
Project2	90	90	90	90	90	50	50	50	150	50	100	100	0
Project3	90	90	90	90	90	0	0	0	0	0	100	100	0

Table 4.2: The actual demand of Product B at each project site over the time horizon

	1	2	3	4	5	6	7	8	9	10	11	12	13
Project 1	40	40	100	100	100	50	50	40	0	0	100	100	0
Project2	40	40	40	40	40	100	50	75	50	50	50	50	0
Project3	40	40	40	40	0	0	0	100	100	100	50	50	0

4.3.1 Vary the storage capacity of one of the project sites

In this case, the impact of limited storage capacity at one of the project sites is investigated to determine the effect on the material flow and the total cost of the CSC. The methodology will allow transshipments to occur between the projects to better balance between the site with excess inventory and the one with shortage. Since this is a case study and we know the actual demands, the storage capacity at the project site with the highest amount of surplus inventory level is restricted. By comparing the actual demand of the three project sites, Project 3 is the one that would have the greatest surplus if adjustments were not made to the material flow schedule so three scenarios with different storage capacities at Project 3 are investigated. The storage capacities uses are

Cap_{3t} = {∞, 400, 0}, $t \in T$ where a capacity of ∞ means there is no restriction on the number of units that can be held in Project 3. Note that Cap_{3t}=400, restricts the capacity to be exactly equal to the total demand in the original plan and Cap_{3t}=0, implies that Project 3 cannot hold any units, so any units received must be used by the project in the same time period they are delivered, otherwise, they are transshipped to other project site with available capacity. The results of applying the 2-stage methodology to this case with the three storage capacity restrictions represented by the total cost, the total inventory level at the end of the planning horizon, the total number of shortages over the entire planning horizon, and total number of transshipments are shown in Table 4.3.

Table 4.3: Comparison between the results of the three storage capacity scenarios

Scenarios	Total Cost ($)	Total Inventory level (units)		Total Number of Shortage (units)		Total Number of transshipment (units)	
		Product A	Product B	Product A	Product B	Product A	Product B
Cap_{3t}=∞	1,612,059	560	0	80	105	240	340
Cap_{3t}=400	1,678,995	560	0	80	105	370	374
$Cap_{3t}=0$	1,702,615	560	0	80	105	549	349

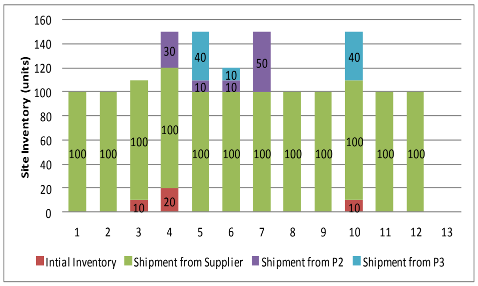
We observe that the total cost increased as the storage capacity decreased. Table 4.4 represents the percentage of increasing in the total cost associated with limiting the storage capacity.

Table 4.4: The percentage of increasing in the total cost associated with limiting the storage capacity

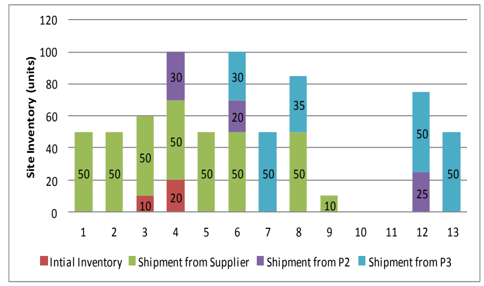
	Cap_{3t}=∞	Cap_{3t}=400	Cap_{3t}=0
Cap_{3t}=∞	-	4.2%	5.6%
Cap_{3t}=400	-	-	1.4%

We observe that there is an increase in the total cost associated with restricting the storage capacity of Project 3 from Cap_{3t}=∞ (Scenario1) to Cap_{3t}=400 (Scenario 2) by 4.2%. The first reason, and the primary one, is the increased in total inventory cost due to shifting stock from one site with a lower inventory cost per unit to another that has a higher cost. Because Project 3 has the lowest inventory cost compared with the other project sites in the CSC, in Scenario 1 it is the storage area for all the inventory units to take the advantage of the lower cost. However, as the storage capacity of Project 3 is reduced (Scenario 2), the opportunity for it to act as a storage area for other sites is decreased. Thus, the inventory units that exceed the storage capacity of Project 3 are shifted to other project site with higher inventory cost. Because the inventory cost of Project 2 is lower than Project 1, the extra units will be shifted there. From the material flow represented in Figures 4.1 and Figure 4.2 for Scenario 1 and Scenario 2 respectively, compare the inventory of Project 2- Product A, and notice how the inventory in Figure 4.2 is starting to accumulate in Project 2 from t=8 to the end of the planning horizon. For example, notice in Figure 4.1 for Scenario 1 at t=8, Project 3-Product A has a total inventory of 100 units with inventory cost of $25/unit, however, in Figure 4.2 for

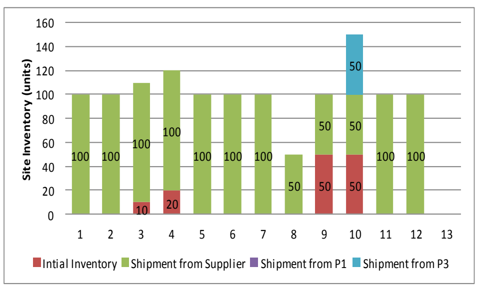
Scenario 2, the number of units in Project 3 decreased to 93 units and the extra 7 units are shifted to Project 2 with higher inventory cost of \$35/unit.



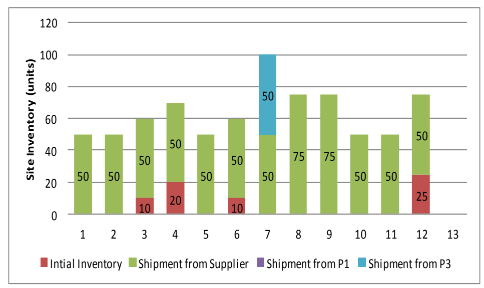
Project 1- Product A



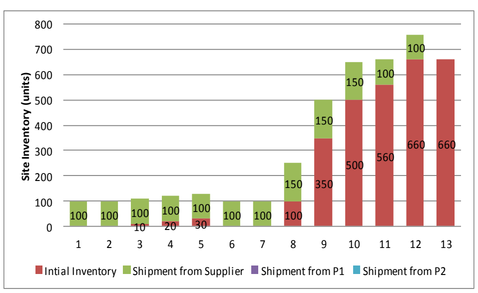
Project 1-Product B



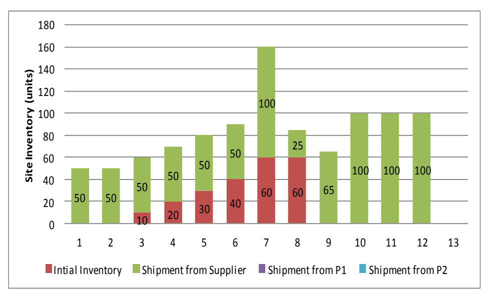
Project 2- Product A



Project 2-Product B

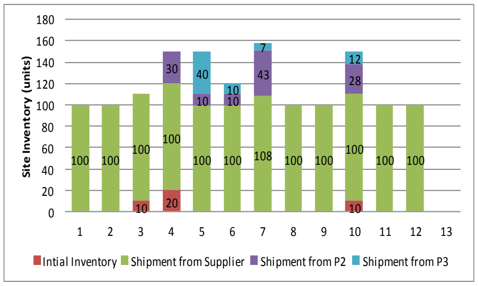


Project 3- Product A

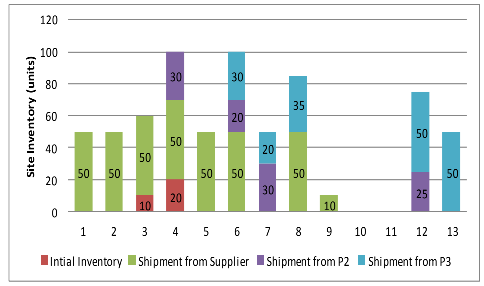


Project 3-Product B

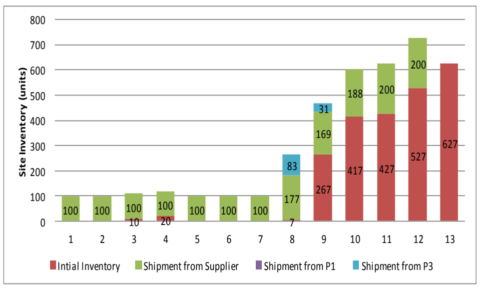
Figure 4.1: Material flow for Scenario 1 (Cap_{3t}=∞)



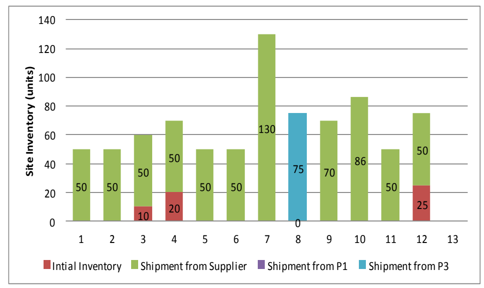
Project 1- Product A



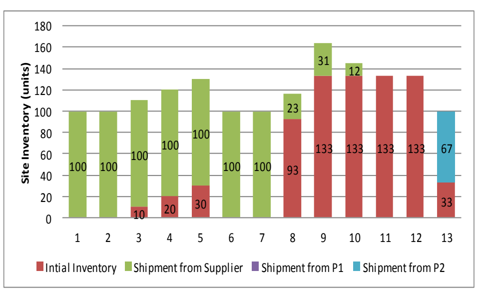
Project 1- Product B



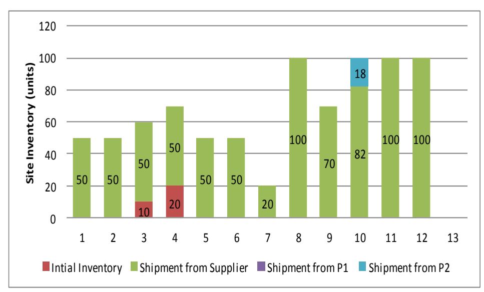
Project 2- Product A



Project 2- Product B



Project 3- Product A



Project 3- Product B

Figure 4.2: Material Flow for Scenario 2 (Cap_{3t}=400)

The second reason of increasing is that the number of units transshipped increase - Product A by 54.2% and Product B by 10% from Scenario 1 to Scenario 2. Recall that the number of units transshipped in Stage 2 is related to the allocation of the forecasted demand in Stage 1 that depends on the updated forecasted demand requested by each project site from Stage 2 and the storage capacity of the project sites. Tables 4.5 and 4.6 show the updated forecasted demand of each product type requested by each project site for the time periods from *t*=7 to *t*=13. The updated forecasted demand of each product type could be "delayed units" (decrease the scheduled forecasted demand from the last Stage 1) or "expedited units" (increase the scheduled forecasted demand from the last Stage 1). For Product A, the requests to delay are more than to expedite. Project 2 requests to delay the updated forecasted demand from 100 units to 50 units from *t*=8 to *t*=10, Project 3 requests delay (stop the shipments) from 100 units to zero from t=8 to the end of the planning horizon, and Project 1 to expedite from 100 units to 150 units at *t*=7.For Product B, the requests to expedite are more than to delay. Project 2 requests to expedite from 50 units to 75 units from t=8 to t=10 and Project 3 to expedite from 50 units to 100 units from t=8 to the end of the planning horizon.

Table 4.5: Updated forecasted demand of Product A

	7	8	9	10	11	12	13
Project 1	150	100	100	100	100	100	0
Project2	100	50	50	50	100	100	0
Project3	100	0	0	0	0	0	0

Table 4.6: Updated forecasted demand of Product B

	7	8	9	10	11	12	13
Project 1	0	50	50	50	50	50	0
Project2	50	75	75	75	50	50	0
Project3	50	100	100	100	100	100	0

In Scenario 1, because Project 3 has the lowest inventory cost and unlimited capacity, we note two features in the Stage 1 optimal allocation: (1) Project 3 is used as a storage area and the delayed units of Product A from Project 2 are transferred to Project 3 instead changing orders with the supplier to build a buffer and to minimize the penalty cost associated with changing orders, (2) using Project 3 will have the most on-hand inventory in Stage 2 because it is used as a storage area. Units are transferred with a priority of satisfying the need for expedited units at Product B will be to the project site with lower inventory level (Project 2) and not to the project with higher shortage cost (Project 3).

