University of Alberta

SIMPHONY SUPPLY CHAIN SIMULATOR

A TOOLKIT FOR MODELING SUPPLY CHAIN COORDINATION AND INFORMATION SHARING

by

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A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In

CONSTRUCTION ENGINEERING AND MANAGEMENT

Department of Civil and Environmental Engineering
Edmonton, Alberta
Canada
Fall, 2006

Your file Votre référence
ISBN: 978-0-494-22254-6
Our file Notre référence
ISBN: 978-0-494-22254-6

Abstract

Challenges laid upon firms and corporations by increasing consumers' expectations in today's highly competitive markets; make them try to adopt new strategies in order to improve their productivity and profitability. One of the research disciplines developed in order to address such challenges is *supply chain management*. By adopting SCM concepts and ideas, firms are trying to integrate their core competencies with those of their suppliers and customers. Quantifying gains and losses of employing any policy in a supply chain requires modeling that supply chain. Simulation has long been an accepted approach in modeling supply chains. This thesis presents a research effort aiming to develop a simulation toolkit which provides researchers and practitioners with the opportunity to simulate and investigate different aspects of different supply chains. This thesis also focuses on the applications of supply chain concepts in construction industry by modeling a construction project's supply chain using the developed simulation toolkit.

Acknowledgment

I would like to express my gratitude to my supervisor Dr. Simaan AbouRizk to whom I am deeply indebted for his constant support and guidance through the course of my graduate studies. Without his helps, this work would not have been accomplished.

I would also like to thank one of my best friends, Dr. Yasser Mohamed for his invaluable advices. I would also like to appreciate the members of my committee for their patience and contributions.

Last but not least, I would like to thank my friends at Hole School of Construction. Their friendship took me through and it will never be forgotten.

To my wife

Sima

And to my parents

Mehrangiz and Mohammad

For their support, love and guidance

Table of Contents

List of Tables

List of Figures

List of Symbols and Abbreviations

α	parameter of exponential smoothing
ε_t	error term in demand equation
μ	mean of distributions
μ_D	demand mean
μ_L	lead time mean
μ_{PR}	productivity mean
ρ	demand correlation factor
σ	standard deviation of distributions
σ_D	demand standard deviation
σ_L	lead time standard deviation
σ_{PR}	productivity standard deviation
BSL	base stock level
D	demand
D_t	demand at time t
FP	failure percentage
h	inventory carrying cost
K	inventory setup cost
L	lead time
L_1	retailer's lead time
L_i	lead time of the ith level member of a supply chain
MTO	make to order
MTS	make to stock
OUL	order-up-to-level
P	forecasting period for moving average forecasting
q	order quantity
q_t^1	order quantity of retailer at time t

q_t^i	order quantity of ith level member of a supply chain at time t
q^*	economic order quantity
ROL	reorder level
r	review period in (r, S_p) inventory policy
s	reorder point in (s, S_c) inventory policy
S_c	order-up-to-level in (s, S_c) inventory policy
S_p	base stock level in (r, S_p) inventory policy
SD	shift duration
VMI	vendor managed inventory
y_t^1	BSL of retailer at time t
y_t^i	BSL of ith level member of a supply chain at time t
z	safety factor

1 Background and Objectives

1.1 Overview

In every industry, satisfying customers' ever growing expectations and keeping an edge in today highly competitive market, is a great challenge. The response of the researchers and practitioners in academia and industry to this challenge contributes to the development of new concepts, strategies and even research disciplines.

One of the research areas that emerged from the accumulation of efforts in several other fields of research to address such a challenge is supply chain management. Adopting the concepts, ideas, policies and strategies developed in supply chain management field of research, firms and corporations in all industries are trying to keep and enhance their productivity and profitability level by incorporating core competencies of their suppliers into their systems. This process can ultimately lead to a fully integrated supply network or a *virtual enterprise*.

Amongst all initiatives and approaches in the supply chain management discipline, one of the recently developed research areas is *coordination and information sharing*. This research area investigates practical coordination policies and information sharing strategies which can produce the results expected from partial or full integration of the supply chain. In another word, since it is not always practical to persuade suppliers to substitute their local optimization objectives by minimizing system-wide cost or maximizing system-wide level of service, some policies and strategies can be implemented to direct such local optimization approaches toward a global objective.

Modeling, which has been long part of supply chain management research area, is also the main research stream in coordination and information sharing. Modeling in this field is employed in order to quantify the benefits of implementing different policies and the share of each chain participant from that benefit. Analytical modeling approaches used to study supply chain of different structures under different situations, focus on serial supply chains which are easier to be analytically formulated. However, the complexity of real-life supply chains and the great number of parameters involved in the modeling of such supply chains, require development of powerful simulation modeling tools that enable researchers and practitioners to model supply chains of complex topology.

The construction industry like any other industry has started to adopt and employ supply chain management concepts and ideas. However, the quantity of research conducted in this area in order to quantify the benefits of implementing such concepts, is very limited. Although simulation studies are common in construction industry at the time being, there have been just a few studies to simulate the supply chain of a construction project.

The research presented in this thesis has successfully produced a supply chain simulation toolkit which provides modelers with the opportunity to study problems regarding supply chain and information sharing. This toolkit has been developed using Simphony as the underlying simulation environment. Since Simphony has been used to model a large number of construction processes, construction researchers can easily use the developed simulation toolkit to investigate different aspects of the supply chains of several construction processes.

1.2 Research Objectives

The objective of this research is to develop a simulation toolkit with all the features required to model most problems related to Coordination and Information Sharing in supply chain and to provide a sample of addressing supply chain issues in the construction industry using the developed simulation toolkit.

To realize these objectives, four steps are identified:

- Understanding the concepts and ideas in supply chain management area and studying the modeling approaches and state of the art in coordination and information sharing.

- Developing a special purpose simulation template in the Simphony environment for modeling coordination and information sharing problems in supply chain.
- Validating the developed supply chain simulation toolkit by comparing the results of the models constructed using this toolkit with the results of the models developed by other researchers to address several different supply chain problems.
- Using the developed supply chain simulation toolkit to model the supply chain of a construction process and to quantify potential benefits of considering supply chain issues in modeling that process.

1.3 Thesis Organization

Chapter 2 of this thesis presents the summary of the literature review conducted during the course of this research. This chapter briefs the reader in the concepts and ideas of supply chain management, supply chain modeling, and coordination and information sharing in supply chain and construction supply chain.

Chapter 3 of the thesis reviews the development of the simulation toolkit for supply chain. This chapter discusses the design goals of this simulation toolkit and different elements developed as part of the Simphony Supply Chain Simulation toolkit. In this chapter all the elements and their attributes are introduced.

Chapter 4 of the thesis focuses on validating the developed supply chain simulation toolkit. In this chapter several problems are modeled using the developed toolkit and then the outcomes of the simulation are compared to the results of other well known models.

Chapter 5 of this thesis uses Simphony Supply Chain Simulator together with another special purpose template developed in Simphony to model the supply chain of a tunneling construction project. In this chapter the parameters affecting the productivity of the tunneling process and the magnitude of their effect are identified.

Chapter 6 of this thesis describes the conclusions, contributions and recommendations for future research.

2 Literature Review

2.1 Introduction

This chapter of the thesis includes the literature review conducted in order to introduce underlying concepts, ideas and definition related to supply chain field of study and moreover to determine the thesis's perspective as the area of interest of this research.

Section 2.2 reviews basic concepts and definitions of supply chain management, key issues in supply chain management and research areas contributed to emergence of supply chain management. Section 2.3 present a survey of literatures related to supply chain modeling. This section includes reviews of different approaches toward supply chain modeling, research fields contributed to supply chain modeling and supply chain simulation tools. Section 2.4 introduces *supply chain coordination and information sharing* as the main focus of this research. This section includes literature reviews in *coordination*, *information sharing* and *bullwhip effect*. Furthermore, this section contains a survey conducted in the state of the art in supply chain coordination and information sharing. Section 2.5 present the summery of the literature survey conducted in the field of construction supply chain.

2.2 Supply Chain Management

Starting in 1980, companies have been applying several new manufacturing concepts and strategies like just-in-time, TQM (total quality management) and lean manufacturing, in order to reduce cost and increase customer satisfaction or level of service. As a result the manufacturing cost in many companies has been reduced to its limit and companies are working in their optimal level. Taking advantage of the continuing advances in communications and transportation, companies started to look into their suppliers and distributors seeking new strategies for further cost reduction and service level improvement in today's competitive market to meet higher customer expectations, a trend which led to the emergence of a new concept called supply chain management.

Sahin and Robinson (2005) and many other researchers believe that the first step initiating the development of the concept considered today as supply chain management was the introduction of the theory of Industrial dynamics by Forrester (1958, 1961) who constructed the theory on the basis of understanding the effects of delays, distortion and oscillation of demand information on supply chain operation and mostly inventory management and production planning.

Forrester's theory was widely neglected until the emergence of supply chain management philosophy. Several companies like Wal-Mart, J.C. Penny and Dell then started to employ strategies and policies developed based on this theory which demonstrated the potential practical gains of implementing such concepts.

According to Chen and Paulraj (2004), some of the areas contributed to emergence of SCM can be mentioned as logistics, distribution and transportation, information technology, organization, purchasing, marketing and production planning. As it is shown in the following figure, three major forces lead the development of SCM concept. This figure also provides us with a framework for SCM research.

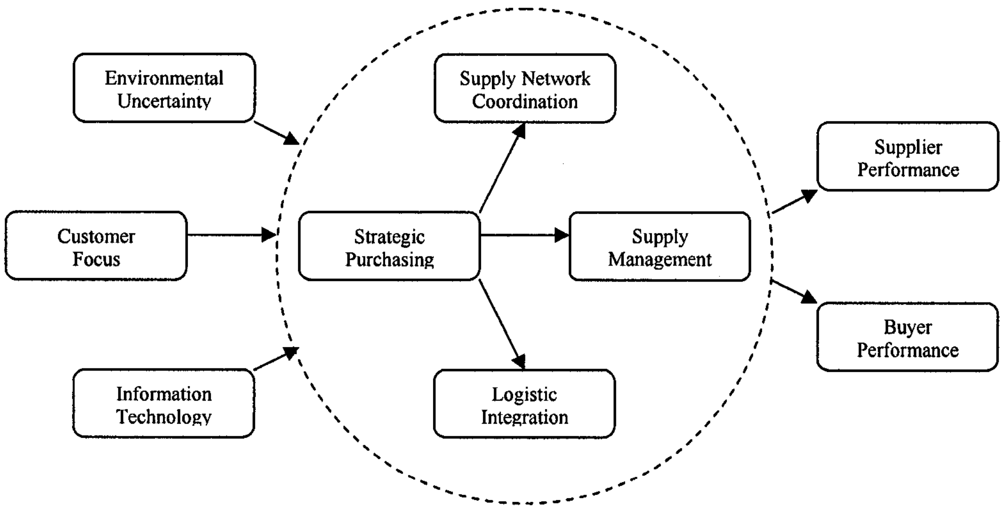


Figure 2-1 Driving forces of supply chain management (Chen & Paulraj, 2005)

Supply chain management can be defined as follow (Simchi-Levi D., Kaminsky P., Simchi-Levi E., 2003):

"SCM is a set of approaches utilized to efficiently integrate suppliers, manufacturers, warehouse and stores, so that merchandise is produced and distributed at the right quantities, to the right locations, and at the right time, in order to minimize system-wide costs while satisfying system level requirements."