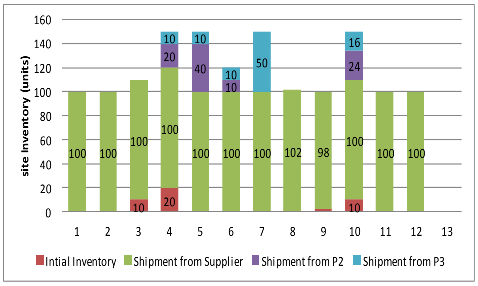
In Scenario 2, as the storage capacity of Project 3 decreased: (1) The number of delayed units of Product A transferred to Project 3 in Stage 1 decreased and the number of transshipments in Stage 2 from Project 3 increased from 240 units in Scenario 1 to 370 units because the storage capacity decreased in Scenario 2. (2) The number of Product B units shipped from the supplier to Project 2 in response to the request for expediting in Stage 1 decreased and the number of units transshipped in Stage 2 from Project 3 to satisfy the expediting request increased from 340 units to 374 units. We can see this at *t*=8, the number of transshipment of Product B in Scenario 1 is zero and increased to 75 in Scenario 2.

As the storage capacity of Project 3 becomes more restricted from $Cap_{3t}=\infty$ (Scenario 1) to $Cap_{3t}=0$ (Scenario 3), the total cost increased by 5.6%. This is because Project 3 can no longer be the storage area for other projects and the inventory is shifted to Project 2. Thus, Project 2 starts carrying the additional inventory from the beginning of the planning horizon. Figure 4.3 compares the material flow of Scenario 3 and Scenario 1. Notice that the inventory level of Project 2 in Scenario 3 increased because transshipments from Project 3 to Project 2 increased to satisfy the storage restriction among the project sites. For example:

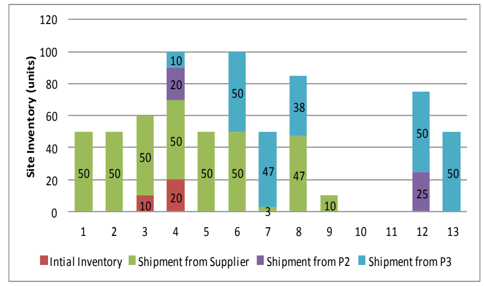
- At *t*=2 , 10 units of Product A and Product B were transshipped from Project 3 to Project 2 so the inventory of Project 2 increased from 10 units to 20 units and the total cost increased by 51.5 %.
- At *t*=3, 10 units of Product A and Product B were transshipped from Project 3 to Project 2 so the inventory of Project 2 increased from 20 units to 40 units and the total cost increased by 37%.
- At *t*=5, 10 units of Product B were transshipped from Project 3 to Project 2 so the inventory of Project 2 increased from 40 units to 50 units and the total cost by 12%.

On the other hand, as the storage capacity of Project 3, decreased, the number of transshipped units in Stage 2 increased by 128.8% for Product A. This is because more units needed to be transshipped from Project 3. Also, the number of transshipped units of

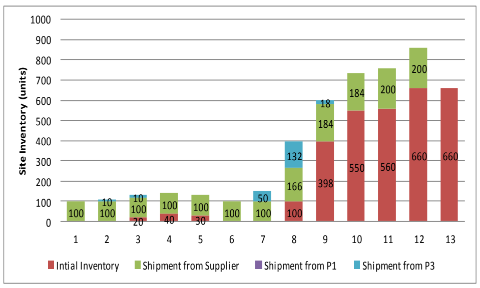
Product B increased by 2.6% because, as the storage capacity of Project 3 decreased to zero, the role of storage area will be shifted from Project 3 to Project 2. The priority of satisfying the expedited units requested in Stage 1 will be shifted from Project 2 to Project 3. The number of transshipped units in Stage 2 at t=8 from Project 3 to Project 2 increased from zero to 15 units to satisfy the shortage in Project 2.



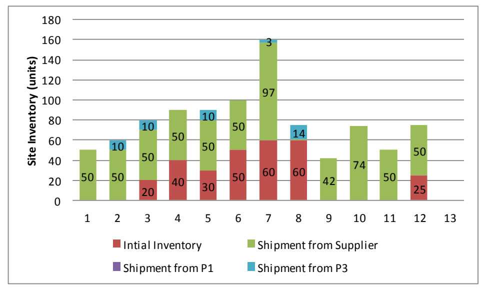
Project 1- Product A



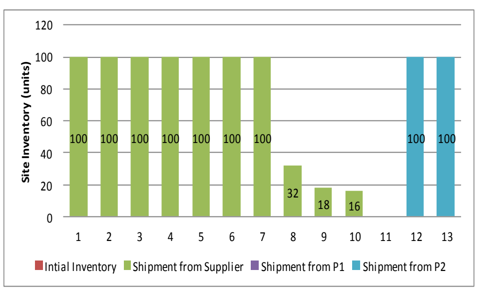
Project 1- Product B



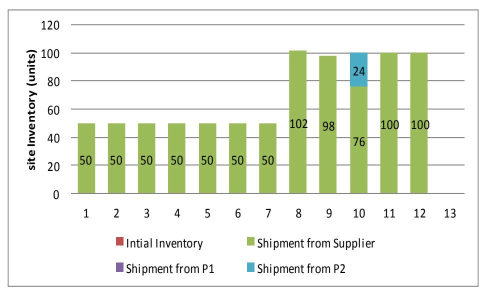
Project 2- Product A



Project 2- Product B



Project 3- Product A



Project 3- Product B

Figure 4.3: Material Flow for Scenario 3 (Cap_{3t}=0)

Finally, the increasing in the total cost associated with decreasing the storage capacity from Cap_{3t}=400(Scenario2) to Cap_{3t}=0 (Scenario 3) is 1.4%. The reasons for this increased total cost are twofold:

- The total number of units (Product A and Product B) shifted from Project 3 to Project 2 by transshipment increased by 33% because the storage capacity in Project 3 decreased.
- An increase in the number of trucks was required to satisfy the requested expediting of Project 1 in Scenario 3. This can be clearly seen at t=4. The optimal solution in Scenario 2 transships 30 units of Product A and Product B from Project 2 to Project 1 using two trucks. The solution of Scenario 3 transships these 30 units differently; 20 units come from Project 2 and 10 units from Project 3 which requires a total of three trucks. This results in increasing the total cost at t=4 by 7.4%.

We observe that the number of transshipment of Product B decreased from Scenario 2 to Scenario 3. The reason for this is because the storage capacity of Project 3 in Scenario 3 is more restricted than in Scenario 2, the inventory level of Project 2 in Scenario 3 is higher than in Scenario 2. As such, we observe that in Scenario 3, the number of transshipment from Project 3 to satisfy the expedited units of Project 2 decreased because the on-hand inventory of Project 2 increased. For example, by comparing Project 2-Product B in Figure 4.1 (Scenario 2) and Figure 4.3 (Scenario 3), notice that at t=7, the inventory level of Project 2 in Scenario 3 is 130 unit higher than 60 units in Scenario 2, and the number of transshipment from Project 3 at t=8 so in Scenario 3 at t=8 is 15 units that is less than 75 units in Scenario 2.

4.3.2 Vary the number of trucks available for transportation in both Stage1 and Stage2

Restricting the transportation capacity is now considered which means that transportation quantities from the supplier to the project sites determined in Stage 1 and the transshipment quantities between the project sites determined in Stage 2 are limited. This is accomplished by restricting maximum number of trucks available in the Stage 1 decision support model (L_1) and the Stage 2 model (L_1). The base case of this case study has no restriction on the number of trucks (unlimited). This case has an optimal solution of 13 trucks in Stage 1 and 4 in Stage 2. The cases investigated now are generated by decreasing these transportation capacities by one truck at each time. We will analyze the effect of restricting transportation capacity of Stage 1 under two levels (L_1=unlimited, L_1=12) and Stage 2 under four levels (L2=4, L_2=3, L_2=2, L_2=1) on the performance of the CSC. Table 4.6 shows the effect of Stage 1 transportation capacity on the total cost, total inventory level, and total number of shortages during the planning horizon. We observe that the Stage 1 transportation capacity with an unlimited number of trucks (L_1=unlimited) has the effect that is produces the minimum average total cost, average total inventory level, and average total number of shortage. There is a reduction in the average total cost by \$4,657 from L_1=12 to L_1= 13 or by 0.3%. And the average total inventory level reduced by 23 units or 4%. The average total number of units short decreased by 23 units or 10%. The reason for this improvement is that when the number of trucks in Stage 1 is unlimited, the required units are delivered to some site to meet any increase in demand and the transshipments in Stage 2 adjust to inventory further if Stage 1 is unable to ship directly because of storage capacity restrictions. We will discuss the effect of Stage 1 transportation capacity on each criterion individually.

Figures 4.4 to 4.6 show the effect of Stage 1 transportation capacity on the total cost, total inventory level, and total number of shortage over different number of trucks in Stage 2. Also, the figures show the effect of Stage 2 transportation capacity over different number of trucks in Stage 1. As mention earlier, the unlimited Stage 1 transportation capacity has the effect on reducing the total cost, total inventory level, and total number of shortage over the number of trucks in Stage 2.

Table 4.7: The effect of Stage 1 transportation capacity on the performance of CSC

Number of trucks in Stage 1 (L1)	Number of trucks in Stage2 (L2)	Total Cost ($)	Total Inventory Level (units)	Total Shortage (units)
Limited (12)	4	1,631,425	567	192
	3	1,633,160	600	225
	2	1,628,535	604	229
	1	1,631,240	700	325
	Average	**1,631,090**	**618**	**243**
Unlimited (13)	4	1,628,345	560	185
	3	1,626,770	567	192
	2	1,626,670	584	209
	1	1,625,285	667	292
	Average	**1,626,768**	**595**	**220**

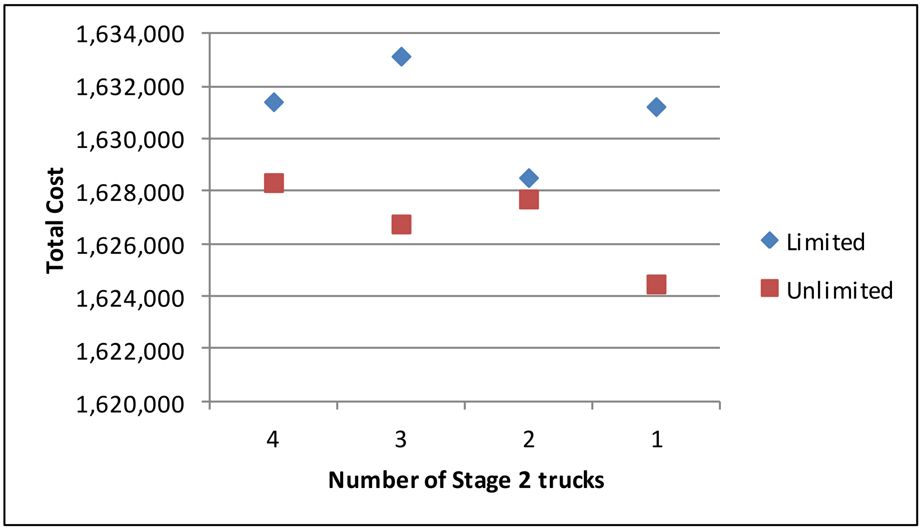


Figure 4.4: The effect of Stage 1 and Stage 2 transportation capacity on the total cost

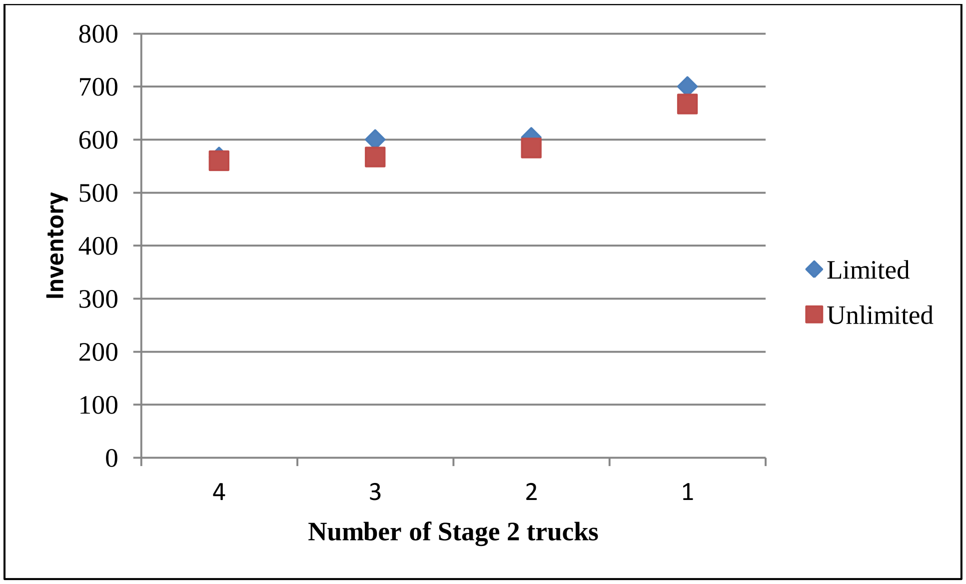


Figure 4.5: The effect of Stage 1 and Stage 2 transportation capacity on the total inventory level

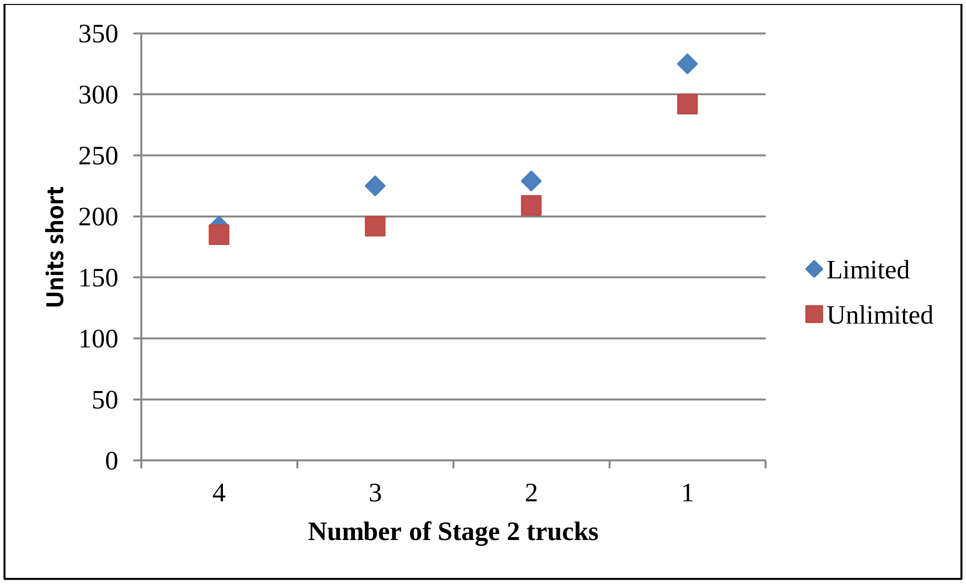
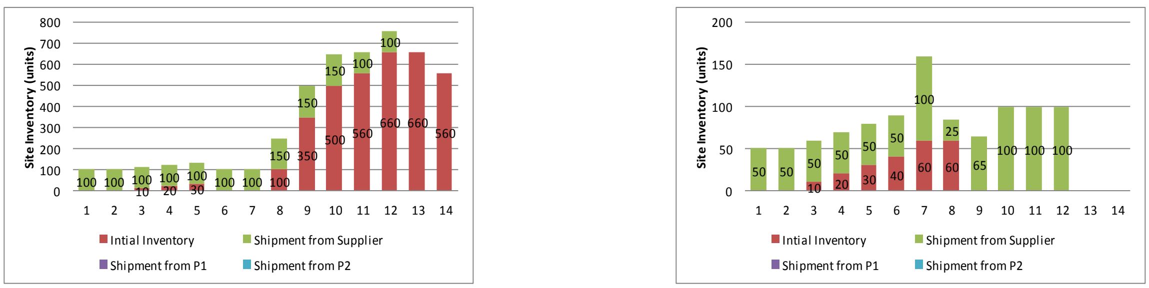


Figure 4.6: The effect of Stage 1 and Stage 2 transportation capacity on the total shortage units

Figures 4.7 and 4.8 compare the material flow between L_1=unlimited and L_1=limited with an unlimited number of trucks in Stage 2 to illustrate interactions between the stages and provide insight into the shape of the total cost figures. For example, the initial forecasted demand for Product B at Project 3 at t=10 was 50 units; however, this forecast at Stage 1 was increased to 100 units. So, Figure 4.7 shows that the supplier is able to satisfy this update and ship 100 units to Project 3 with an unlimited number of trucks available in Stage 1. In case of a limited number of trucks in Stage 1, Figure 4.8 shows that the supplier will only be able to ship only 75 units at t=10. As such, the total cost in Stage 1 will increase because of the shortage cost associated with not satisfying the expedited demand of Product B at Project 3. In addition, because the expedited units of Product B at Project 3 are not satisfied from the supplier when

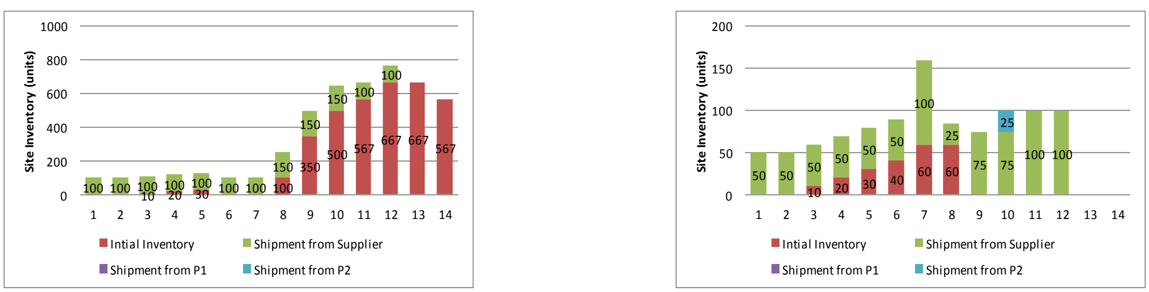
L_1=limited, there is transshipment of 25 units of Product B from Project 2 to Project 3 at *t*=10 to avoid a shortage at Project 3. In total, these costs increase the total cost of Product B at Project 3 at *t*=10 by 10% and the total cost from L_1=unlimited and L_1=limited increased by 0.3%.



Project 3-Product A

Project 3-Product B

Figure 4.7: Material Flow with (L_1= unlimited, L_2=4



Project 3- Product A

Project 3-Product B

Figure 4.8: Material Flow with (L_1= unlimited, L_2=4)

Furthermore, from Figures 4.5 and 4.6 we observed that both inventory and number of shortages are proportional to the number of trucks in both Stage 1 and Stage 2 which is totally right because the demand will not be met. However, in Figure 4.4 we observe that the total cost of CSC is not proportional to the number of trucks. Reducing the transshipment capacity in Stage 2 has different impact on the total cost based on the total cost of Stage 2 that depends on the total number of transshipped units, total number of shortage units, and total inventory level. The reasons are discussed below:

- Reducing the number of trucks from L_2=4 to L_2=3, decreases the total cost for L_1=unlimited by $1,575 and increase it for L_1=limited by $1,735.
  - For L1=unlimited in Table 4.8, at *t*=7, Project 1 received 50 units of Product B from Project 3 when L_2=4 but zero units when L_2=3. Similarly, at *t*=10 Project 1 received 40 units Product A from Project 3 when L_2=4 but only 33 units when L_2=3. By comparing the results of Stage 2 between L_2=4 and L_2=3, the reduction in the number of transshipments is 42 units, that is more than the increasing in the number of shortage and total inventory is only 7. So, based on the cost parameters in this case study example, the total cost of Stage 2 decreased from L_2=4 and L_2=3 by $1,575.
  - For L1=limited in Table 4.9, at *t*=7, Project 1 received 50 units of Product B from Project 3 when L_2=4 but zero units when L_2=3. At *t*=10 Project 1 received 33 units Product A from Project 3 when L_2=4 but zero units when L_2=3. By comparing the results of Stage 2 between L_2=4 and L_2=3, the reduction in the number of transshipments is 58 units, that is greater than the increasing in the number of shortage and the total inventory is 33 units, so the total cost of Stage 2 increased from L_2=4 and L_2=3 by $1,735.

Table 4.8: Material flow for reducing the transshipment capacity in Stage 2 from L_2=4 to L_2=3 (L1=unlimited)

L_1 L_2	*t*	type	STAGE 1			STAGE 2							
			Scheduled Shipment			Route	units	Inv.Level			Short. Level		
			P1	P2	P3			P1	P2	P3	P1	P2	P3
L_1=13 L_2=4	7	A	100	100	100	P2 to P1	50	0	0	100	0	0	0
		B	0	50	100	P3 to P1 P3 to P2	50 50	0	0	60	0	0	0
	10	A	100	50	150	P3 to P1 P3 to P2	40 50	0	0	560	0	0	0
		B	0	50	100	-	-	0	0	0	0	0	0
L_1=13 L_2=3	7	A	100	100	100	P2 to P1	50	0	0	100	0	0	0
		B	0	50	100	P3 to P2	50	0	0	110	50	0	0
	10	A	100	50	150	P3 to P1 P3 to P2	33 50	0	0	567	7	0	0
		B	0	50	100	-	-	0	0	0	0	0	0

Table 4.9: Material flow for reducing the transshipment capacity in Stage 2 from L_2=4 to L_2=3 (L1=limited)

L_1 L_2	*t*	type	STAGE 1			STAGE 2							
			Scheduled Shipment			Route	units	Inv.Level			Short. Level		
			P1	P2	P3			P1	P2	P3	P1	P2	P3
L_1=12 L_2=4	7	A	100	100	100	P2 to P1	50	0	0	100	0	0	0
		B	0	50	100	P3 to P1 P3 to P2	50 50	0	0	60	0	0	0
	10	A	100	50	150	P3 to P1 P3 to P2	33 50	0	0	567	7	0	0
		B	0	75	75	P2 to P3	50	0	0	0	0	0	0
L_1=12 L_2=3	7	A	100	100	100	P2 to P1	50	0	0	100	0	0	0
		B	0	50	100	P3 to P2	50	0	0	110	0	0	0
	10	A	100	50	150	P3 to P2	50	0	0	600	40	0	0
		B	0	75	75	P2 to P3	25	0	0	0	0	0	0

- Reducing the number of trucks in Stage 2 from L_2=3 to L_2=2, increases the total cost for L_1=unlimited by \$950 and decreases it for L_1=limited by \$4,625.
  - For L_1=unlimited in Table 4.10, at *t*=7, Project 1 received 50 units of Product A from Project 2 when L_2=3 but 33 units when L_2=2 because of the truck capacity restriction. Similarly, at *t*=10 Project 2 received 50 units of Product A from Project 3 when L_2=3 but only 33 units when L_2=2. By comparing the results of Stage 2 between L_2=3 and L_2=2, the reduction in the number of transshipments is 38 units, the increasing in the number of shortage and the total inventory level is 17 units. So, based on the cost

parameters in this case study example, the total cost of Stage 2 increased from L_2=3 to L_2=2 by $1,230.

- For L_1=limited in Table 4.11, at *t*=7, Project 1 received 50 units of Product A from Project 2 when L_2=3 but 18 units when L_2=2. At *t*=10 Project 2 received 50 units Product A from Project 3 when L_2=3 but 18 units when L_2=2. By comparing the results of Stage 2 between L_2=3 and L_2=2, the reduction in the number of transshipments is 70 units and the increasing in the number of shortage and the total inventory level is 33 units. So, the total cost of Stage 2 decreased from L_2=3 and L_2=2 by $4,935.