As it can be interpreted from the definition, supply chain management requires taking into consideration each and every activity within a firm or between firms which has any impact on meeting the final customer's expectation. SCM is a set of system approaches to the whole network of suppliers, factories, warehouses, wholesalers and retailers. This set of approaches is being applied with the aim of integrating all these supply chain members' activities at strategic, tactical or operational levels. The ultimate objective of applying these approaches is to become efficient across the entire network.

As a direct consequence of such a system-wide approach, the challenges and difficulties lay upon designing and maintaining an efficient system, increase exponentially compared with the challenges and difficulties of designing and maintaining such a system in a single facility. Furthermore, different and conflicting objectives and goals of different members of the supply network, dynamic and time evolving nature of the system and potential competition between different members of the network make it much harder to achieve a globally optimal situation.

The other source of increasing difficulties in integrating a supply network is the uncertainty associated with its variables. Supply and demand uncertainty, error embedded in forecasting models and methods and the accuracy and availability of information are some of the factors contributing to emerging and increasing such uncertainty.

In order to attain integration necessary for a better performing supply network, a better understanding of supply chain's concepts, key issues, initiatives and approaches and its benefits for all parties involved is crucial. Such understanding would stimulate sharing of the technological and strategic efforts which consequently leads to better flow of information, materials and finances.

Key Issues in SCM include a wide variety of a firm's activities at different levels, from strategic level through tactical to operational level. According to Simchi-Levi et al. (2003) strategic decisions are the decisions that have long-lasting effects on the firm such as the decisions regarding the capacity of warehouses or production capacity of a factory. Tactical decisions are mid-run decisions which are usually updated annually such as inventory policies and production and purchasing decisions. Operational decisions are day-to-day decisions made at firm such as scheduling or truck loading. Some of the issues considered as the key issues at the aforementioned decision levels are (Simchi-Levi. et al., 2003):

- **Distribution network configuration** which deals with designing or redesigning a network of warehouses, wholesalers and retailers in order to have a more efficient system and to be able to meet the level of service required by the customers.
- **Inventory control** which addresses the policies undertaken by different members of the supply network in order to have enough materials in the stock that enable them to maintain the appropriate level of service while keeping the system cost efficient.
- **Supply contracts** as the means of establishing suppliers-buyers relationships both in past and in present which can be reconsidered to help realization of a globally efficient system.
- **Distribution strategies** which address different distribution policies and their possible gains or expenses for each of the members involved.
- **Supply chain integration and strategic planning** which discuses about the different techniques which can be used to integrate the whole supply network consisted of different members with different and sometimes conflicting objectives.

- **Procurement strategies** which involve the issues related to make versus buy decisions and also supplier selection.
- **Information technology and decision support systems** as a basis of supply chain management.

Approaches and initiatives undertaken by researchers and professionals to address issues related to SCM can be categorized as follows (Chen & Paulraj, 2005):

- **Strategic Purchasing** as the integration of internal and external exchange functions
- **Supply Management** which focuses on different aspects of buyer-supplier relationship including:

  a) *Communication* which deals with the efficiency and effectiveness of different methods of communication.
  b) *Supplier base reduction* which addresses the issue of reducing the number of suppliers and allocating the majority of purchased items to few suppliers.
  c) *Long-term relationship* which investigates the impact of long-term buyer-supplier relationship.
  d) *Supplier selection* which emphasizes the importance of the process of supplier selection and required criteria.
  e) *Supplier Certification* which involves the through examination of vendor's performance to improve trust, communication and product quality.
  f) *Supplier involvement* which focuses on participation of the suppliers in the product development process.
  g) *Cross-functional teams* which probes the functionality of the teams made by people working together from both buyer and supplier organizations.
  h) *Trust and Commitment* which can be considered as the foundation of SCM and addresses issues like long-term contracts and information sharing.

- **Logistics Integration** which deals with the methods of guarantying the delivery of the necessary amount of goods to the right place and at the right time.
- **Supply Network coordination** which includes efforts to analytically model and optimize the supply chain.

2.3 Supply Chain Modeling

Global optimization is one of the main objectives of SCM practice. It resulted in mathematical modeling approaches which contribute to a sizable number of researches in SCM studies. Most of these modeling approaches address two main issues or an integration of them (Chen & Paulraj 2005):

1) Production planning and inventory control
2) Distribution and logistics

The early analytical modeling approaches for SCM were deterministic models while many of the recently developed models have more than one unknown variable following a particular probability and/or statistical distribution.

Because of the high complexity of the models and large number of decision variables involved, it is computationally impossible to find the optimal solution in modeling a real supply chain. Simulation methods have been widely utilized as one of the best and sometimes the only way of dealing with such complexity and uncertainty.

Further comparison and distinction between analytical and simulation modeling of supply chain has been done by Chatfield (2001) with regard to the two major goals of this modeling which are *utility* and *realism*. Realism of the model is greatly based on the desired decision level. While operational decisions need detailed model, strategic decisions need abstract models. Model utility depends mostly on the model developed and the purpose of model development which can be obtaining insight into the supply chain performance, solution analysis, policy evaluation and optimization.

Simulation studies of supply chain are often referred to as *descriptive* models because the developed simulation models so far, don't provide any optimal solution. Simulation models have been employed to get insight about a certain supply chain structure or to compare different strategies in the supply chain. Other descriptive models of supply chain are:

- Forecasting models which focus on predicting important factors for production such as demand rate, price or raw material's cost based on historical data.
- Cost relationships which describe how different factors influence a firm's direct and indirect costs.
- Resource utilization relationships which address resource allocation to and resource utilization of different production activities.

Simulation models can be described as the most complete descriptive models that can accommodate other types of descriptive models within themselves to simulate a firm's dynamic behavior over periods of time.

Other types of models in supply chain discipline are mostly *normative*. The word normative is mainly used to refer to mathematical programming models trying to solve a partial or global optimization problem with regard to a supply network. Since there has not yet been a major research interest in optimizing simulation models in supply chain area, according to Simchi-Levi et al. (2003), the best practice available at the time being is to optimize the supply chain using analytical methods and evaluate the answer further by employing simulation studies.

Jeremy F. Shapiro (2001) mentions the disciplines from which supply chain modeling incorporates many concepts as:

- Strategy formation and the theory of the firm
- Logistics, production and inventory management
- Management accounting

- Demand forecasting and marketing science
- Operational research

Supply chain models have been categorized by several researchers in different ways. The most common categorization is to divide these models into three sets:

- Deterministic analytical models
- Stochastic analytical models
- Simulation models

Different researchers intend to include other categories in order to be able to distinguish other types of models as well. M. B. Beammon (1998) has categorized supply chain models into four categories including the three aforementioned categories alongside with economic models. H. Min and G. Zhou (2002) classified supply chain models into four categories three of which are the main categories mentioned above by replacing simulation models class by a class named hybrid models (including the same type of models). The fourth category of models these Min et al. outlines n their research is IT-driven models to distinguish the models aiming to integrate various tiers of supply network on real-time using software designed to enhance information availability for supply chain members.

2.3.1 Deterministic Analytical Models

This class of supply chain models includes the models in which all the variables are known and specified and there is no uncertainty involved for any of them. This type of models can be found mostly in the old literatures. Some examples of such models are reviewed in this section accordingly.

Newhart, Statt and Vasco (1993) tried to design the supply network of a company making corrosion-resistant steel coils. They used a two-phased approach to design an optimal supply chain to evaluate four different scenarios of locating different parts of supply network in different locations. In the first phase, using a mathematical program together with a heuristic model, they tried to minimize the number of distinct product types held in inventory in the whole supply network. In the second phase they employed spreadsheet modeling to determine the minimum amount needed for safety stock required to meet customer demand with lead-time fluctuation.

V. T. Voudouris (1996) mathematically modeled processes in a fine chemical industry plant consisted of mixing, packaging and inventory states. He considered two types of resources: the ones required to maintain material flow and the space-required type. He used a mathematical programming approach and formulated an analytical model for the problem with objective function of maximum flexibility in absorbing demand.

L. K. Nozick and M. A. Turnquist (2001) developed a mathematical model to address the problem of optimal positioning of distribution centers. They proposed an integrated view considering facility cost, transportation cost, inventory cost and customer satisfaction or service level requirement. Finally they applied the developed approach on an automotive industry case study.

E. Melachrinoudis and H. Min (2000) proposed a dynamic, multi-objective, mix-integer programming model to address the challenge of distribution centers relocation and phase-out decisions. They developed their model based on a case study of a firm intending to move its manufacturing plant to a new location. The objectives they considered in the developed mathematical model were to maximize total profit, minimize total access time for customers and maximize aggregated location incentive.

2.3.2 Stochastic Analytical Models

This category of models contains the models with some non-deterministic variables. These variables are normally assumed to follow a certain statistical distribution, so there are uncertainties associated with such variables. Some instances of this class of models are surveyed in this section.

Pyke and Cohen (1994) developed two stochastic analytical models. The first model developed by Pyke and Cohen in 1993 is a mathematical programming model applied to a three level single product supply network consisted of a manufacturer, a warehouse and a retailer. They used this model to minimize the total cost subject to constant setup, processing and replenishment time. In their second model developed in 1994, the authors use the same mathematical programming for network with multiple products.

S. Chopra, G. Reinhardt and M. Dada (2004) used non-deterministic mathematical modeling to investigate the impact of uncertainty associated with the lead time on the amount of safety stock needed. As a result the demonstrated that for firms operating below a certain service level threshold, reducing lead time variability will not result in reducing inventory level and inventory cost whereas reducing lead time itself will have such a result.

Arcelus, Kumar and Serinivasan (2005) developed a mathematical model to investigate the integration of pricing policy and ordering policy of a retailer trying to maximize its profit facing stochastic price-dependant customer demand under different manufacturing incentives.

2.3.3 Simulation Models

Simulation models or as mentioned before "hybrid" models are another category of models which can accommodated both deterministic and stochastic variables. Supply chain simulation models include models designed to solve a specific problem and also models or software constructed to allow users to develop their desired supply network with variety of structures.

S. Terzi and S. Cavalieri (2004) have conducted a literature survey on simulation models for supply chain. They have classified the models according to three major criteria:

- Scope and objectives: this criterion scales the level of the problem and the objectives which the simulation model has been developed to address. Two major objectives considered for a simulation model by the authors are network design configuration and supply chain strategic decision support. The scope of the simulation models is determined based on the processes the model is able to address. Some of the supply chain processes are: demand and sales planning, inventory planning, distribution planning and production planning.
- Simulation paradigm and technology: this criterion observes the simulation tool and language utilized and the paradigm adopted for the simulation model.
- Development stages: this criterion addresses the level to which simulation application have been developed. These levels are conceptual level, software description, experience description and testing activity.

The supply chain simulation models reviewed by S. Terzi, S. Cavalieri (2004) are all developed to address a specific problem for a specific network structure. Some of the most recently developed supply chain simulation models of this type are reviewed in the following.

A. A. Tiger and P. Simpson (2003) used discrete event simulation to design the supply network of a multi-billion dollar technology-based company with more than half of its market in Asia-Pacific region. The authors together with the company professionals have tried to make a decision regarding direct shipping from a US-based consolidation point in order to achieve economical load factor. Several sources of complexity in the problem and substantial need for flexibility and real-time analysis make authors choose discrete event simulation as the only way of dealing with such a complicated problem.

Sen, Pokharel and YuLei (2004) conducted a research on different supply chain positioning strategy the equivalent concept for production positioning strategy in a single firm. As there are several production positioning strategies such as make-to-stock (MTS), make-to-order (MTO), assemble-to-order (ATO) and engineer-to-order (ETO), there are different supply chain positioning strategies as well. The authors considered three different strategies of build-to-order (BTO), build-to-stock (BTS) and assemble-to-order (ATO) for evaluation and comparison by applying them in supply chains with different structures using simulation.

J. S. Ryan Daniel and C. Rajendran (2005) employed simulation to test the optimized base-stock levels generated by genetic. They used genetic algorithm to minimize total inventory cost across the whole supply network and then after they tested these optimized base-stock level by running several simulation models for supply chain with different morphology.

D. J. van der Zee and J.G. van der Vorst (2005) reviewed many simulation tools for supply chain and outlined their shortcomings and proposed a new conceptual supply chain simulation framework. In this research, they noticed the major weakness of most of the supply chain simulation tools to be lack of explicit control rules in the modeled supply network. Based on this, they proposed to use intelligent agents in simulation in order to have modeling block capable of making some decision or adjusting some parameters on their own. Finally they presented a case study applying their conceptual framework.

E. Fleisch and C. Tellkamp (2005) studied a common problem in physical goods dealership. They investigated inventory inaccuracy problem due to theft, low process quality and unsold items and finally developing a simulation model consisted of three echelons, they concluded that having inventory inaccuracy reduced by updating inventory parameters periodically will reduce inventory cost and stock-out level.

Hwarng, Chong, Xie and Burgess (2005) used simulation in order to investigate the effects of several assumptions regarding simplification of demand patterns and lead times in a wide variety of supply network structures. They analyzed four different coordination policies and measured the benefits gained for each party involved in the network in terms of average stock level, backorder level and cost.

2.3.4 Supply Chain Simulation Tools

At the time being, there are few simulation tools available which allow users to construct their own supply chain using simulation blocks or elements. According to Chatfield (2001) the first attempts toward building a simulation modeling environment for supply chain problems initiated in 1995 with the partnership of IBM which resulted in prototype *Toolkit* based on SimProcess simulation language. In 2000 another general simulation tool for supply chain was introduced by LiamaSoft Inc. with the name of *Supply Chain Guru* which was based on ProModel. The most recent effort for developing a general purpose supply chain simulator was done by Dean C. Chatfield as his PhD desertion at 2001 in the college of business of Pennsylvania State University. This research resulted in development of *SCML* (XML based) supply chain simulator.

Base on the comparison made by Chatfield (2001), amongst all these modeling environment, SCML is the only one which provides users with accessing to the codes and also with customizing the policies and defining complex scenarios for each modeling block or element. Also SCML's modeling focus is order life-cycle while the rest of mentioned simulators focus on supply chain location.

2.4 Supply Chain Coordination and Information Sharing

There are three major flows in a typical supply chain:

1- financial flow
2- information flow
3- material flow

A better understanding of the processes in supply chain can be obtained just by a closer look into these three flows. Two main concepts developed for addressing issues related to these flows are coordination and information sharing.

Sahin and Robinson (2002) have conducted a through literature review in coordination and information sharing in supply chain. Coordination in supply chain focuses on the degree to which all decisions in the supply chain are integrated with the aim of optimizing the system-wide profit and/or level of service. It can be interpreted then, that any incentives and information not compatible with the global objectives result in lack of coordination. Even with all information available, supply network's outcome can be sub-optimal if supply chain participants aim to optimize their own objectives. Coordination can occur under both centralized and decentralized decision making. Under centralized decision making condition a single participant tries to optimize the whole network utilizing its power of influence over other participants in the network while in decentralized decision making status coordination mechanism are employed in order to align available information and incentives to insure consideration of global objectives by individual decision makers.

Information sharing in supply chain discusses the degree to which different information sharing policies can affect the supply chain of different structures. Information sharing literatures try to determine to what extend having access to information of other parties involved in supply network can affect another participant's well being. The degree of information sharing then refers to availability of information for different members of a supply chain. Under no information sharing status, the only demand information that a firm has, is the actual demand pattern of its immediate customers. On the other hand on the state of full information sharing all the information required by a firm for decision making is available.

2.4.1 Coordination

Coordination is divided into two major divisions of financial and non-financial coordination by Sahin and Robinson (2005). Financial coordination includes methods such as quantity discounts used in order to insure the compliance of manufacturer's pricing policy with system global objectives. Non-financial coordination includes methods as follow:

- Buy back and return policies designed to allow retailer to return any portion of the original order placed at a pre-agreed upon price.
- VMI or vendor managed inventory is another coordination policy which let the supplier manage the retailer inventory in attempt of decreasing or eliminating bullwhip effect.
- Echelon inventory which is an inventory policy where all supply chain members in one echelon use one inventory or warehouse and the supplier just provide materials to this warehouse in order to decrease bullwhip effect by having different customer's order oscillation offsetting each other.

In a review of coordination policies, J. D. Thomas and P. M. Griffin (1996) have categorized coordination policies into three categories:

- Buyer-vendor coordination under which the authors discuss the possible coordination between customer and supplier which result in lower cost of material handling and potential saving which can be accordingly divided between the two parties involved. The majority of literatures addressing this include models to solve the problem of obtaining an optimal order quantity which minimize system-wide material handling and inventory costs.
- Production distribution coordination is a category of literatures trying to model the tradeoff between production planning policies and transportation strategies. These two major problems are often separated by inventory management issues and usually are under different departments' responsibilities. The main endeavor in these literatures is to develop models for minimizing system-wide production and transportation costs while maintaining the desired level of service to the customers.
- Inventory distribution coordination which authors considers as one of the origins of supply chain coordination literatures is another category of coordination strategies. Researches conducted in this area are mainly focused on determining inventory policies along the supply chain in order to minimize system-wide inventory cost while trying to meet customer demand. Different models have been

developed under different assumptions regarding demand patterns, lead-times, production capacities, etc. for various structures of supply network.

Sarmah, Acharya and Goyal (2005) have also conducted a survey in supply chain coordination literatures. They have focused on buyer-supplier coordination, explored the models developed to address buyer-supplier coordination and organized reviewed models into four different groups as follow:

- Vendor's/Manufacturer's perspective models under which authors have gathered the models trying to maximize supplier's yearly net profit by adopting different lot size. The main assumption of these models is that customers always order according to their optimal order quantities.
- Joint buyer and seller's perspective models is a term authors have used for the models trying to minimize the system-wide cost of material handling and inventory cost by using coordinated lot sizes or quantity discounts.
- Buyer and seller's coordination models under game theoretic framework are included in the third category by the authors. These models have studied the buyer vendor coordination through quantity discount as non-cooperative and cooperative games. In non-cooperative game models, every player tries to maximize its profit or minimize its cost regardless of other player's gain or loss. On the other hand, in a cooperative game model, the total profit of the network is maximized under the condition that no player looses more than it does in a non-cooperative game solution.
- Many buyer and single vendor coordination models are the last category authors developed to cover all the models that assumes more than one buyer in supply chain for any aforementioned objective functions.

Some more recent literatures in the area of supply chain coordination are reviewed in the following.

H. Shin and W. C. Benton (2004) investigated the effects of environmental factors on quantity discount based inventory coordination between a buyer and a supplier. They used a simulation model to determine how different factors such as demand variation, inventory cost structure ratio and buyer's order frequency would affect different quantity discount policies. Their final objective was to identify the best quantity discount policy under different environmental factors.

Q. Wang (2005) studied a decentralized two-echelon system with multi-buyer and single supplier structure. Assuming heterogeneity of customers' orders, he constructed a model to show that discount policies based on order size and annual volume can produce near optimum solution for the system and therefore they can be very effective coordination strategies.

D. Gupta and W. Weerawat (2005) considered a manufacturer and its component suppliers in their research. They evaluated the effects of different policies undertaken by manufacturers in order to affect component suppliers' inventory policies. Three alternative strategies studied by the authors were components inventory level specifying, simple revenue sharing policy and two-part revenue sharing scheme. They concluded that the last policy would result in supply chain coordination under which both manufacturer and supplier could earn benefit.

2.4.2 Information Sharing

There are several different issues investigated in the area of information sharing in supply chain. Information quality, the value of information, demand forecasting techniques, the benefits of information sharing for supply chain members and level of information sharing are some of the topics which have been under study by many researchers.

Huang, Lau and Mak (2004) have conducted a through literature survey on the impact of production information sharing on supply chain performance. They have constructed a framework and organized the reviewed literature according to this framework. The key elements the authored have used in order to categorize these articles are Supply chain structure, Level of decision, Production information model, Sharing modes, Dynamic performance index model, Supply chain dynamics model, Impact analysis of dynamic performances.

They have explored several categories of production information in supply network namely Product information. Process information, Lead time information, Cost information, Quality information, Resource information, inventory information, planning information and order information. They have also proposed two modes for information sharing: timeliness and neighborhood to determine the time and extent of information sharing in the supply network consequently.

Li, Yan, Wang and Xia (2005) have also conducted another valuable review on the models trying to assess the value of information sharing in the supply chain. They have reviewed twelve recently developed models which tried to reveal the value of information sharing, evaluate the extent of this value and capture the factors influencing this value in supply chain. They have organized the reviewed models in the following two tables and by comparative analyzing of them, suggested that the main reason of the diversified results of the value of information assessed by is the difference in underlying assumptions.

Some instances of more recent research endeavors trying to cover different aspects of information sharing in supply chain are review in the following.

P. Fiala (2005) has studied the role of information sharing in supply chain, the system dynamic modeling of supply chain and finally the system dynamic modeling of cooperation and information sharing in supply chain.

F. Sahin and E. P. Robinson (2002) have studied the impact of information sharing and coordination in make-to-order supply chain in order to identify the benefits of coordination and information sharing and to determine that to what extent each of these two concepts contribute to the benefits. They have also investigated the allocation of the benefits among the network participants.

Yao, Yue, Wang and Liu (2005) have mathematically modeled a supply chain with a manufacturer and a retailer with both direct channel and indirect channel for customers. Manufacturer uses direct channel to access customers directly while it keeps the indirect channel to fulfill customer's demand through retailer. The authors analyzed different return policies and benefits gained from each policy by each channel member under conditions of information sharing and no-information sharing. The main assumption of the model is that none of the channel members knows the ratio of the customer's demand in direct channel and indirect channel. The authors have concluded that under information sharing condition, both parties involved would gain some benefits.

Zhang, Tan, Robb and Zheng (2006) have conducted a research on the strategy of advance shipping notice when a supplier in the network shares its shipping information with its immediate customer downstream the supply chain. The authors have shown that with a periodic review inventory policy, under no information sharing condition, uncertainties associated with fulfillment of customer's orders would leave the customer with no choice but to build up a safety stock. On the other hand, with information sharing, the customer may have enough time to resolve such uncertainties.

2.4.3 Bullwhip Effect

The very first issue analyzed with respect to information sharing in supply chain was a phenomenon named *Bullwhip* effect. It has been proven mathematically that the variability of orders increases moving upstream the supply chain. The degree of this amplification is not known for every supply chain structure and is yet to be assessed using analytical or simulation models. But it can be shown mathematically that for a simple two echelon buyer-supplier supply chain with just one buyer and one supplier, there is the following lower limit which is a function of L (lead time) and P (forecasting time periods) for such amplification:

$$\frac{Var(q)}{Var(D)} \geq 1 + \frac{2L}{P} + \frac{2L^2}{P^2}$$ (Equation 2-1)

q= supplier's order quantity

D=buyer's demand

Bullwhip effect can be harmful for a factory at the beginning of the chain where it should carry excessive capacities for production and inventory at periods of time with high demand while there are periods of time with very low demand when no profit can be made out of these capacities.