Table 4.10: Material flow for reducing the transshipment capacity in Stage 2 from L_2=3 to L_2=2 (L_1=unlimited)

L_1 L_2	*t*	type	STAGE 1			STAGE 2							
			Scheduled Shipment			Route	units	Inv.Level			Short. Level		
			P1	P2	P3			P1	P2	P3	P1	P2	P3
L_1=13 L_2=3	7	A	100	100	100	P2 to P1	50	0	0	100	0	0	0
		B	0	50	100	P3 to P2	50	0	0	110	50	0	0
	10	A	100	50	150	P3 to P1 P3 to P2	33 50	0	0	567	7	0	0
		B	0	50	100	-	-	0	0	0	0	0	0
L_1=13 L_2=2	7	A	104	100	96	P2 to P1	33	0	17	100	13	0	0
		B	0	50	100	P3 to P2	50	0	0	110	50	0	0
	10	A	100	50	150	P3 to P1 P3 to P2	33 33	0	0	584	7	0	0
		B	0	50	100	-	-	0	0	0	0	0	0

Table 4.11: Material flow for reducing the transshipment capacity in Stage 2 from L_2=3 to L_2=2 (L_1=limited)

L_1 L_2	*t*	type	STAGE 1			STAGE 2							
			Scheduled Shipment			Route	units	Inv.Level			Short. Level		
			P1	P2	P3			P1	P2	P3	P1	P2	P3
L_1=12 L_2=3	7	A	100	100	100	P2 to P1	50	0	0	100	0	0	0
		B	0	50	100	P3 to P2	50	0	0	110	0	0	0
	10	A	100	50	150	P3 to P2	50	0	0	600	40	0	0
		B	0	75	75	P2 to P3	25	0	0	0	0	0	0
L_1=12 L_2=2	7	A	132	100	68	P2 to P1	18	0	32	72	0	0	0
		B	2	50	98	P3 to P2	50	0	0	108	48	0	0
	10	A	100	50	150	P3 to P2	18	0	0	604	40	0	0
		B	0	75	75	P2 to P3	25	0	0	0	0	0	0

- Reducing the number of trucks in Stage 2 from L_2=2 to L_2=1, decreases the total cost for L_1=unlimited by \$3,235and increases it for L_1=limited by \$2,705.
  - For L_1=unlimited in Table 4.12, at *t*=7, Project 1 received 33 units of Product A from Project 2 when L_2=2 but 10 units when L_2=1. At *t*=10 Project 2 received 33 units of Product A from Project 3 when L_2=2 but zero units when L_2=1. At *t*=12 Project 1 received 50 units of Product B from Project 3 when L_2=2 but zero units when L_2=1.By comparing the results of Stage 2 between L_2=2 and L_2=1, the reduction in the number of transshipments is 192 units, the increasing in the number of shortage and

the inventory is 83 units. So, the total cost of Stage 2 decreased from L_2=2 to L_2=1 by $1,345.

- For L1=limited in Table 4.13, at *t*=7, Project 1 received 18 units of Product A from Project 2 when L_2=2 but zero units when L_2=1. At *t*=10 Project 2 received 18 units Product A from Project 3 when L_2=2 but zero units when L_2=1. At *t*=12 Project 1 received 50 units of Product B from Project 3 when L_2=2 but zero units when L_2=1 By comparing the results of Stage 2 between L_2=2 and L_2=1 L_1=limited, the reduction in the number of transshipments is 155 units and the increasing in the number of shortage and the inventory level is 96 units, so the total cost of Stage 2 increased from L_2=2 to L_2=1 by $7,055.

Table 4.12: Material flow for reducing the transshipment capacity in Stage 2 from L_2=2 to L_2=1 (L_1=unlimited)

L_1 L_2	*t*	type	STAGE 1			STAGE 2							
			Scheduled Shipment			Route	units	Inv.Level			Short. Level		
			P1	P2	P3			P1	P2	P3	P1	P2	P3
L_1=13 L_2=2	7	A	104	100	96	P2 to P1	33	0	17	100	13	0	0
		B	0	50	100	P3 to P2	50	0	0	110	50	0	0
	10	A	100	50	150	P3 to P1 P3 to P2	33 33	0	0	584	7	0	0
		B	0	50	100	-	-	0	0	0	0	0	0
	12	A	100	100	100	-	-	0	0	684	0	0	0
		B	0	50	100	P2 to P1 P3 to P1	25 50	0	0	0	25	0	0
L_1=13 L_2=1	7	A	150	100	50	-	-	0	50	100	0	0	0
		B	0	0	140	P3 to P2	50	0	0	140	50	0	0
	10	A	100	50	150	P3 to P1	33	0	0	617	7	0	0
		B	0	50	100	-	-	0	0	0	0	0	0
	12	A	100	100	100	-	-	0	0	717	0	0	0
		B	0	50	100	P2 to P1	25	0	0	50	75	0	0

Table 4.13: Material flow for reducing the transshipment capacity in Stage 2 from L_2=2 to L_2=1 (L_1=limited)

L_1 L_2	*t*	type	STAGE 1			STAGE 2							
			Scheduled Shipment			Route	units	Inv.Level			Short. Level		
			P1	P2	P3			P1	P2	P3	P1	P2	P3
L_1=12 L_2=2	7	A	104	100	96	P2 to P1	33	0	17	100	13	0	0
		B	0	50	100	P3 to P2	50	0	0	110	50	0	0
	10	A	100	50	150	P3 to P1 P3 to P2	33 33	0	0	584	7	0	0
		B	0	50	100	-	-	0	0	0	0	0	0
	12	A	100	100	100	P2 to P1	50	0	0	100	0	0	0
		B	0	50	100	P3 to P2	50	0	0	110	0	0	0
L_1=12 L_2=1	7	A	150	100	50	-	-	0	50	100	0	0	0
		B	25	50	75	P3 to P2	50	0	0	115	25	0	0
	10	A	100	50	150	-	-	0	0	650	40	0	0
		B	0	75	75	P2 to P3	25	0	0	110	0	0	0
	12	A	100	100	100	-	0	0	0	750	0	0	0
		B	0	50	100	P2 to P1	25	0	0	50	0	0	0

4.4. Conclusions and Future Research

In this chapter, the two-stage methodology for managing and controlling the material flow between multiple projects in CSC is extended to include multiple products with different volumes under a significantly more constrained environment to add more realism and complexity to the project's planning and scheduling. The key function is to analyze and compare the impact of the storage and transportation capacity constraints on

CSC behavior and on construction projects' performance under the case of limited production capacity at the supplier. The underlying deterministic optimization models have been modified to include these capacity constraints. The methodology was applied to two examples; the first example varied the storage capacity at one of the project sites, the results showed the resilience and flexibility of the proposed methodology with the incorporation of transshipment in controlling and managing the CSC with different storage capacities. The controls of the material flow were effectively optimized by enhancing the sharing and collaboration practices between the project sites and the supplier. The second example varies the transportation capacity in Stage 1 and the transportation capacity in Stage 2. The methodology continued to effectively control the restriction in the capacity and mitigate the risk of delay in schedule and decrease the excess inventory.

CHAPTER FIVE

A TWO-STAGE METHODOLOGY WITH EXTERNAL STORAE SITE FOR MULTIPLE-MATERIAL FLOW CONTROL IN CONSTRUCTION SUPPLY CHAIN

5.1. Introduction

In Chapter 4, a two-stage methodology was proposed to coordinate the feed-forward control of advanced order placement with a supplier to a feedback local control in the form of adding the ability to transship materials between projects to improve efficiency and reduce costs. It focused on the single supplier integrated production and transshipment problem with a multiple products.

In this chapter, the methodology is used as a design tool for the CSC because it is modified to include an external storage site not associated with one of the projects. The idea is to add this feature to a highly constrained environment to explore its effectiveness at buffering the impact of variability and maintaining project schedule at low cost. The methodology addresses an integrated Production and Transshipment Problem of Single supplier, Multiple projects, Multiple materials, and an external storage area which henceforth, will be referred to as PTPSMME.

The proposed two-stage methodology (PTPSMME) operates as before. Stage 1 is the current order fulfillment process used at project sites while Stage 2 adds the opportunity for transshipments to occur between the projects and the storage sites. Transportations and transshipments both occur using a limited number of trucks, each with equal but finite weight capacity. In Stage 1, orders are placed with the supplier and shipped directly to the project sites without holding intermediate inventory. The external storage site may receive shipments from the supplier to build buffer against the demand variation. Also, each project site can hold its inventory at project's warehouse. Stage 2 offers the opportunity to redeploy the materials based on actual demand. Materials are transported from the supplier to each project site based on their initial scheduled delivery dates and Stage 2 will provide information to Stage 1 if the actual and forecasted demand agreed. In the case of disruption at one or more of the project sites or at suppliers, Stage 2 optimization model will accommodate it by adjusting inventory using a deterministic optimization model. Stage 2 will determine if transshipments between the project sites and the between the project sites and the external storage site will reduce the total cost and provide Stage 1 with information of inventory level and updated forecasted demand of each project site.

The contribution of this extension is both in inclusion of extra storage site and adding significant capacity constraints to the system. The capacity constraints encompass the production, storage, and transportation. Our main focus is to analyze and compare the impact of the external storage site on CSC behavior and on construction projects' performance under highly constrained model for different transportation scenarios.

5.2. Mixed Integer Programming Model for the PTPSMME

The two-stage methodology with a single supplier possessing limited production capacity of a single product that is used at all project sites that have unlimited storage capacity was outlined in Chapter 3. The methodology was extended to include two products with different volumes, limited storage capacity at the project sites, and limited transportation capacity (limited number of trucks) in Chapter 4. Here, the problem of Chapter 4 will be extended in way that uses it to explore the efficacy of changing the design of the CSC by adding an external storage site.

The CSC network here considered suppliers with finite production capacity and no inventory charges associated with any stock held there. Transit times from the suppliers to project sites as well as the times to load and unload are not considered. The supplier *i* must deliver *k* product types to N sites (project sites and storage site). Future deliveries from the suppliers can be adjusted periodically based on updated forecasted demand in Stage 1; and, the ability to transship materials between project sites and the external storage site is possible based on the control of Stage 2.

Several assumptions are made related to the delivery trucks in Stage 1 and Stage 2 to add more realism to the problem which, in this methodology, means additional restrictions. (1) A fleet of identical trucks is used to ship the products from the suppliers to each project site, between the project sites, and between the project sites and the external storage site. (2) Multiple routes and multiple stops on a route are not permitted; that is, each truck delivers to only one site during a single trip. (3) Each truck has a maximum total weight restriction that should not be exceeded. (4) Each truck has a limited amount of product *k* that could carry. (5) Each supplier, project site, and external storage site has its own trucks. (6) The total number of trucks at each supplier, project site, and external storage site is limited.

5.2.1. Mathematical Model of Stage 1

Stage 1 of the methodology uses a deterministic model to determine the shipments of each product type *k* to each site *j* respecting the production and the transportation capacity of supplier *i*. That is, Stage 1 determines the material flow at the beginning of time period *t*=1 for the entire planning horizon based on forecasted consumption, and then updates the orders to the supplier (and, hence, the material flow) at predetermined intervals, τ, thereafter. Stage 1 executes in the following order: (1) At time period *t*=1, the initial forecasted demand D_{jkt} for each product *k* at each site *j* for each time period *t* is used to determine the number of units to be shipped in all future periods, X_{ijkt}. (2) At the next updating period τ, Stage 2 will provide information to Stage 1 regarding the inventory level of each product $I_{j,k,t-1}$ at each site *j* with any updating in the forecasted demand D_{jkt} that is different from the initial one in the beginning of the time horizon (for example, if the project is expecting to expedite or to delay then the project manager could request updating on the initial forecasted demand). (3) Stage 1 will compare the inputs of Stage 2 ($I_{j,k,t-1}$ and D_{jkt}) with the production capacity of supplier *i* to find the number of units to be shipped to each project site, X_{ijkt}, that produces the minimum total cost. This completes the updated feed forward part of the controller, Stage1.