There are several proposed remedies for Bullwhip effect which employ different strategies for coordination or increasing information sharing. The assessment of the value of information sharing in supply chains with different structures, the impact of different inventory and/or distribution policies on this value and the evaluation of different remedies of Bullwhip effect in supply chains with different structures are yet to be done.

The phenomenon of increasing the variation of the orders being placed by participants of supply chain from downstream to upstream, first was demonstrated by Forrester in his works published in 1958 and 1961. Other researchers tried to prove the existence of such problem in supply chain following Forrester. Sterman (1989) designed an experiment in MIT named *Bear Game* in which he simulated a serial four echelon supply chain with no information sharing under decentralized decision making. Through this experience he demonstrated that how a small variance in order placed downstream the supply chain can cause a major order swing at the other end of the chain.

Lee, So and Tang (2000) developed a mathematical model of a two echelon supply chain containing a manufacturer and a retailer. Utilizing the developed model, the authors tried to show that how information sharing benefits the manufacturers by decreasing the variability of orders placed by retailer especially under specific circumstances with high demand variation, high demand correlation and long lead times. They suggested then, that retailer also can negotiate with the manufacturers to share the benefits of information sharing.

Lee, Padmanabhan and Whang (2004) hypothesized an ideal situation for a serial supply chain where demand is stationary, lead time is fixed and re-supply is infinite, purchase cost is stationary and there is no fixed order cost. They argued that under these four assumptions there would be no amplification of demand and by relaxing each of these assumptions, order variance would increase moving upstream the supply chain. According to this discussion, they considered that four main causes of bullwhip effect are:

- Demand signal processing which refers to using previous demand data to forecast future demand when demand is non stationary.
- The rationing game which refers to the situation when the supply is limited and retailers' order won't get replenished completely. Such situation will result in over-ordering of the product by each retailer trying to secure more units which consequently cause bullwhip effect.
- Order batching which refers to accumulation of several retailers' orders in each period of time. It can be shown that such accumulation can increase order variation of the manufacturer when orders place to retailers is not stationary.
- Price variation which causes bullwhip effect by retailers' trying to minimize their inventory cost.

In another effort for quantifying bullwhip effect in a serial supply chain and investigating the extent of contribution of different factors to this phenomenon, Chen, Drezner, Ryan and Simchi-Levi (2000) mathematically modeled a two echelon supply chain. They considered demand forecasting and lead time as two major sources of bullwhip effect and formulated a lower limit for the ratio of variances of two successive members of supply chain under the assumption of retailer's orders being symmetrically distributed. They also showed that how this lower limit would be affected by information sharing.

Dejonckheere, Disney, Lambrecht and Towill (2004) also studied Bullwhip effect in supply chain. They used control system engineering method complemented by spreadsheet analysis. By obtaining transfer functions for a two echelon supply chain consisting of a customer and a retailer, they successfully modeled a supply chain under two different assumption of centralized and decentralized demand information. They also constructed the transfer functions for simple multi period moving average forecasting method and exponential smoothing forecasting method. They also employed two replenishment rules in their study, order-up-to level inventory policy and a smoothing replenishment policy. In their smoothing replenishment rule, the work-in-process inventory and target net stock levels involved in order-up-to level policy were smoothen by being multiplied by a factor equal or less than one. They found the smoothing rule more effective in reducing Bullwhip effect.

2.4.4 State of the Art in Coordination and Information in Supply Chain

In this section some of the most recent research endeavors to model different problems with respect to coordination and information in supply chain under various different assumptions are reviewed. The literatures chosen for this section are all 2005 or 2006 articles addressing centralized or decentralized information, vendor managed inventory policy, cross-decking and different forecasting methods.

Kim, Chatfield, Harrison and Hayya (2005) mathematically studied the effect of stochastic lead time on Bullwhip effect in two echelon and multi echelon supply chain. The authors used the model developed by Chen et al. as the base for their study and they also used the result produced by that model for comparison purposes.

One of the main assumptions of the formula provided by Chen et al. (2000) in quantifying Bullwhip effect was the constant lead time all along the supply chain. Kim et al. (2005) changed this assumption and considered a supply chain with stochastic lead times. They assumed lead time being from a statistical distribution with mean of μ_L and variance of σ_L^2 for all members of supply chain. They further assumed that all members have access to these values and can accordingly adjust their replenishment rules.

Kim et al. (2005) made another assumption that differentiated their model from that of Chen's (2000). Instead of multiplying the forecasted demand rate for the next period by lead time L_1 to calculate the order-up-to level, they used the sum of forecast values for L_1 periods of time. The replenishment rule used by both group of authors is as follow:

$$q_t^1 = y_t^1 - y_{t-1}^1 + D_{t-1} \qquad \text{(Equation 2-2)}$$

q_t^1 = Retailer's demand rate at time t

D_{t-1} = Customer's demand rate at time t-1

Chen et al. (2000) suggested using of the following equation to calculate y_t^1:

$$y_t^1 = \frac{L_1 \sum_{1}^{P} D_{t-i}}{P} \text{=Retailer's BSL (base stock level) at time t} \qquad \text{(Equation 2-3)}$$

P = the number of time periods being used for forecasting

L_1 = retailer's lead time

While Kim et al. (2005) used the equation below instead:

$$y_t^1 = \frac{\sum_{j=0}^{L_1-1} \sum_{i=1}^{P} D_{t-i+j}}{P} \qquad \text{(Equation 2-4)}$$

Using the above definition for y_t^1, Kim et al. managed to omit a L_1 factor from the closed form equation for Bullwhip effect provided by Chen et al. (2000) they employed this equation to quantify the Bullwhip effect in a multi echelon serial supply chain consisted of a customer, a retailer, a wholesaler, a distributor and a factory. They considered both situations of information sharing and information not sharing. The obtained results of their model showed less magnitude for Bullwhip effect moving upstream the supply chain compared to the results of the study conducted by Chen et al. (2000) in both cases. It was also shown by means of comparison of the results that, stochastic lead time causes a higher magnitude of Bullwhip effect than constant lead time. The following two equations for the ratio of variances of the orders places by retailer to the orders placed by customer with constant lead time, show Kim's formula versus Chen's formula.

$$\frac{Var(q)}{Var(D)} = 1 + \frac{2L_1}{P} + \frac{2L_1^{\,2}}{P^2} \qquad \text{(Equation 2-5)}$$

Formula developed by Chen et al. (2000)

$$\frac{Var(q)}{Var(D)} = 1 + \frac{2}{P} + \frac{2L_1}{P^2} \qquad \text{(Equation 2-6)}$$

Formula developed by Kim et al. (2005)

Waller, Cassady and Ozment (2005) studied the impact of cross-docking on inventory under the assumption of decentralized demand information. According to Simchi-Levi et al. (2003) cross-docking is a distribution strategy where warehouses work as inventory coordination points rather than inventory storage points. In such a system, goods arrived from manufacturer to the warehouse, are transferred to vehicles shipping goods to the retailers as rapidly as possible. The main idea of cross-docking is to minimize the time goods spend in warehouses.

Waller et al. (2005) considered a three echelon supply chain including several customers, several retailers and one distributor. They assumed implementing of cross-docking by all retailers without using of an echelon inventory at the distributors' level. Echelon inventory is supposed to contain the entire inventory in the supply chain of a given echelon and below. They modeled the problem in order to investigate the benefits of such a system in terms of inventory reduction under decentralized decision making.

Echelon inventory and cross-docking are two different systems which can be employed together. So by employing one of the two and not using the other, there are totally four different systems which can be adopted by members of supply chain. All these four different systems can be under centralized or decentralized demand information. A centralized demand information system may or may not result in a centralized decision making system. Waller et al. (2005) studied the cross-docking strategy without echelon inventory under decentralized decision making in a supply chain constructed of several retailers and one distribution center. The following figure is the illustration of the echelon inventory system.

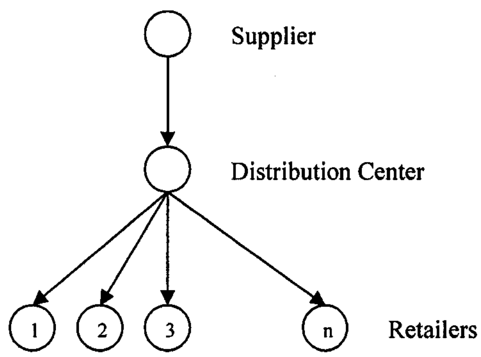


Figure 2-2 Echelon inventory system with several retailers Waller et al. (2005)

The authors assumed the demand of ε_{jk} for retailer number j in time period k. they assumed that ε_{jk} is independent and identically distributed with mean of d_s and variance of σ_s^2. To be able to calculate the variance of the orders being placed by all retailers to the distributor, they considered three types of ordering by retailers:

- Perfectly balanced ordering in which case, the constant number of retailers place orders in any given period of time.
- Random ordering in which case the number of retailers placing orders in a given period of time is a random variable. The authors considered this number to be binomial random variable.

- Positively correlated ordering which is the case when either no retailer places an order or all retailers place orders for any time period with a probability associated with each of theses two scenarios.

Waller et al. (2005) then calculated the whole inventory held by all retailers and distributor for each of the three scenarios with and without cross-docking. They used the resulted formulas assess the magnitude of reduction in the amount of total inventory held by retailers and distributor and also the magnitude of reduction in the total inventory cost of all parties involved. They then determined the lower and upper bounds for both these reductions. The following tables show the bounds presented by Waller et al. (2005).

Table 2-1 Lower bound of inventory reduction by Waller et al. (2005)

Order type	Lower bound of inventory reduction
Perfectly balanced and Random	$\frac{d_s T_s + 2z\sigma_s (T_s + L_s)^{1/2} + d_s T_d}{d_s T_s + 2z\sigma_s (T_s + L_s + L_d + L_c)^{1/2}}$
Positively correlated	$\frac{d_s T_s + 2z\sigma_s (T_s + L_s)^{1/2} + d_s T_d + z_d d_s ((T_s - 1)(T_d + L_d))^{1/2}}{d_s T_s + 2z\sigma_s (T_s + L_s + L_d + L_c)^{1/2}}$

Table 2-2 Lower bound of cost reduction by Waller et al. (2005)

Order type	Lower bound of inventory reduction
Perfectly balanced and Random	$\frac{C_s (d_s T_s + 2z\sigma_s (T_s + L_s)^{1/2}) + C_d d_s T_d}{C_s (d_s T_s + 2z\sigma_s (T_s + L_s + L_d + L_c)^{1/2})}$
Positively correlated	$\frac{C_s (d_s T_s + 2z\sigma_s (T_s + L_s)^{1/2}) + C_d (d_s T_d + z_d d_s ((T_s - 1)(T_d + L_d))^{1/2})}{C_s (d_s T_s + 2z\sigma_s (T_s + L_s + L_d + L_c)^{1/2})}$

Table 2-3 Upper bound of inventory reduction by Waller et al. (2005)

Order type	Upper bound of inventory reduction
Perfectly balanced	$\frac{(T_s + T_d)}{T_s}$
Random	$n + \frac{T_d}{T_s} + \frac{2}{nT_s} z_d (n(T_s - 1)(T_d + L_d))^{1/2}$
Positively correlated	$n + \frac{T_d}{T_s} + \frac{2}{T_s} z_d (n(T_s - 1)(T_d + L_d))^{1/2}$

Table 2-4 Upper bound of cost reduction by Waller et al. (2005)

Order type	Upper bound of inventory reduction
Perfectly balanced	$\frac{(T_s C_s + T_d C_d)}{T_s C_s}$
Random	$n + \frac{C_s}{C_d} (\frac{T_d}{T_s} + \frac{2}{nT_s} z_d (n(T_s - 1)(T_d + L_d))^{1/2})$
Positively correlated	$n + \frac{C_s}{C_d} (\frac{T_d}{T_s} + \frac{2}{T_s} z_d (n(T_s - 1)(T_d + L_d))^{1/2})$

T_s, L_s, z and C_s are review period, lead time, safety factor and inventory holding cost for retailers while T_d, L_d z_d and C_d are the same parameters for distributor. There are n retailers participated in the supply network and L_c is cross-docking lead time.

Yao, Evers and Dresner (2005) conducted a research to investigate the benefits of adopting vendor managed inventory practice or VMI. They considered a simple serial supply chain with a customer, a retailer and a distributor. The customer's demand was assumed to be deterministic. They modeled the supply network both with and without employing VMI and studied the differences in inventory total cost including inventory carrying cost and ordering cost.

VMI or vendor managed inventory is a practice in which retailer does not place any order to its upstream supplier and instead, the supplier itself manages the retailer's inventory and make shipments in appropriate times to fill the inventory of the retailer up to a certain level. Employing VMI practice in supply chain has shown promising result in terms of reducing total inventory amount in the network, increasing service level of the retailer and decrease total system-wide inventory cost.

Yao et al. (2005) assumed both retailer and distributor to use continuous inventory policy with zero lead time which means any order being placed can be received at the same time. They also assumed that adopting vendor managed inventory system does not eliminate retailer's ordering cost completely.

By having lead time for both retailer and distributor equal to zero and using economic lot size model, Yao et al. (2005) formulated the total inventory cost for the whole supply chain under both assumptions of using and not using vendor managed inventory. They further investigated each party's inventory holding cost and benefit with respect to three ratios: the ratio of distributor's inventory carrying cost to the retailer's represented by d, the ratio of distributor's ordering cost to the retailer's without VMI represented by g and the same ratio with VMI represented by g'. The following tables represent the result of this study.

Table 2-5 Total inventory cost with and without VMI

Scenario	Total inventory cost
Without VMI	$\sqrt{2R}(\sqrt{CH}+\sqrt{ch})$
With VMI	$\sqrt{2R}(\sqrt{CH}+\sqrt{c'(H+h)}$

Table 2-6 Total inventory holding cost with and without VMI

Scenario	Distributor	Retailer
Without VMI	$0.5\sqrt{2R}\sqrt{CH}$	$0.5\sqrt{2R}\sqrt{ch}$
With VMI	$0.5\sqrt{2R}\sqrt{CH}(1+\sqrt{d/g'(d+1)}$	$0.5\sqrt{2R}\sqrt{c'h}(1/\sqrt{d+1})$

Table 2-7 Benefits of VMI for distributor and retailer

Scenario	Total inventory cost reduction percentage
Without VMI	$\sqrt{d/g'(d+1)}$
With VMI	$\sqrt{g/g'(d+1)}$

R is total demand, c (substituted by c' in case of employing VMI) and h are ordering and inventory carrying costs of retailer while C and H are those of distributor.

T. Hosoda and S. M. Disney (2006) conducted a study to determine the variance amplification in supply chain when all participants employ minimum mean square error (MMSE) forecasting technique. They assumed first-order autoregressive customer demand pattern in the form of:

$$D_t = d + \rho D_{t-1} + \varepsilon_t \qquad \text{(Equation 2-7)}$$

They assumed the absolute value of ρ to be less than one and ε_t to be independent and identically distributed with mean of 0 and variance of σ_ε^2. Parameter d was assumed to be zero. By having a four echelon supply chain consisted of a customer, a retailer, a distributor and a manufacturer with all the supply chain members following an order-up-to level inventory policy, they analytically derived the exact equations for Bullwhip effect. They also quantify the variance of the net inventory levels for all supply chain participants.

The authors find the most important factors to affect the bullwhip effect are the accumulated lead time from the customer to each member of supply chain and the local lead time. They concluded that number of echelons in a supply chain does not have any impact on the magnitude of Bullwhip effect. Local lead time of each firm was found to have the most effect on the variance of net inventory levels which was found to be identical to the conditional variance of the forecast error.

The authors also found out that the by having all members of the serial supply chain following an order-up-to inventory policy and adopting minimum mean square error forecasting technique, the orders being placed by all of them would be in the following form which is known as ARMA (1, 1) process.

$$q_{t+1} = \rho q_t + \varepsilon_{t+1} - \theta_1 \varepsilon_t \qquad \text{(Equation 2-8)}$$

The expressions developed by Hosoda and Disney (2006) for the variances of the orders being placed by the retailer, the distributor and the manufacturer are presented by the following equations consequently.

$$\sigma_R^2 = \left(\frac{(1-\rho^{l1+1})^2 + \rho^2(1-\rho^{l1})^2 - 2\rho^2(1-\rho^{l1+1})(1-\rho^{l1})}{(1-\rho)^2(1-\rho^2)} \right) \sigma_\varepsilon^2 \qquad \text{(Equation 2-9)}$$

$$\sigma_D^2 = \left(\frac{(1-\rho^{l1+l2+1})^2 + \rho^2(1-\rho^{l1+l2})^2 - 2\rho^2(1-\rho^{l1+l2+1})(1-\rho^{l1+l2})}{(1-\rho)^2(1-\rho^2)} \right) \sigma_\varepsilon^2 \qquad \text{(Equation 2-10)}$$

$$\sigma_M^2 = \left(\frac{(1-\rho^{l1+l2+l3+1})^2 + \rho^2(1-\rho^{l1+l2+l3})^2 - 2\rho^2(1-\rho^{l1+l2+l3+1})(1-\rho^{l1+l2+l3})}{(1-\rho)^2(1-\rho^2)} \right) \sigma_\varepsilon^2$$

(Equation 2-11)

The variance of net stock levels for the retailer, distributor and manufacturer are presented by the following expressions accordingly.

$$\sigma_{nsR}^2 = \left(\frac{l1(1-\rho^2) + \rho(1-\rho^{l1})(\rho^{l1+1} - \rho - 2)}{(1-\rho)^2(1-\rho^2)} \right) \sigma_\varepsilon^2 \qquad \text{(Equation 2-12)}$$

$$\sigma_{nsD}^2 = \left(\frac{l2(1-\rho^2) + \rho^{l1+1}(1-\rho^{l2})(\rho^{l1+1} + \rho^{l1+l2+1} - 2\rho - 2)}{(1-\rho)^2(1-\rho^2)} \right) \sigma_\varepsilon^2 \qquad \text{(Equation 2-13)}$$

$$\sigma_{nsM}^2 = \left(\frac{l3(1-\rho^2) + \rho^{l1+l2+1}(1-\rho^{l3})(\rho^{l1+l2+1} + \rho^{l1+l2+l3+1} - 2\rho - 2)}{(1-\rho)^2(1-\rho^2)} \right) \sigma_\varepsilon^2 \qquad \text{(Equation 2-14)}$$

$l1$, $l2$ and $l3$ are retailer's, distributor's and manufacturer's lead time respectively.

S. Kumar and J. Kropp (2006) studied a multi-product multi-agent supply chain. They considered a sample hypothetical supply chain consisted of five layers: customers, retailers, distributors, manufacturers and suppliers of raw materials. They assumed to have seven suppliers, three distributors, two manufacturers and four suppliers. All members of the model supply chain were supposed to be able to receive orders from downstream firms according to their market shares. Three products were considered to flow in the supply network namely products A, B and C. Each product was supposed to require a combination of certain amounts of three components to be produced. The components were represented by symbols I, V and X. the following table shows these requirements.

Table 2-8 Components required by each product (Kumar & Kropp, 2006)

Product\Component	I	V	X
A	1	1	0
B	0	1	1
C	1	0	1

The authors modeled the supply chain using Excel and Mont Carlo simulation. They considered constant market share for each firm involved in the supply network. To study this supply network they focused on the manufacturers and changed the parameters of manufacturer firms. They used a normal distribution for demand process and also another independent normal distribution for forecasting simulation. All firms in the supply network were assumed to adopt vendor managed inventory technique to eliminate any ordering cost. The retailers were assumed to meet customers' demand with no stock out. According to authors these assumptions were made because of the difficulty and complexity of modeling product delivery processes. Moreover, the manufacturers were assumed to be able to meet retailers' demand partially through direct supply channels. The following figure shows the whole simulated supply chain with the products and components supplied by each member.

The authors then assumed random values for inventory and transportation costs as well as for production and raw material costs. They also set constant prices for all products and components. By running the simulation for different scenarios, the authors demonstrated how different policies employed by manufacturers can affect the whole supply chain and the costs of other parties involved. Because of limitation of their simulation, they just considered not information sharing status.

Zhang et al. (2006) studied the effect of sharing shipment quantity information in supply chain. Sharing quantity information, a practice also known as advance shipment notice lets the immediate downstream customer of any member of supply chain know the exact quantity of demanded material being delivered by that member. This strategy helps that customer to update its next order quantity or to place an order to another supplier to maintain its desired level of service.

The authors considered two cases, one with shipment information sharing (SIS) and one with no shipment information sharing (NSIS). They assumed that the customer firm in the supply chain updates its next order quantity to make up for the lost portion of its first order. Therefore any portion of the order placed by the customer firm at time t that the supplier firm is not able to meet, adds up to the customer firm's order at time t+1 under SIS or at time t+L (L is lead time) under NSIS. The authors also assumed that both customer firm and supplier firm adopt order-up-to level inventory policy with a constant base stock level.

Zhang et al. (2006) studied two scenarios under all these assumptions. In the first scenario, they assumed that the supplier firm does not make up for the lost part of the order placed by the customer firm. In this scenario, the customer places an order which is consequently processed by the supplier and gets filled either totally or partially. In the case of partial replenishment, the supplier firm will not take any further action to deliver the lost portion of the order to the customer firm. In the second scenario, however, after each partial replenishment by the supplier firm, it make up for the lost portion of the order in m periods of time which means that portion of the demand gets filled with the delay of m time periods. The authors assumed a constant m in their study.

They considered a two echelon serial supply chain consisted of a retailer and a manufacturer. The assumed that the end customers' orders meet by the retailer to be from a normal distribution. They made the same assumption for manufacturer's fill rate. They also assumed that manufacturer's fill rate and end customers' demand to be independent. Based on all these assumptions, the authors analytically quantified retailer's net stock level and fill rate for both aforementioned scenarios under shipment information sharing and no shipment information sharing.

The following expressions show net stock level and fill rate of the retailer for the first scenario with manufacturer ignoring the lost portion of the order.

$$\lim_{t\to\infty} 1/t \sum E(n_t) = SS + (1 - 1/\beta')d \quad \text{(Equation 2-15)}$$

$$\lim_{t\to\infty} 1/t \sum E(n_t') = SS + (1 - 1/\beta')Ld \quad \text{(Equation 2-16)}$$

SS is the retailer's safety stock while symbols n_t and n_t' represent its net stock level with and without shipment information sharing consequently and β' is manufacturer's fill rate. According to the formulas above, the reduction in net stock level realized by retailer due to advance shipment notice strategy is:

$$\lim_{t\to\infty} 1/t \sum E(\Delta n_t) = (L-1)(1/\beta' - 1)d \quad \text{(Equation 2-17)}$$

By getting the first partial derivative of the net stock level reduction with respect to L and β', Zhang et al. concluded that the benefit gained by retailer in terms of net stock level reduction would be more significant in case of having long lead times while increasing β' which means higher fill rate by manufacturer, reduces the magnitude of such benefit.