To accommodate the fact that the updated forecasted consumption D_{jkt} might exceed the supplier capacity, penalty costs are assigned to these expediting requests based on the time that the order was scheduled for shipment. Specifically, the penalty cost for updating an order that was scheduled to be shipped nearer the current period is higher than a shipment scheduled for delivery further in the future. In addition, it is possible that the forecasted consumption cannot be satisfied because of constraints in the system. This is accommodated by inclusion of a term that tracks the number of items "shorted" and it is denoted S_{jkt}. Note that in this methodology, shorting items can happen for three reasons. (1) There is insufficient supplier production capacity. (2) The storage capacity at the construction site is full and cannot accept a shipment. (3) The scheduled quantities required to meet the updated demand exceeds the capacity or the allowed weight of the trucks. Finally, it is possible that delayed consumption would suggest that shipments be delayed. This is accommodated within the model with the delayed units assigned to a penalty cost. The magnitude of the penalty varies as is does with shorting orders scheduled for shipment closer to the current time are penalized more than orders scheduled further in the future. The following notation is used in the optimization model that supports decisions made in Stage 1:

Indices

$i \in S = \{1, 2, ..., \mathrm{S}\}$ the set of suppliers

$j \in N = \{1, 2, ..., \mathrm{N}\}$ the set of project sites that includes the external storage site

$t \in T = \{1, 2, ..., \mathrm{T}\}$ time periods up to the end of the planning horizon, T

$k \in K = \{1, 2, ..., \mathrm{K}\}$ the set of types of unique products

Input Parameters

C^{1}_{ijkt} ordering cost for a unit of product *k* procured from supplier *i* by site *j* at time *t*, *i*∈S, *j*∈*N*, *k*∈*K*, *t*∈*T* ($/unit)

UT^{1}_{ijt}	transportation cost associated with each truck used to transport the orders from supplier i to site j at time t, $i \in S$, $j \in N$, $t \in T$ ($/mile)
PC_{kt}	penalty cost to expedite or delay unit of product k at time t, $k \in K$, $t \in T$ ($/unit)
Q^{1}_{jkt}	per unit cost of shortage of product k at site j during time t, $j \in N$, $k \in K$, $t \in T$ ($/unit)
Q^{2}_{jkt}	per unit cost of inventory of product k at site j during time t, $j \in N$, $k \in K$, $t \in T$ ($/unit)
D_{jkt}	forecasted demand of product k at site j at time t, $j \in N$, $k \in K$, $t \in T$ (units)
F_{ijkt}	number of units scheduled to be shipped from supplier i to site j at t from the previous Stage 1 update, $i \in S$, $j \in N, k \in K, t \in T$ (units)
Cap_{it}	production capacity of supplier i at time period t, $i \in S$, $t \in T$ (units)
$Invcap_{jt}$	the storage capacity of site j at t, $j \in N$, $t \in T$ (ft^3)
v_k	the volume of product k, $k \in K$ (ft^3/unit)
w_k	the weight of product k, $k \in K$ (pounds/unit)
W	the maximum weight a truck can carry (pounds)
η_k	the maximum weight of product k a truck can carry, $k \in K$ (units)
L_{1i}	the maximum number of trucks available at supplier i , $i \in S$

<u>Computed variables</u>

U_{jkt}	total number of expedited and delayed units of product k requested by site j at time t, $j \in N, k \in K, t \in T$ (units)

S_{jkt} number of units of product k that are short at site j at time t, $j\in N,k\in K,t\in T$ (units)

I_{jkt} end of period on-hand inventory of product k at site j at time t, $j\in N,k\in K,t\in T$ (units)

M^1_{ijt} number of trucks used to ship all orders the from supplier i to site j at time t, $i\in S$, $j\in N$, $k\in K,t\in T$

Decision variables

X_{ijkt} number of units of product k transported from supplier i to site j at time t (units)

With these variables, the following Stage1 model is proposed for the PTPSMME problem:

$$Min\ \ Z=\sum_{i\in S}\sum_{j\in N}\sum_{k\in K}\sum_{t\in T}\left(C^1_{ijkt}X_{ijkt}+UT^1_{ijt}M^1_{ijt}\right)+\sum_{j\in N}\sum_{k\in K}\sum_{t\in T}PC_{kt}U_{jkt}+\sum_{j\in N}\sum_{k\in K}\sum_{t\in T}Q^1_{jkt}S_{jkt}+\sum_{j\in N}\sum_{k\in K}\sum_{t\in T}Q^2_{jkt}I_{jkt}$$

Subject to:

$$U^+_{jkt}=\sum_{i\in S}\left(X_{ijkt}-F_{ijkt}\right)\qquad \forall j\in N,k\in K,t\in T \qquad (1)$$

$$U^-_{jkt}=\sum_{i\in S}\left(F_{ijkt}-X_{ijkt}\right)\qquad \forall j\in N,k\in K,t\in T \qquad (2)$$

$$U_{jkt}=U^+_{jkt}+U^-_{jkt}\qquad \forall j\in N,k\in K,t\in T \qquad (3)$$

$$I_{jkt}=I_{j,k,t-1}+\sum_{i\in S}X_{ijkt}-D_{jkt}+S_{jkt}\qquad \forall j\in N,k\in K,t\in T \qquad (4)$$

$$I_{j,k,t-1} = a \qquad j \in N, k \in K, t \in T, \text{ where } a = 0 \text{ at } t = 1 \tag{5}$$

$$\sum_{j \in N} X_{ijkt} \leq Cap_{ikt} \qquad \forall i \in S, k \in K, t \in T \tag{6}$$

$$\sum_{i \in S} \sum_{k \in K} v_k * X_{ijkt} \leq Invcap_{jt} \qquad \forall j \in N, t \in T \tag{7}$$

$$\sum_{k \in K} w_k * X_{ijkt} / W = M^1_{ijt} \qquad \forall\ i \in S, j \in N, t \in T \tag{8}$$

$$M^1_{ijt} \leq \mathrm{L}_{1i} \qquad \forall\ i \in S, j \in N, t \in T \tag{9}$$

$$w_k * X_{ijkt} \leq \eta_k \qquad \forall\ i \in S, j \in N, k \in K, t \in T \tag{10}$$

$$X_{ijkt} \geq 0 \tag{11}$$

Constraints (1), (2), and (3) determine the number of units of each product type to be expedited, delayed, and the total units changed at *t*. Constraint (4) is the inventory balance for each product type in each time period at the sites. Constraint (5) defines the inventory from the previous period and it is assumed that the planning horizon begins with zero at each site. Constraints (6) and (7) enforce the supplier production capacity and site storage capacity restriction. Constraint (8) calculates the required number of trucks to ship the orders to each site under the restriction of the maximum weight per a truck. Constraint (9) limits the maximum number of available trucks at each supplier. Constraint (10) restricts the maximum weight of product type *k* that can be in each shipment. Finally, the non-negativity constraint is represented in (11).

5.2.2. Mathematical Model of Stage 2

Stage 2 of the methodology is a feedback-type controller that utilizes a deterministic model based on actual consumption and the forecasted deliveries from the supplier in the future. This model determines the transshipments between the project sites as well as between project sites and the external storage site respecting the transportation constraints (i.e., the limited number of trucks and their maximum allowable weight). The model includes costs for transportation, shortages, and holding inventory. The decisions in Stage 2 allow adjustments in inventory at the project sites and the external storage site to accommodate disruptions. Clearly, this strategy will have the most beneficial effects if performed between Stage 1 updates; however, as noted in Chapter 3, since Stage 1 and Stage 2 are most often completely independent, this is not necessarily the case. The objective function of the optimization model that determines Stage 2 actions minimizes the costs of transportation associated with transshipping, inventory, and shortages. Each project site has limited storage capacity to accommodate all of the products; however, the external storage site is assumed to have unlimited storage capacity. It is assumed that all product types can be transported together and/or stored together, but each product type can have a unique weight and volume. In this model, storage capacity is restricted based on total volume while the truck capacity is restricted based on total weight. The following notation is used in the Stage 2 optimization model:

<u>Indices</u>

$i \in S = \{1, 2, ..., \mathrm{S}\}$ the set of suppliers

$j \in N = \{1, 2, ..., \mathrm{N}\}$ the set of project sites that includes the external storage site

$t \in T = \{1, 2, ..., \mathrm{T}\}$ time periods up to the end of the planning horizon, T

$k \in K = \{1, 2, ..., \mathrm{K}\}$ the set of types of unique products

Input Parameters

C^2_{djkt}	the ordering cost for a unit of product *k* procured from site *d* by site *j* at time *t* , $d,j \in N$, $k \in K$, $t \in T$ (\$/unit)
$UT^2{}_{djt}$	transportation cost from site *d* to site *j* at time *t*, $d,j \in N$, $t \in T$ (\$/mile)
Q^1_{jkt}	per unit shortage cost of product *k* at site *j* during *t* , $j \in N$, $k \in K$, $t \in T$ (\$/unit)
Q^2_{jkt}	per unit holding cost of product *k* at site *j* during time *t*, $j \in N$, $k \in K$, $t \in T$ (\$/unit)
Δ_{jkt}	actual demand of product *k* at site *j* at time *t*, $j \in N$, $k \in K$, $t \in T$ (units)
v_k	the volume of product *k*, $k \in K$ (ft^3/unit)
w_k	the weight of product *k*, $k \in K$ (ft^3/unit)
W	the maximum weight a truck can carry (pounds)
$Invcap_{jt}$	the storage capacity of site *j* at *t*, $j \in N$, $t \in T$ (ft^3)
L_{2d}	the maximum number of trucks available at site *d*

Input Parameters from Stage 1

F_{ijkt}	number of units of product type *k* scheduled to be shipped from supplier *i* to site *j* at *t* according to latest update of Stage 1, $i \in S$, $j \in N$, $k \in K$, $t \in T$ (units)
D_{jkt}	forecasted demand of product type *k* at site *j* at time *t*, $j \in N$, $k \in K$, $t \in T$, (units)

Computed variables

I_{jkt} end of period on-hand inventory of product k at site j at time t, $j \in N$, $t \in T$, $k \in K$ (units)

S_{jkt} projected number of units of product k that will be short at site j at time t, $j \in N$, $t \in T$ (units)

M^2_{djt} number of trucks used to ship the units of product type k from site d to site j at time t, $d, j \in N$, $t \in T$

Decision variables

Y_{djkt} number of units of product k transported from site d to site j at time t, $d, j \in N$, $k \in K$, $t \in T$ (units)

With these variables, the following Stage 2 model is proposed for the PTPSMME problem:

$$Min\ \ Z = \sum_{d \in N} \sum_{j \in N} \sum_{k \in K} \sum_{t \in T} \left(C^2_{djkt} Y_{djkt} + UT_{djt} M^2_{djt} \right) + \sum_{j \in N} \sum_{k \in K} \sum_{t \in T} Q^1_{jkt} S_{jkt} + \sum_{j \in N} \sum_{k \in K} \sum_{t \in T} Q^2_{jkt} I_{jkt}$$

Subject to:

$$I_{jkt} = I_{j,k,t-1} + \sum_{i \in S} F_{ijkt} + \sum_{d \in N} Y_{djkt} - \sum_{b \in N} Y_{jbkt} + D_{jkt} + S_{jkt} \quad \forall j \in N, k \in K, t \in T \tag{1}$$

$$I_{jkt} = I_{j,k,t-1} + \sum_{i \in S} F_{ijkt} + \sum_{d \in N} Y_{djkt} - \sum_{b \in N} Y_{jbkt} + D_{j,k,t-1} - \Delta_{j,k,t-1} - D_{jkt} + S_{jkt} \quad \forall j \in N, k \in K, t \in T \tag{2}$$

$$\sum_{b \in N} Y_{jbkt} \le I_{j,k,t-1} + D_{j,k,t-1} - \Delta_{j,k,t-1} \quad \forall j \in N, k \in K, t \in T \tag{3}$$

$$\sum_{d\in N}\sum_{k\in K} v_k * Y_{djkt} \leq Invcap_{jt} \qquad \forall j \in N, t \in T \tag{4}$$

$$\sum_{k\in K} w_k * Y_{djkt} / W = M^2{}_{djt} \qquad \forall\, d, j \in N, t \in T \tag{5}$$

$$M^2{}_{djt} \leq \mathrm{L}_{2d} \qquad \forall\, d, j \in N, t \in T \tag{6}$$

$$w_k * Y_{djkt} \leq \eta_k \qquad \forall\, d, j \in N, k \in K, t \in T \tag{7}$$

$$I_{j,k,t-1} = a \qquad j \in N, k \in K, t \in T, \text{ where } a = 0 \text{ at } t = 1 \tag{8}$$

$$Y_{djkt} \geq 0 \tag{9}$$

Constraint (1) is the material balance in the first period after Stage 1 update of the material flow from the suppliers to the sites and it is based on the forecasted demand. Constraint (2) is the material balance in the periods after the first one after a Stage 1 update and using actual demand. Constraint (3) limits the number of units that can be transshipped to the on-hand inventory. Constraint (4) ensures that the total number of transshipped units does not exceed the storage capacity of the site. Constraint (5) calculates the required number of trucks to perform transshipments between the sites under the weight restriction of the truck. Constraint (6) is the restriction on maximum number of trucks available at each site in Stage 2. Constraint (7) restricts the maximum weight of product type *k* that can be in each shipment to represent a weight restriction. Constraint (8) defines the inventory from the previous period. Finally, the non-negativity constraint is included in (9).