Authors' analysis for retailer's net stock level and fill rate for the second scenario where manufacturer makes up for the lost portions of the orders, showed no significant benefit for sharing the shipment quantity information.

2.5 Supply Chain Management in Construction

As for other manufacturing concepts and ideas adopted by construction industries, SCM is not yet a mature subject in construction area. Although there have been researches addressing transportation and/or inventory in construction industry, usually these issues have been studied in just one layer or tier of the whole supply chain.

With few exceptions of trying to incorporate SCM strategies and tactics into construction companies or projects, because of natural differences between manufacturing and construction, the improvement opportunities of applying SCM concept in construction have not been yet thoroughly explored.

Jiang, O'Brien and Issa (2005) studied two methods of modeling construction supply chain performance management. They identified supply chain performance drivers in construction and set a series of key performance indicators. They modeled the supply chain of a residential construction company and tried to measure its supply chain performance.

Vaidyanathan and O'Brien (2005) tried to explore opportunities for IT implementation in construction industry. They studied supply chain concept and methods in manufacturing and construction comparatively and also investigated IT tools used in construction industry. They reviewed implementation experiences in order to find out the challenges of construction supply chain and made some recommendation based on their findings.

Cox and Ireland (2002) studied different aspects of UK construction industry in order to provide better understanding of its supply chain. They mapped the industry supply chain, reviewed best practices and tried to provide a better way of thinking regarding the problems in UK construction industry.

Palaneeswaran, Kumaraswamy and Thomas (2003) also conducted a through study of construction supply chain. They carried out their research from an interesting point of view of highlighting major problems in current practice of construction and trying to propose a framework for supply chain concepts implementation instead of seeking what they call "ad hoc" remedies for different issues in isolation. They characterized the weak links of construction supply chain as follows:

- Adversarial relationship between clients and contractors.
- Inadequate recognition of risk and benefit sharing.
- Fragmented approaches.
- Narrow-minded win-lose attitude.
- Power domination and contractual commitment problems resulting in disputes and claims.
- Short-term focuses.
- Inadequate information exchange and restricted communication.
- Minimal or no direct interaction.

They also identified factors related to cultural differences that can directly or indirectly affect construction supply chain and finally proposed a conceptual framework for construction supply chain consisted of driving forces which can lead the industry toward relational contracting.

Tommelein, Akel and Boyers (2003) in another construction supply chain study investigated a construction company's tactics as a case study. The construction company studied had been implementing these tactics in order to fully integrate its supply chain by means of 100% equity stake. Some supply chain tactics used by this company were identifying core competencies, optimizing supply chain roles, considering downstream stakeholders values, and developing products jointly with suppliers and improving product demand forecast.

In an interesting research in construction supply chain, Walsh K., Hershauer J., Tommelein I. and Walsh T. (2004), modeled a project supply chain in Simphony and showed the potential gains of applying such a concept in construction environment. First, in a survey of supply chain simulation case studies, they demonstrated that most construction supply chain simulation have focused on process improvement and almost no simulation modeled has been developed to address inventory management and demand management in construction supply chain. In the next part of the article, they presented a case study of a construction company trying to interfere in its stainless-steel supply chain in order to reduce the lead time. They modeled the company's supply chain using CYCLONE template of Simphony and considered three different scenarios for positioning inventory. They demonstrated that using of pre-positioned inventory at distributor to hold stainless steel materials instead of holding materials before steel mill would reduce complete deliver time by 75%.

2.6 Conclusions

In this chapter, basic concepts, ideas, key issues and research areas of supply chain management domain were reviewed. Then, approaches toward modeling supply chain problems were introduced. Coordination and information sharing in supply chain was explored and a literature survey of state of the art in coordination and information sharing was presented. At the end, literatures in construction supply chain were summarized.

Based on the literatures review conducted in this chapter, most researches conducted in supply chain modeling were found to develop stand alone supply chain models. These stand alone supply chain models were developed with the objective of addressing a specific problem. Only few instances of researches were found to be dedicated to develop a general modeling framework for supply chain problems.

By reviewing the literatures in construction supply chain, a major shortcoming was found to be lacking of analytical perspective. Construction supply chain researches focus on the benefits of adopting supply chain strategies into the construction domain but there are few literatures trying to model and quantify these benefits.

To address these two shortcomings in supply chain modeling and construction supply chain research areas, the main objective of the research presented in this thesis was set to develop a supply chain simulation toolkit. This toolkit was developed as a general modeling framework for simulating supply chain coordination and information sharing problem.

3 Simphony Supply Chain Simulator (SSCS) Development

3.1 Introduction

Simulation has been employed by many researchers as one of the useful tools to solve supply chain problems. Most of the simulation models developed by different researchers in academia or industry have been based on continuous simulation methodology utilizing mathematical expression to model a specific supply chain problem. Also, most of the supply chain simulation models were developed to address a specific issue in supply chain for a certain range of supply chain structures. Reviewing literatures shows that most of these models have been developed to deal with serial supply chain structure, single product network and limited number of policies. However, there have been some endeavors to develop supply chain simulation engines in order to provide an environment that enables users to model the specific problem of their interest.

In the construction domain, simulation has been used for more than a decade, but in comparison with other industries, construction simulation studies are very limited. Simulation studies conducted in construction area mostly focus on process improvement. Some instances of such studies are simulation of tunneling process, tower crane utilization simulation, dewatering simulation and earth moving process simulation. Although simulation tools and techniques are mature enough in dealing with construction process improvement problems, there has not been any through research endeavor to address inventory management, transportation and order processing and forecasting issues in construction industry.

This chapter of the thesis reviews the development process of one of the few simulation toolkits designed especially for modeling supply chain problems. The simulation toolkit reviewed in this section is constructed as a special purpose template in Simphony. Section 3.2 of this chapter discusses the design goals set for the development of the supply chain simulation template. Section 3.3 focuses on the developed conceptual model for Simphony Supply Chain Simulator. Section 3.4 reviews the elements that constitute the simulation toolkit and their attributes and parameters.

3.2 Design Goals

Most literatures regarding supply chain in construction industry contain discussion about how supply chain concepts can be adopted by construction industries or what problems and challenges are on the way of such adoption. These studies will help all construction researchers and practitioners have a better understanding of all aspects of construction industry and the problems that can be answered using supply chain tactics, even though they rarely present a modeled case to back up their arguments. Few researchers used simulation to model a construction supply chain and tried to run different scenarios regarding inventory policies or demand patterns.

In this study an effort has been made to overcome some of the mentioned shortcoming regarding supply chain simulation and construction supply chain modeling. With respect to general supply chain modeling and simulation this study aims at developing a supply chain simulation kit which provides supply chain modelers with a modeling environment that helps them develop a model for almost any specific problem regarding supply chain information sharing, bullwhip effect, inventory policy, transportation policy and forecasting. Moreover, this study aims to make such development using a construction-friendly simulation setting. This enables construction practitioners to joint the developed modeling toolkit with other simulation models they use for construction processes.

One of the most advanced simulation tools in construction is Simphony (Hajjar, D., AbouRizk, S., 1999). Simphony is a general purpose, object-oriented, discrete event simulation environment which allows developing of multiple special-purpose simulation tools within it. In order to fulfill the intentions of this study, it was decided to use Simphony as the simulation engine to have the developed model compatible with several other simulation tools developed for construction using the same environment.

Three main design goals were set for the development of a supply chain simulator. These three main goals:

- **Flexibility**: The developed supply chain simulator should be flexible enough to allow every user to define special-purpose policies for inventory or transportation, different degree of information sharing and coordination, different production, inventory and transportation cost functions and different process setting. Every user should be able to customize the simulation units and blocks for solving specific problems.
- **Extendibility**: The developed supply chain simulator should be easily extendible in future to accommodate more strategies and policies in simulation blocks and to allow user to model any type of supply chain structure and design.
- **Compatibility**: The developed simulation setting should be compatible with other developed simulation models for construction processes. This capability will be very helpful in modeling construction supply chains.

3.3 Proposed Supply Chain Simulation Model

Based on the design goals set for development of the supply chain simulation tool, a conceptual model for supply chain simulation was developed. In this conceptual model the overall functions and transactions of supply chain that have to be simulated were reviewed. The functions and transactions considered for simulation of supply chain were as follow:

- **Production**: Production is the one of the main functions of supply chain. A supply network can be seen as a virtual enterprise which produces and delivers goods and services to the customers. There are two main different methods in production (Sen, W., Pokharel, S., & YuLei, W., 2004):

    a. Make-to-order is a production strategy used when customer's order is received prior to production. In make-to-order production systems, quantity demanded is small and demand is not stationary and hence difficult to forecast. Production planning is order-based and delivery time is long and risk is high. Because of one-of-a-kind production nature, construction industry is a good example of implementing make-to-order production strategy.

b. Make-to-stock is a production strategy suitable for mass production of one type of product. In this type of production, production and operation are scheduled according to the demand forecasting results. Industries using this strategy can benefit from economy of scale while they may suffer from lack of flexibility. The main role in such a production system is played by inventory.

- **Distribution**: Distribution is what makes it possible to have materials flow in the supply chain. Each plant or firm determines its own distribution strategy according to its market requirement. Three main different distribution strategies are as follow (Simchi-Levi et al., 2003):

  a. Warehousing: Warehousing is the classical method of distribution in which there are warehouses between supplier (manufacturer or fabricator or wholesaler) and customer (retailer). These warehouses keep stock of materials and ship them according to the customer's order.
  b. Direct shipment: in this strategy, there are no warehouses. Products and goods are delivered directly from the supplier to the customer without any other parties involved in the process.
  c. Cross-docking: In this system, products are distributed continuously from suppliers to customers through warehouses. The different of this system and classic warehousing is that the warehouses don't keep any product in inventory for more than a specific duration.

- **Inventory**: Inventory management plays a major role in supply chain coordination. It has a substantial impact on customer service level and system-wide cost of the supply chain. Inventory appears in several forms in a supply chain: Raw material inventory, Work-in-process inventory (WIP) and Finished product inventory. Holding materials in stock and the inventory level are decisions made by each firm with the objectives of inventory cost minimization. According to economic lot size model (Simchi-Levi et al., 2003), if fixed setup cost of inventory is *K* incurred each time an ordered is placed, inventory carrying cost is *h* per unit per day for an item held, for a fixed order quantity of *q* in a time cycle of length *T*, total inventory cost is: *K+hTq/2*. so it can be shown that with D as the constant rate of demand *economic order quantity* is:

$$q^{*} = \sqrt{\frac{2KD}{h}} \qquad \text{(Equation 3-1)}$$

Two main types of inventory policies to determine the time and quantity of order are (Simchi-Levi et al., 2003):

a. Continuous review policy: in which inventory level is reviewed every day and a decision is made about ordering and the quantity of order. This policy is also called (s, S_c) policy where s and S_c represent reorder point and order-up-to-level point. After each review if the stock level is below s, an order has to be place to bring up the inventory level up to S_c. Reorder level is determined so that the amount of inventory left can cover expected customer's demand until new materials are received. Assuming that the average daily customer's demand is following a statistical distribution, s can be defined as:

$$s = L\mu + z\sigma\sqrt{L} \qquad \text{(Equation 3-2)}$$

Where L represents constant lead time, σ and μ are parameters of demand distribution and z is a safety factor associated with the level of service required.