5.3. Case Study Examples

The impact that the additional restrictions on storage and transportation capacity as well as the new design that adds external storage site on the operation on the CSC is now explored by a series of case studies. Three cases are investigated to reflect these modifications. Figure 5.1 presents the concept of each case which is summarized as follows:

Case 1: This is the base case in which the CSC does not have an external storage site and transshipments can only occur between the project sites.

Case 2: The addition of an external storage site is now included. Here, the external storage site acts like a distribution center for the project sites in the sense that transshipments are only allowed between the external storage site and the project sites; no transshipments can occur between project sites. This general strategy was reported to be effective in several of the case studies contained in the CII report from RT 172 (Tommelein, Walsh, & Hershauer, 2003)

Case 3: Allowable operations in the modified CSC that included external storage site expanded to include transshipments between project sites as well as between project sites and the external storage site.

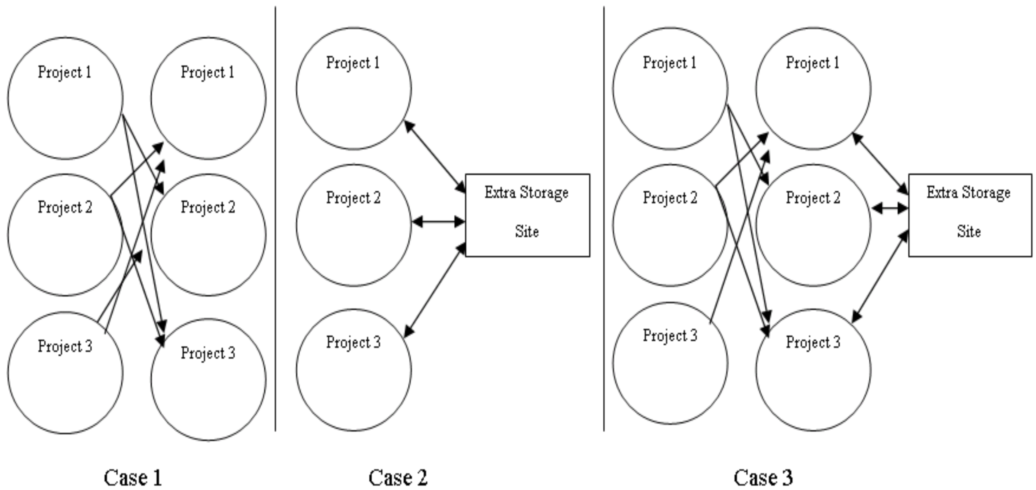


Figure 5.1: The Material flow and transshipment policy for different CSC configurations

For all the cases, the following assumptions are made:

15) There are three project sites (1, 2 and 3) which can consume two Products (A and B).A 13 period planning horizon (T=13) is considered.

16) The updating period (τ) of Stage 1 and the transshipment period (*f*) of Stage 2 are the same as the optimal findings in PTPSMS in Chapter 3. The findings indicate that, the longer the updating period (τ =6) which reflects how frequent is the communication between the central planning in Stage 1 and the site coordinator in Stage2 and the shorter the transshipment period (*f=1*) that allows transshipment to occur every period during the time horizon, the minimum the total cost of the whole CSC.

17) A single supplier produces two different products (Product A and Product B) with limited production capacity to each of them. Hence, *i*=1 always.

18) In Stage 1, the cost for site *j* to order one unit of Product A (Product B) from the supplier at time *t* is \$150/unit (\$200/unit). That is, C^{1}_{1jAt} = \$150/unit and C^{1}_{1jBt} = \$200/unit.

19) In Stage 1 and Stage 2, the transportation cost to deliver one unit of Product A (Product B) from the supplier to each project site and between the project sites is fixed at \$1/mile. That is, UT^{1}_{ijt} and UT^{2}_{djt} =\$1/mile.

20) The distance of the external storage site from the supplier in Stage 1 is 70 miles and from the project sites in Stage 2 is 40 miles that is assumed to be longer than the distance of the project sites from the supplier and the distance between site to site that is assumed to be 30 miles.

21) The maximum number of trucks available at the supplier in Stage 1 is limited (L_1= 12 trucks) and in Stage 2, the maximum number of trucks available for each site (L_2= 1 truck).

22) All the project sites are assumed to have limited storage capacity which can hold both Product A and Product B.

23) The cost of shortage of both Product A and Product B at site *j* during time *t* is assumed to be Q^{1}_{jt} = \$80, \$90, and \$100/unit for *j*=1, 2, and 3 respectively. No shortage cost associated with the storage area.

24) The holding cost of both Product A and Product B among the project sites *j* is assumed to be Q^{2}_{jkt} =\$45, \$35, \$25, and \$15/unit for *j*=1, 2, 3, and storage site respectively.

25) The weight of each product type k is assumed to be w_k = 30 and 10 (pounds/unit) for k =A and B respectively.

26) The maximum weight each truck can carry (W=1000 pounds/truck).

27) There is restriction on the maximum weight of Product A that can be carried by each truck (w_A=500 pounds/truck).

28) In Stage 2, the cost for site j to order one unit of Product A (Product B) from the site d at time t is ($100/unit). That is, C^{2}_{djAt} = $100/unit and C^{2}_{djBt} = $100/unit.

29) During the Stage 1 updating period τ, each construction project coordinator will submit new updated demands of Product A and Product B for the coming t periods. That is the cost to expedite or delay an order scheduled for delivery in the next period is PC_t $100/unit, $75/unit for scheduled delivery two periods in the future, $50/unit for three periods in the future, and $25/unit for four periods in the future. The update cost is assumed to be zero for any period more than 4 months. This cost is assumed to be the same for both Product A and Product B.

30) The initial forecasted demand used by Stage 1 is for Product A to be consumed at a rate of 100 units/period in each of the 12 periods (t=1,2, …, 12) and for Product B to be consumed at a rate of 50 units per period for each of the 12 periods. At t=13 the initial demand forecast is zero for both Product A and Product B.

31) It is assume that the needed demand (called actual demand henceforth) of Product A is presented in Table 5.1. This reflects several realistic situations that can occur in practice.

   a. Project 1 expedites the work by 30% during two different intervals: between *t*=3 and *t*=7 and then *t*=9.
   b. Project 2 slows the work by 50% during two different intervals: between *t*=6 and *t*=8 and then *t*=10. Also, there is an expediting by 30% at *t*=9.
   c. Project 3 is completely stopped at period *t*=6 and remains in that condition until *t*=10.

32) The actual demands presented in Table 5.2 reflect the fact that actual demand of Product B changes as follows:

   a. Project 1 expedites the work by 50% during two different intervals: between *t*=3 and *t*=5 and then *t*=11 and *t*=12.
   b. Project 2 expedites by 50 % at *t*=6 and by 25% at *t*=8.
   c. Project 3 is completely stopped between *t*= 5 and *t*=7 and then expedites by 50% from *t*=8 to *t*=10.

Table 5.1: The actual demand of Product A at each project site over the time horizon

	1	2	3	4	5	6	7	8	9	10	11	12	13
Project 1	90	90	150	150	150	150	150	90	150	100	100	100	0
Project2	90	90	90	90	90	50	50	50	150	50	100	100	0
Project3	90	90	90	90	90	0	0	0	0	0	100	100	0

Table 5.2: The actual demand of Product B at each project site over the time horizon

	1	2	3	4	5	6	7	8	9	10	11	12	13
Project 1	40	40	100	100	100	50	50	40	0	0	100	100	0
Project2	40	40	40	40	40	100	50	75	50	50	50	50	0
Project3	40	40	40	40	0	0	0	100	100	100	50	50	0

The methodology is now applied to the three CSC configurations described earlier as cases 1, 2, and 3. For each case, two different scenarios are considered reflecting different transshipment capacities. Scenario 1 limits the number of trucks while Scenario 2 assumes an unlimited number of trucks. The methodology is applied to all three cases, each under both scenarios, with the models solved using ILOG OPL Development Studio version 5.5 and tested on a single core of a SONY OptiPlex 980 computer running the Windows 7 Enterprise 64 bit operating system with an Intel(R) Core(TM) i5 CPU860@ 2.80GHz, and 8GB RAM. The results are shown in Table 5.3.

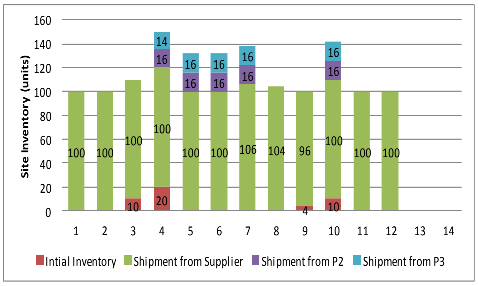
Table 5.3: Comparison between the results of the three configurations' cases under different transshipment capacity

Cases	Total Cost ($)		Total Inventory level (units)				Total Number of Shortage (units)			
	Scenario 1	Scenario 2	Scenario 1		Scenario 2		Scenario 1		Scenario 2	
			A	B	A	B	A	B	A	B
1	1,638,825	1,636,085	586	0	560	0	106	105	80	107
2	1,605,490	1,563,565	1,063	0	560	0	283	105	80	105
3	1,603,760	1,563,565	1,050	0	560	0	225	105	80	105

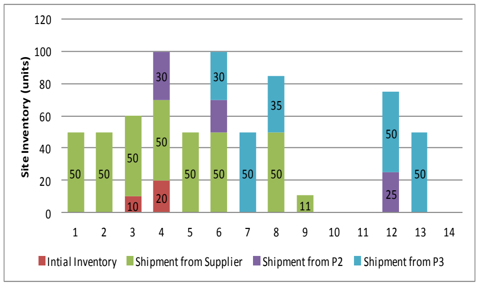
Scenario 1: Because the storage site provides a buffer to hold extra units with a lower inventory cost than any of the project sites, any extra inventory units at each project site are transferred to the external storage site to take advantage of the low cost even if they do not exceed the inventory capacity constraint of the project sites. As such, there is a noticeable decrease in the total cost from Case 1 (no external storage site) to Case 2 (the external storage site is added; transshipments exclusively between sites and the external storage, not site to site) by 2%. For example, compare the inventory level of Products A and B at the beginning t=3 and t=4 for Project 1 in Figures 5.2 and 5.3. We observe that the inventory of both product types decreased from 10 and 20 units to zero respectively because they are transshipped to the external storage site. As such, the total cost at t=3 reduced from $2100 in Case 1 to $ 990 in Case 2 or by 53% and at t=4, that the inventory of both product types decreased from 20 units to zero the total cost reduced from $4200 in Case 1 to $1890 in Case 2 or by 55%.

On the other hand, at t=3, the actual demand of Project 1 is increased by 50 units for both Product A and product B, so transshipments with a total of 30 units of Product A and 50 units of Product B are required at *t*=4 to satisfy these shortages at Project 1. The methodology handles this situation uniquely in each Case. Figure 5.3 shows that in Case 2, a single truck at the external storage site will transship 16 units of Product A and 50 units of Product B to Project 1 based on the weight restriction. Figure 5.2, however, shows that in Case 1, both Project 2 and Project 3 will participate in transshipping units to Project 1 with one truck from each of them. The capability of Case 1 in satisfying the expedited demand and reduce the number of shortage units of Product A in Project 1 is more than in Case 2 because the number of trucks available for transshipment increased. However, the total cost at *t*=4 in Case 2 is still lower than Case 1 because the inventory level of Project 3 in Case 2 (zero units) is lower than Case 1 (20 units).

At the end of *t*=6, both the inventory level and the updated forecasted demand (expedite or delay) of each project site is passed to Stage 1 for updating. Project 2 requests to decrease the scheduled demand of Product A from 100 units to 50 units from *t*=8 to *t*=10 and Project 3 requests to stop the scheduled shipment from 100 units to zero from *t*=8 to *t*=12. Because changing the orders (to delay) from the supplier is associated with penalty cost, the optimal solution transferred (change the direction of the shipment with no penalty cost) these delayed units of Product A (requested from Project 2 and Project 3) from the supplier to the project site with the lowest inventory cost as a buffer against demand variation. In Case 2, the opportunity to send these units to the storage area which has the lowest inventory cost will enhance the reduction in the total cost by 2.4%.

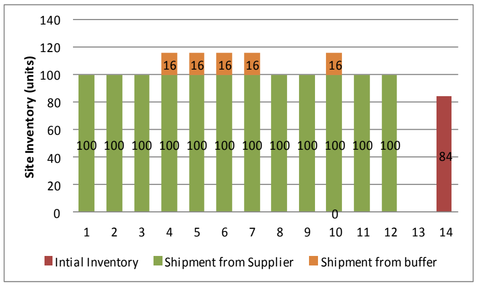


Project 1- Product A

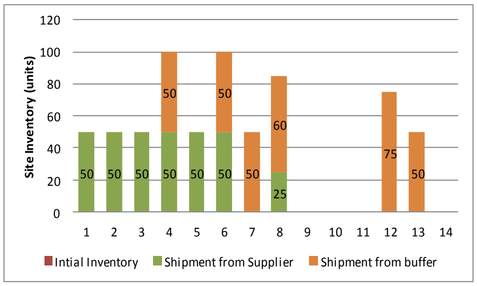


Project 1- Product B

Figure 5.2: Material flow of Product A and Product B in Project 1 (Case 1)



Project 1- Product A



Project 1- Product B

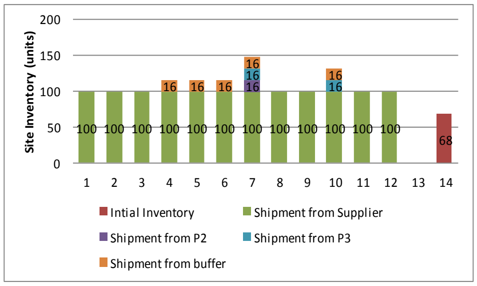
Figure 5.3: Material flow of Product A and Product B in Project 1 (Case 2)

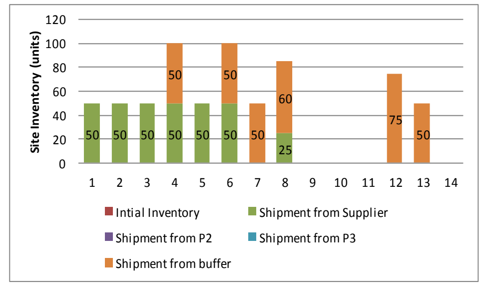
At the end of this comparison between Case 1 and Case 2 the following insights are made: (1) Adding an external storage area even with the restriction that the transshipments can only be made between it and the sites (Case 2) has a positive impact on reducing the total inventory cost and increasing the buffer of the CSC to overcome any disruptions in the future. (2) Even if the external storage area is not added in the CSC (Case1), allowing transshipments between sites can effectively reduce the number of units short at the project sites during the planning horizon because the total number available at the project sites is more than the number of trucks at the external storage site

(L_2=1). Thus, the final status of each project at the end of the planning horizon under Case 1 is better than Case 2 because Project 3 is under shortage with 46 units of Product A at *t*=13 in Case 2, however, in Case 1 no shortages at the end of the planning horizon at any of the project site. There might be some added reasons for adding the external storage site that is not currently included in the model. For example, centrally holding inventory adds the advantage of a risk pooling. Restricting transshipments to routes between sites and the external storage is potentially easier to implement and execute as well. There are certainly downsides as well, especially when limited transportation capacity is available.

There is also a significant reduction in the total cost from $1,638,825 to $1,603,760 or 2.14% from (Case 1) of only site to site transshipments to (Case 3) of having both site to site and the external storage site. The reason is adding an external storage site in Case 3 will reduce total inventory cost by transferring as many units as possible based on the number of trucks and the weight restrictions from the project sites to the external storage site in order to take advantage of the low inventory cost. On the other hand, because Project 3 has lower inventory cost than Project 1 and Project 2, more inventory units will be held at Project 3. As such, because Project 3 will have higher inventory level than Project 1 and Project 2, it will have higher participation in transshipment than Project 1 and Project 2. This will result in decreasing the inventory of Project 3 until some point where it will be under shortage and the external storage site with limited number of trucks cannot fulfill its shortage. Thus, the performance of the CSC in terms of the final status (schedule) of the project sites is negative because Project 3 will end up with shortage by 52 units.

Finally, the savings associated with adding site to site transshipment to the network that also includes the external storage site is 0.1% or $1,510 (from Case 2 to Case 3). This reduction is associated with the extra transshipments from Project 2 and Project 3 to Project 1 which decreased the total number of units short during the planning horizon by 5%. The material flow to Project 1 in Case 3 is represented in Figure 5.4. This figure shows the additional transshipments from both Project 2 and Project 3 to Project 1. For example, at t=7, 16 units are transshipped from both Project 2 and Project 3 to Project 1 which reduced the shortage of Project 1 from 34 units to 2 units and the total cost from $14,310 to $14,050 or by 2%. It has been shown how the participation of Project 3 in transshipment to other project sites to has a positive impact on the total cost and the total number of shortages during most of the planning horizon. However, towards the end of the planning horizon, the inventory level of Project 3 decreases to a point at which there are insufficient Product A units to satisfy this demand and the number of shortage units increased from 46 units in Case 2 to 52 units in Case 3. As a result, the total cost at t=13 increased from $28,195 to $31,060 or by 10%.





Project 1- Product A　　　　　　Project 1- Product B

Figure 5.4: Material flow of Product A and Product B in Project 1 (Case 3)

We again caution about interpreting these results as universally true since this is only one case study with one set of parameters and any generalizations must be studied much more carefully and within the context of a specific problem. With that said, it seems clear that adding an external storage site and transshipment between the project sites (Case 3) should be considered if the total cost of the CSC and building inventory buffer are the main concerns. Building an inventory buffer is important in reducing the impact of demand variation by balancing the demand-supply at each project site and also being a hedge against the high penalty cost of updating the orders or insufficient supplier capacity that maybe unable to satisfy the demand. However, the inventory cost at where the buffer is held is important. Figure 5.5 compares the total inventory level at each project site among three cases. It can be noticed how the inventory at the project sites decreased when the external storage site is incorporated.

On the hand, if the total number of shortages and the status of the project sites at the end of the planning horizon is the main consideration, then Case 1 is better and no need for a storage site. Figure 5.6 compares the total number of shortages at each project site between the three cases. It can be noticed how the total number of shortages increased when the storage site is added to the CSC. Table 5.4 provides the precise part of the material flow for the optimal CSC design with minimum cost in Scenario 1 (Case 3) for time periods (*t*=8 to *t*=13).

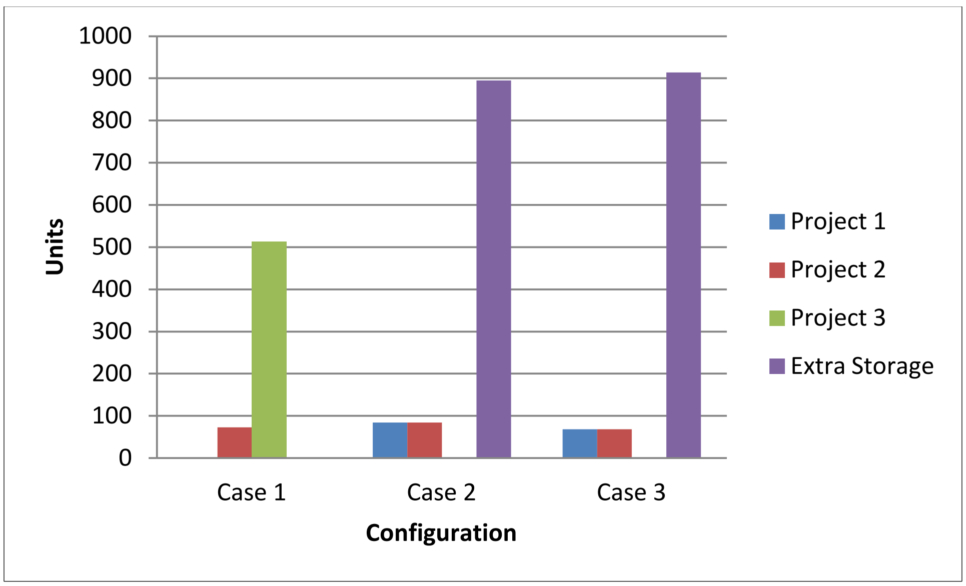


Figure 5.5: The total inventory level at each project site under the three different configurations in Scenario 1

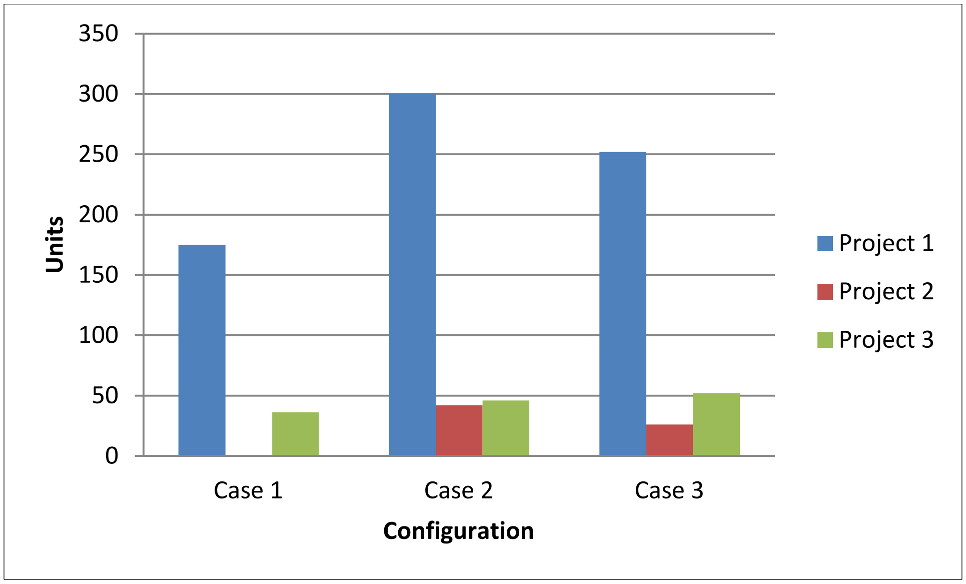


Figure 5.6: The number of shortage units at each project site under the three different configurations in Scenario 1

Table 5.4: The Material Flow of Project 1 in Case 3 from (*t*=8 to *t*=13) under Scenario 1

t	Type	STAGE 1				STAGE 2									
		Scheduled Shipment				Route	units	Inv. Level				Short. Level			
		P1	P2	P3	SS			P1	P2	P3	SS	P1	P2	P3	SS
8	A	100	51	16	133	P2 to SS P3 to SS	16 16	0	53	184	237	0	0	0	0
	B	25	75	50	0	SS to P1	60	15	0	0	0	0	0	0	0
9	A	100	65	2	133	P1 to SS P2 to SS P3 to SS	10 16 16	0	52	170	448	0	0	0	0
	B	0	50	100	0	-	-	0	0	0	0	40	25	0	0
10	A	100	67	0	133	P3 to P1 P3 to P2 P3 to SS SS toP1 SS to P2	16 15 16 16 16	0	0	123	565	18	0	0	0
	B	0	50	100	0	-	-	0	0	0	0	0	0	0	0
11	A	100	67	0	133	P3 to P2 P3 to SS SS to P2	16 16 16	0	0	91	698	0	0	0	0
	B	0	50	100	0	P2 to SS	25	0	0	0	25	0	0	0	0
12	A	100	100	0	100	SS to P3	9	0	0	0	789	0	0	0	0
	B	0	50	100	0	P3 to SS SS to P1	50 75	0	0	0	0	25	0	0	0
13	A	0	0	0	0	P1 to P3 P1 to SS P2 to P3 P2 to SS SS to P3	16 16 16 16 16	68	68	0	914	0	0	52	0
	B	0	0	0	0	P3 to SS SS to P1	50 50	0	0	0	0	0	0	0	0

Scenario2: In this scenario, the number of trucks available for transshipment in Stage 2 is unlimited. By expanding in transshipment capacity, the results of the three cases previous described in Table 5.3 show that there is a saving by 4% from Case 1 (no external storage site) to Case 2 (the external storage site is added; transshipments allowed between the external storage and each site but not between sites) for the same reasons provided in Scenario 1. That is, the external storage site provides a buffer for extra units with a lower inventory cost than any of the project sites. Thus, the inventory of both Product A and Product B shifts to the external storage site to take the advantage of the low inventory cost. Moreover, we observe that adding an external storage site with unlimited number of trucks changes the location of the inventory in the CSC while the total inventory level is the same when compared with Scenario 1. Figure 5.7 compares the results of the total inventory level at the end of the planning horizon between the three cases under the second scenario.