With variable lead time, s can be calculated using the following similar equation:

$$s = \mu_D \mu_L + z\sqrt{\mu_L \sigma_D^2 + \mu_D \sigma_L^2} \qquad \text{(Equation 3-3)}$$

Where μ_D and σ_D are demand distribution parameters while μ_L and σ_L are lead time distribution parameters.

Order-up-to level can be determined as:

$$S_c = s + q^* \qquad \text{(Equation 3-4)}$$

b. Periodic review policy: in which inventory level is reviewed at regular intervals and the appropriate decision regarding the amount of ordering is made. This policy is also known as (r, S_p) policy. At each period (r days), the inventory level is reviewed and an order is placed to bring up the inventory level up to S_p. S_p is known as base-stock level and should be determined so that expected customer's demand can be met until the next review:

$$S_p = (r + L)\mu + z\sigma\sqrt{(r + L)} \qquad \text{(Equation 3-5)}$$

- **Forecasting**: Forecasting is another main concept in supply chain modeling. As discussed before, inventory management plays the main role in supply chain coordination and as demonstrated, inventory policies usually deal with variable demand and lead time. In order to maintain a satisfying level of service, forecasting is necessary. There are several methods of forecasting:

a. Judgment methods: These methods try to structure the opinions of variety of experts in a systematic way. Some examples are sale-force composite method which is a logical method of combining different salesperson's sales estimate, panels of experts which is a communication method between experts to share information in order to agree upon a superior forecast and Delphi method which is a structural way of reaching an agreed upon forecast by avoiding dominating power of some individual decision makers.
b. Market research methods: Market researches are usually used for newly introduced product. This method uses a group of potential customers and observes their response to the product. The response data of the selected group then is used to estimate the potential demand for the product.
c. Time-series methods: these methods use past data to estimate future data. Some of the techniques commonly used are:

    - Moving average which uses the average of past date over a specific period of time as the forecast.
    - Exponential smoothing which used a waited average instead of simple average.
    - Regression analysis which is used for data with trends.

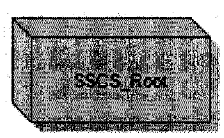
- **Information sharing**: Another important concept in supply chain modeling is information sharing. The proposed supply chain simulation tool should include some features to model different levels of information sharing and coordination in supply chain.
- **Transportation**: Transportation is also an important issue in supply chain. Different methods of product transportation and delivery have to be considered in the proposed simulation tool.

- **Demand**: Customer demand simulation is one of the important features of any supply chain simulator. Any simulation tool trying to model supply chain should be able to model and simulate different demand patterns.

3.4 Simphony Supply Chain Modeling Elements

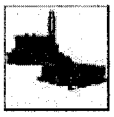
Selecting Simphony as the simulation engine provides users with many general and special purpose modeling templates developed inside it. Therefore for purposes of this study and to maintain flexibility of the proposed simulation tool, it was decided that production, distribution and transportation are to be modeled by any user individually. On the other hand inventory policies, information sharing, demand patterns and forecasting have to be provided by the proposed supply chain simulator. To build SSCS capable of providing different inventory policies, level of information sharing, demand patterns and forecasting methods, twelve simulation blocks (elements) have been constructed. A review of these elements' characteristics including their logical procedures, parameters, outputs and statistics is presented in the following.

3.4.1 Root Element



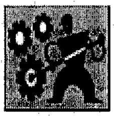
This element is a parent element designed to encompass all other elements in the template. This element represents a supply chain or part of a supply chain which is simulated. It has two outputs and two statistics as "Cost" and "Production" which make it possible for the user to assign value to them as outputs to see the final gross cost or rate of production or to collect statistics to see how cost and production rate evolves with time.

3.4.2 Agent Element



This element represents a common member of supply chain. It may represent a raw material supplier, a manufacturer, a distributor or a retailer. All the firms involved in a simulated supply chain can be represented by an agent element with different details. It can contain functions of inventory, order processing, ordering, backordering, transportation, production and several different other functions upon user's need. This element has two parameters, two outputs and two statistics. The outputs and statistics are "Cost" and "Production" again to enable user to gain final information as well as timely information as needed. The parameters are "Name" and "z" corresponding consequently to element's name and the safety factor defined by the user for inventory management and agent's level of service to its customers.

3.4.3 Process Element



This element was designed to contain the production processes that a user wants to model. It has one parameter, two output and two statistics:

- "Process name" is to let user choose the name of the process.

The outputs of this element are:

- "Cost" is to allow user to assign cost values to it and have the final result.

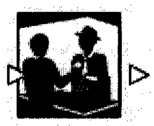
- "Production" is to allow user to assign production rate values to it and have the final result.

The statistics of this element are:

- "Cost" is to allow user to assign cost values to it and have the result as statistical distribution.
- "Production" is to allow user to assign production rate values to it and have the result as statistical distribution.

The first three elements discussed above are not functional elements. It means that a supply chain or part of it can be modeled without using these elements. These elements are just parent or root elements designed mostly to enable the user to organize the developed simulation model.

3.4.4 Customer Element



This element was developed to simulate customer demand patterns in SSCS template. Demand in a supply chain can be stationary, non-stationary, constant or variable. It can follow a trend or a statistical distribution, demand at each time period can be independent of demand at previous periods or it can be dependent on them. A good supply chain simulator should be capable of providing users with the opportunity to model different types of demand pattern. This element has four parameters which let user define the desired demand pattern. These parameters are "Time of first create", "Time between creates", "Size of each order" and "Number of orders to create".

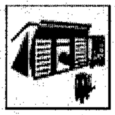
- "Time of first create" refers to the time which the very first order is created in the simulation. It is a user defined parameter and can be any positive number. User can assign a number bigger than zero to this parameter to simulate entering a new firm to supply chain. This parameter can be a positive number or a formula which can be a statistical distribution or any other user defined function.
- "Time between creates" is a parameter refers to the duration of time between two successive order. User can define this parameter to simulate customer demand rate in each stage of supply chain modeled. If the element is used to simulate the flow of coming customers to a retailer, "Time between creates" can be one time unit (a day or an hour) and if the element is used to simulate the orders being placed by a retailer to a distributor, the aforementioned parameter can be equal to a longer period of time (a week). "Time between creates" can be defined as a statistical distribution or a formula by user. Using statistical distribution option, user can define this parameter as either constant or any of these distributions: uniform, triangular, normal, and exponential or beta.
- "Size of each order" is another user defined parameter for this element referring to the size of orders being placed by the customer each time. This parameter is also can be defined as a statistical distribution or a formula. User can use formula as a method to link this parameter with other parameters, outputs, statistics or attributes of other elements or entities simulated. Order size and time between creates together can be used to obtain customer's demand rate.
- "Number of orders to create" corresponds to the duration or iterations that user want to use for simulation. Customer element exactly produces the number of entities equal to this parameter and stops functioning after that. It is also possible to have a closed loop made by "Common" template elements in symphony to overcome such a limitation and define simulation duration in another way. This parameter can be defined as a constant or by a formula which can be a distribution or a function of any other parameter in the model.

By defining all the four parameters and by running the simulation, at the exact point of time specified by "time of first create" parameter, "Customer" element starts creating entities and sending them out from its output connection point. The first entity is created at that exact moment while other entities are created at time intervals defined by "time between creates" parameter. Each entity created has an attribute representing the order size being place by the element. The procedure continues until the number of entities created reaches the "Number of orders to create".

Customer element also has an input connection point which represents receiving the fulfilled orders by customer and consumption of the product. The entities entering the element from this connection point are destroyed.

The next four elements reviewed here were designed to simulate inventory function in a supply chain. These elements are inventory element, material element, order and single order elements.

3.4.5 Inventory Element



Inventory element was developed to simulate inventory function in supply chain. Like a real inventory it can contain different "Material" elements each of which represents one of the products or materials being stored in stock. This element can also contain several "Order" elements each of which corresponds to a type of order being placed to the inventory. This element is a functional element that can be used by itself or as a child of another element like "Agent" element. This element has four parameters, one output and two statistics. The parameters are:

- "Name" is a user defined parameter representing the name of the element.
- "Entity attribute for quantity of granted material" is a user defined parameter corresponding to the name of entity's attribute containing the quantity of material granted.

- "Entity attribute for quantity of denied material" is a user defined parameter corresponding to the name of entity's attribute containing the quantity of material denied.
- "Capacity" is a parameter refers to storage capacity of the modeled stock. This parameter can be used to assign extra cost for excess quantity of material in stock or to refuse to accept new materials until there is enough room available.

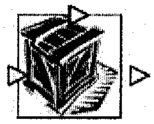
All parameters can be defined as constant (number or text) or as formula. The output of the element is:

- "Current level" refers to the current level of inventory space that can be used as an important parameter for determining the amount of surplus in stock.

The statistics are:

- "File length" is to have a statistical record of the number of orders waiting to be filled.
- "Waiting time" is to have a statistical record of the waiting time of orders waiting to be filled.

3.4.6 Material Element



This element was designed to model the various different products and goods stored in an inventory. An "Inventory" element can contain several "Material" elements and any placed order can require a combination of any of these materials to be filled. The parameters of this element are:

- "Description" as a parameter to let user define a name for the specific type of material represented by each "Material" element.
- "Total quantity of material" representing the total amount of materials available as an initial condition to start simulation.
- "Ordering policy" referring to the inventory policy and limited to periodic and continuous policies described in previous sections.
- "Review period" to let user define the review period for periodic policy.
- "Reorder level" representing s in (s, S_c) policy.
- "Order-up-to level" representing S_c in (s, S_c) policy.
- "Base stock level" defining S_p in (r, S_p) policy.
- "Backorder level" defining the maximum amount allowed to be returned to the supplier.
- "Capacity needed per item" to define the space needed for each unit of the product being stored in order to assess the available space or excess volume of materials.
- "Inventory carrying cost" representing h in continuous inventory policy.
- "Inventory setup cost" representing K in continuous inventory policy.
- "Entity attribute for quantity of materials received" to define which attribute's value corresponds to the amount of materials being received.
- "Entity attribute for order quantity" to define the name of attribute to which order quantity should be assigned.
- "Entity attribute for backorder quantity" to define the name of attribute to which backorder quantity should be assigned.

Parameter "review period" can be defined as a constant or by a statistical distribution or a formula. All other numerical parameters can be either defined as a constant or by a formula.

This element has only one output and one statistic. The output is "Current quantity of available material" to show the amount of materials being stored in stock at each time.

This variable can be used by other elements or entities in the simulation model. The statistic of this element is "Utilization" which can be used to show what percentage of the stocked quantity of any type of material is being used at any time.

There are four simulation events defined inside this element. These events are "receive", "order", "review" and "backorder". Event "receive" is designed to simulate material receiving by the element. Whenever an entity enters the element, according to the attribute name defined by user in "entity attribute for materials received", the value of the entity attribute with that name adds up to the current level of materials available.

"Order" event simulates continuous inventory policy according to which at each time that the current level of materials stored goes blow a certain point named "reorder level", an order has to be placed to raise the level to a specific point named "order-up-to level".

"Review" event deals with periodic inventory policy. At each period of time defined by "period" attribute of the element, this event is triggered and the current level of materials in stock is checked and it is raised up to a point called "base stock level".