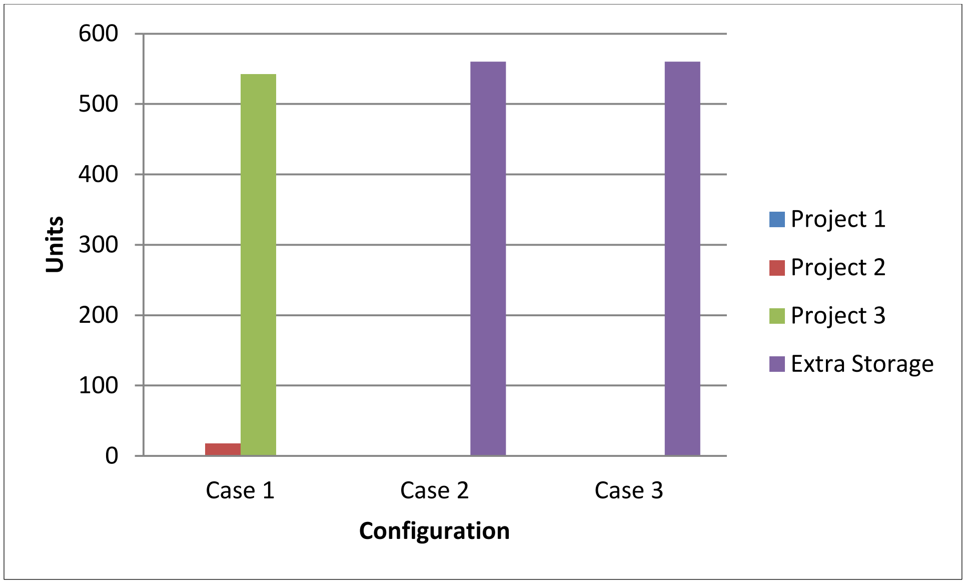


Figure 5.7: The total inventory level at each project site under the three different configurations in Scenario 2

Notice that the total inventory level is 560 units (560 units Product A and zero Product B) in Case 1 and it is distributed among Projects 1, 2, and 3 with 0, 18, and 542 units, respectively. However, in Case 2, the same units of the total inventory level are held at the external storage site. This reduced the inventory cost at t=13 from $14,180 to $8400 or by 41%.

On the other hand, we observe that by increasing the transshipment capacity in Scenario 2, the negative impact in Scenario 1 of having shortages in Project 3 at the end of the planning horizon is no longer existed. Further, there are no shortages at any project site because the external storage area has both inventory and sufficient trucks capacity to fulfill the demands throughout the CSC.

At the end of t=6, the updated forecasted demand of each project site is passed to the supplier in Stage 1. Project 2 and Project 3 request a decrease (delay) in their demand of Product A, however, the optimal solution in both Case 1 and Case 2 did not fulfill the delay requested at any project site because of the high penalty cost. As such, the surplus units created by the delay are transferred from the supplier to the project site with the lowest inventory cost and are held there as a buffer against any demand variation.

There is a noticeable decrease in the total cost of Stage 1 associated with adding the external storage area. If the storage area is added (Case 2), the total cost of Stage 1 is reduced from $555,440 to $530,650 or 5% compared with Case 1.There are two reasons for this. (1) In Case 2, the delayed units of Product A are transferred from the supplier to the external storage site with lower inventory cost than transferring the delayed units to Project 3 in Case 1. (2) In case 2, the shortage of Product B units caused by expediting in Project 3 decreased because adding external storage site provides more trucks to satisfy the increased demand associated compared with Case 1 and this definitely affected the total cost because Project 3 has the highest shortage cost.

Finally, adding site to site transshipment to the network that includes external storage site (from Case 2 to Case 3) has no effect on the results and the material flow of the CSC. This true because the increase in the transshipment capacity meant that the project sites were able to transfer their entire inventory to the external storage site without keeping any extra units at their site. Thus, the external storage site was able to use its entire capacity to accommodate the increasing in the demand without the need for transshipments from the project sites. Table 5.4 provides the precise part of the material flow in Project 1 for the optimal CSC design with minimum cost in Scenario 2 (Case 2) during the time periods (*t*=8 to *t*=13).

Table 5.5: The Material Flow of Project 1 in Case 2 from (*t*=8 to *t*=13) under Scenario 2

t	type	STAGE 1				STAGE 2									
		Scheduled Shipment				Route	units	Inv. Level				Short. Level			
		P1	P2	P3	SS			P1	P2	P3	SS	P1	P2	P3	SS
8	A	100	51	16	133	P2 to SS P3 to SS	50 100	0	0	0	399	0	0	0	0
	B	25	75	50	0	SS to P1 P3 to SS	60 50	15	0	0	0	0	0	0	0
9	A	100	65	2	133	P1 to SS P2 to SS P3 to SS	10 16 16	0	0	2	558	0	0	0	0
	B	0	50	100	0	-	-	0	0	0	0	40	25	0	0
10	A	100	67	0	133	SS toP1 SS to P2	50 83	0	0	2	558	0	0	0	0
	B	0	50	100	0	-	-	0	0	0	0	0	0	0	0
11	A	100	67	0	133	SS to P2	33	0	0	2	658	0	0	0	0
	B	0	50	100	0	P2 to SS	25	0	0	0	25	0	0	0	0
12	A	100	100	0	100	SS to P3	98	0	0	0	660	0	0	0	0
	B	0	50	100	0	P3 to SS SS to P1	50 75	0	0	0	0	25	0	0	0
13	A	0	0	0	0	P1 to SS P2 to SS	100 100	0	0	0	560	0	0	0	0
	B	0	0	0	0	P3 to SS SS to P1	50 50	0	0	0	0	0	0	0	0

5.4. Conclusions

The two-stage methodology with external storage site that is not associated with one of the projects in a much more highly constrained environment was introduced in this chapter. Three different CSC configurations were compared to investigate the impact of adding external storage on CSC behavior and on construction projects' performance. In Case 1, the design of the CSC does not have an external storage site and transshipments can only occur between the project sites. In Case 2, the design includes the external storage site with transshipments only allowed between the external storage site and the project sites. Finally, Case 3 expanded Case 2 to include transshipments between project sites as well as between project sites and the external storage site.

The methodology is applied to two sets of scenarios based on a real case in Kuwait with different transshipment capacity at each of them. The models were solved using OPL and subsequently validated through experimentation and comparison with spreadsheet calculations.

Finally, the results of the case study with limited Stage 1 transportation capacity and unlimited transshipment capacity exhibit that the optimal CSC design includes an external storage site with no transshipments between the project sites has the minimum total cost.

CHAPTER SIX

CONCLUSIONS

This dissertation proposes a two-stage methodology for controlling material flow in the CSC of construction projects that represents a paradigm shift from the current control strategy. In the current system, each project is controlled independently from all other projects and uses a near-pure push control that places most if not all orders with suppliers near the beginning of a project via a materials requirements planning system; then uses expediting or delaying to accommodate variability in actual construction schedule. This research focuses on developing a methodology that exploits synergies between projects by embedding collaboration in CSC. The methodology continues to utilize push orders in a different way but also adds the ability to transship materials between multiple projects that are being executed simultaneously.Stage 1 of the methodology controls the interface with the suppliers and mirrors the current push procurement strategy while Stage 2 provides the opportunity for transshipment between the projects. Each stage uses a deterministic optimization model solved at different frequencies to determine the optimal material flow decisions that minimized the total cost of CSC. Collaboration is facilitated by having the stages sharing their information with each other at predetermined times where updated decisions are made based on current, global knowledge. We also illustrated how this methodology can be used in practice and the types of information that can be gleaned through testing it on a number of cases based on the real example of multiple construction projects in Kuwait.

Chapter 3 addresses an integrated Production and Transshipment problem of Single supplier with limited production capacity, Multiple projects with unlimited storage capacity, and Single material using unlimited number of capacitated trucks (PTPSMS). The two-stage methodology has been applied to carefully constructed case studies with different updating and transshipment periods at which Stage 1 and Stage 2 executed respectively. First, we compared the current system with no transshipment over the proposed paradigm shift to investigate the efficacy of using transshipment in the construction environment. The results show that the proposed methodology has a significant impact on controlling risk and buffering their impact. We observe that projects stay on schedule, within budget, and the enormous inventory level at the project sites is reduced. Next we explore the impact of the different updating and transshipment periods at which Stage 1 and Stage 2 are executed on the total cost of the CSC. The results show that transshipment is not always beneficial in construction; the impact heavily depends on the frequency of the updating and transshipment time periods. The long, less frequent updating periods and short, high frequent transshipment periods decrease the total cost of the CSC. Further, when the transshipment period is longer than the updating period, transshipment between the project sites is not required. As such, This chapter provides the optimal time periods for executing each stage of the two-stage methodology to use them for extra case study examples in the future.

Chapter 4 extends the PTPSMS in chapter 3 to a more constrained environment. It addresses an integrated Production and Transshipment problem of Single supplier with limited production capacity, Multiple projects with limited storage capacity, and Multiple materials using limited number of capacitated trucks (PTPSMM). In this chapter the underlying mathematical models have been modified to include these features. The primary goal is to analyze and compare the impact of the storage and transportation capacity constraints on CSC behavior and on construction projects' performance. Therefore, a number of case study examples are provided to investigate the types of controls that are best. The results show that building buffer at the project site with low inventory cost is beneficial, so there is a need for a storage area that will reduce the inventory cost, the number of transshipments, and the penalty cost of updating the demand. Moreover, the results show that the number of trucks in Stage 1 has more effect on the total cost of the CSC than the number of trucks in Stage 2. Finally, the results show that there is no relation between the performance of the transshipment strategy in Stage 2 and increasing the number f trucks.

In chapter 5 we study different configurations of the CSC. We add an extra storage site not associated with any project and investigate its impact on the total cost of CSC under different number of trucks available for transshipments from the extra storage site. The results show that the incorporation of the external storage site has a positive impact on minimizing the total cost of the CSC. Further, the results show that as the number of trucks at the extra storage site increases, it is more beneficial to control the CSC of multiple project s by the external storage site and transshipments between it and the project sites.

This research could be extended by: First, improving the fidelity of the decision support models. In this research, the assumption of instantaneous replenishment rather than including a lead time could significantly change the numerical results and it is the most important next step in adding realism.

Second, this research could be extended by taking the big idea of the extra storage area in last chapter to use this as a CSC design methodology. For example, look at storage and transportation capacity to determine how much storage to have at each site and where to add additional buffers is they would be effective. It could also be used to investigate the saving of moving towards some standard components in the project design to facilitate more robust material availability; hence, unanticipated problems are more easily accommodated and requests to expedite might be easier to accommodate as well.

Third, extend the general notion in this dissertation to multiple products with different geometries that impact utilization of trucks and storage areas. This would likely be tied to different types of truck that are available as well as their routing.

Furthermore, the problem is inherently stochastic in nature – variable consumption of products, variable lead times, variability quality, etc. This needs to be addressed explicitly maybe using stochastic programming or stochastic DP.

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