Event "backorder" is for sending back excess amount of materials that can not be stored in stock because of space limitation. This event is triggered whenever there is excess amount of materials and it sends out an entity with an attribute with the name specified by user and the value equal to the minimum of the amount of excess material and backorder level.

3.4.7 Order Element

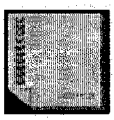
Another element designed to help simulating inventory policies is "Order" element. This element together with "Single order" element is used to simulate the procedure of order processing. "Order" element has six parameters:

- "Inventory name" which allows user to define the "Inventory" element related to the "Order" element. In other word, "Order" element uses the "Inventory" element with the name specified by this parameter in order to fill the orders being placed.
- "Deny unavailable order" is a parameter which allows user to define if the "Inventory" element linked to "Order" element works like a resource or a stock. User has two options for this parameter, "Yes" and "No". "Yes" means that the orders either get filled if there are enough materials in the stock or get denied if there are not enough materials in the stock, so the entity representing an order is sent out by the element either way. "No" means that if the order is filled then the entity can go but if the order is not filled, the entity should stay in the line until there are enough materials available.
- "Order quantity" is designed to let user define the order quantities of the entities representing orders in the model. User can use this parameter and link it to the entities' attribute containing order size information.
- "Partial replenishment" is a parameter which can be used to determine whether replenishment can be done partially or not. In partial replenishment, if there are not enough materials available to fill an order completely, the available amount of materials can be assigned to that order to fill it partially.
- "Priority" can be used by user to determine the priority of the orders being placed. It allow to simulate the case in which one or some of the orders are more

important and of higher priority. This parameter can be linked to other elements or entities' attributes.

- "Order type" gives user two choices, "All" and "Any". If an order is of type "All", it means that order is requesting for all the materials defined by "Single order" elements as the element's child elements. On the other hand, choosing "Any" means that the order can be filled by any of those materials. As an example, there may be an "Order" element with two "Single order" elements named A and B as its child elements each of which is linked to a "Material" element. In such a case, user can choose "All" to simulate the situation in which both A and B are required to fill an order. User can choose "Any" to simulate the situation in which either of the materials can be used to fill the order.

3.4.8 Single Order Element



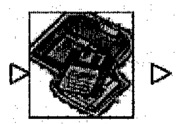
"Single order" element can be only used as a child element of an "Order" element. This element is used to specify the type of the material being requested by the orders placed on "Order" element. This element has three parameters:

- "Material to request" is a parameter used to determine the Material represented by the "Single order" element. The names of all the materials defined before are available in a drop-down list from which user can choose. User can choose either one of the materials' names in the list or an option to link this parameter to an entity's attribute by selecting ""linked to entity attribute"".
- "Name of the linked entity attribute" gives user the opportunity to define the name of the attribute to which the previous parameter should be linked.
- "Amount of material" is used to determine the amount of the linked material needed by any single order being placed.

In SSCS, an order is simulated as the information carried by an entity as the value of one of the entity's attributes. When an "Order" element receives such an entity, it reads the value of that attribute. That attribute's name is pre-specified by "Order quantity" parameter of the "Order" element. According to the value of that attribute and the "Order" element's child elements which are "Single order" elements and are linked to "Material" elements defined before in the simulation model, the order is processed.

In order to simulate information sharing and forecasting process in SSCS, two elements were developed, "Data" element and "Forecasting" element.

3.4.9 Data Element



"Data" element is an element designed to keep the record of the data of interest. This element read the data being carried by an entity and specified by the user and put this data in a sequential table. The table has just one column and variable number of rows. The first data being read by the element takes the first row and so on. The data collected by "Data" element can be later used by other elements especially "Forecasting" element. This element has two parameters and two outputs. The parameters are:

- "Name" is a parameter which allows user to specify the name of the element.
- "Name of the linked entity attribute" is a parameter designed to let user specify the name of the entity attribute containing the data that should be read by the element.

The outputs of the element are:

- "Data list" is a table containing all the data read by the element sequentially. The first data read, come in the first row.
- "Number of data read" shows the number of the data read by the element which is equal to the number of the rows of the data table.

3.4.10 Forecasting Element

This element was designed to simulate forecasting procedures. Forecasting is one of the important issues in information sharing in supply chain. The information shared by different parties involved in a supply chain is mostly used to improve forecasts. This element has ten parameters and four output:

- "Name" can be used by user to specify the name of the element.
- "Forecasting method" is a parameter which can be used to determine the method of forecasting. User has to options for forecasting method, "moving average" and "exponential smoothing".
- "Number of periods" is a parameter which let user to specify number of periods to be used for forecasting. This number is used for "moving average" method since for exponential smoothing all the data available are usually used. User can either choose "All" to use all the data available or enter a number.
- "Data element" is designed to allow user specify the "Data" element linked to the "Forecasting" element. The data of the specified "Data" element are used to perform forecasting.
- "a coefficient" is a parameter represents α multiplier in "exponential smoothing" method.
- "Clear the data list" gives user the option to choose whether or not to clear the data available in "Data" element linked to "Forecasting" element after performing

forecasting. The options available for user to choose from are “Yes” and “No” shown in a drop-down list.

- “Entity attribute for forecast” is for user to specify the name of the entity attribute to which the element assigns the forecast result.
- “Entity attribute for mean” is for user to specify the name of the entity attribute to which the element assigns the mean of all data used for forecasting.
- “Entity attribute for variance” is for user to specify the name of the entity attribute to which the element assigns the variance of all data used for forecasting.
- “Entity attribute for sum” is for user to specify the name of the entity attribute to which the element assigns the sum of all data used for forecasting.

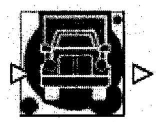
Element’s outputs are:

- “Forecast” shows forecast result.
- “Mean” shows the mean of data used for forecasting.
- “Variance” shows the variance of all data used for forecasting.
- “Sum” shows the sum of all data used for forecasting.

According to the values assigned to the parameters of the “Forecasting” element by user, when an entity is received by the element, it triggers the event named “Forecast” which finds the “Data” element specified by user and reads the proper number of rows of data table as specified by user. The values for “Forecast”, “Mean”, “Variance” and “Sum” are then calculated and assigned to the entity attributes with the names specified by the user and after that, the entity with four new attributes is sent out from the element. The user can simulate the different levels of information sharing in supply chain by using different “Data” elements to be the source of the data for “Forecasting” element.

To simulate transportation and other types of transaction in SSCS, two elements were developed. In Simphony, using single-directional arcs stretched from one element to another is the common method of connecting two elements together in order for entities to move from one element to the other. Simulating a complex supply chain with several firms in each echelon needs using a large number of arcs. To keep the model clear, it was decided to design the following two elements which help teleporting entities between two different elements.

3.4.11 Transaction Element



This element was developed to handle transportation and other kids of transaction required in a simulated supply chain. This element was designed to contain four "Data" and four "Forecasting" elements as its child elements. For this purpose, "Destination" elements should be used as its child elements. "Transportation" element has five parameters and four statistics:

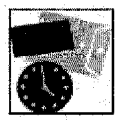
- "Name" is designed to let user indicate the element's name.
- "Transaction process time" is a parameter which allows user to specify how long it takes for the cargo to be ready to be shipped.
- "Attribute name for origin" gives user the option to specify the attribute name containing information regarding the origin of the entity.
- "Attribute name for destination" allows user to indicate the name of the attribute containing information regarding entity's destination.
- "Forecasting method" is an attribute which help user to determine the forecasting method of the "Forecasting" child elements of the element.

The statistics for this element are:

- "Demand" which is designed to let user collect gross demand data.
- "Lead time" which is designed to let user collect gross lead time data.

- "Material" which is designed to let user collect gross product shipment quantity data.
- "Order" which is designed to let user collect gross order quantity data.

3.4.12 Destination Element



"Destination" element was designed to be used as a child element of "Transaction" element. Each "Destination" element is associated with one of the "Agent" elements in the simulation model. Entities can be transferred to another "Agent" element by "Transaction" element only if there is a child "Destination" element associated with that "Agent" element, inside the "Transaction" element. "Destination" element has three parameters:

- "Name" is a parameter which allows user to indicate the destined "Agent" element to which entity is supposed to be transferred.
- "Product transaction duration" is a parameter to specify the duration of the transaction process for any physical transaction.
- "Information transaction duration" is a parameter to specify the duration of the transaction process for any information transaction.

"Destination" element also has four statistics:

- "Demand" which is designed to let user collect demand data of the "Agent" element represented by the "Destination" element.
- "Lead time" which is designed to let user collect lead time data of the "Agent" element represented by the "Destination" element.

- "Material" which is designed to let user collect product shipment quantity data of the "Agent" element represented by the "Destination" element.
- "Order" which is designed to let user collect order quantity data of the "Agent" element represented by the "Destination" element.

As mentioned above "Transaction" element and "Destination" element were designed to simulate transaction processes in supply chain. "Transaction" elements have to be used as child elements of "Agent" elements. "Destination" elements are supposed to be used as child elements of "Transaction" elements.

Whenever an entity is received by a "Transaction" element (which is a child element of an "Agent" element), the element checks the entity's destination by checking one of the entity's attributes with the name previously indicated by user using "Attribute name for destination" parameter. The element then initiates a search for an "Agent" element with this name in the simulated model and after finding such "Agent" element, it starts to look into that "Agent" element's child elements of type "Transaction".

The purpose of the second search is to find a "Transaction" element which is a child of the identified "Agent" element and has a child "Destination" element which has the same name with the original "Transaction" element's parent element which is an "Agent" element. By finding such a "Transaction" element, an event is then initiated to transfer out an entity from that element after a delay duration indicated by the user using either "Product transaction duration" or "Information transaction duration".

User can use the "Data" and "Forecasting" elements designed inside each "Transaction" and "Destination" element to collect data and perform forecasting about demand patterns, lead time, order placement and product delivery of each of the "Agent" elements which has any type of transaction with the "Transaction" parent element. The data collected can later be used to change ordering policies during simulation. It is also possible for the user to use the element's statistics to collect such data.

4 Validation of Simphony Supply Chain Simulator

4.1 Introduction

After developing any special purpose or general purpose simulation model or tool, that simulation model or tool should be validated. Validation is a crucial step for all developed simulation models and includes comparison of the result of the proposed simulation model with the results generated by another validated model. Clearly for the purpose of comparison, the same problem with the exact characteristics should be modeled in both proposed and referenced simulation tools.

For SSCS, the development steps were discussed in the previous section. All elements were introduced and their attributes and functions were reviewed. In validation stage, a supply chain model should be constructed using those elements and the outcomes of simulation should be compared to the outcomes of the same model simulated by a validated supply chain simulator.

In this chapter the validation process of the developed supply chain simulation toolkit is presented. Section 4.2 review supply chain information sharing simulation models used as reference for validation. Section 4.3 introduces the models developed using elements of SSCS. Section 4.4 reviews the validation process for moving average forecasting method. Section 4.5 presents the result of validation process for exponential smoothing forecasting method. Section 4.6 investigates the impact of using real time data for updating agent's parameters on Bullwhip effect. Section 4.7 presents a review of the conclusions.

4.2 Supply Chain Information Sharing Simulation

After reviewing several supply chain simulation models, a supply chain simulation study conducted by Chatfield, Kim, Harrison and Hayya (2004) was selected as the first reference simulation study. In this study, authors have tried to investigate the value of information and the impact of information sharing on Bullwhip effect in a serial supply chain under the conditions of constant lead time and stochastic lead time. The simulation model they developed was compared against two other supply chain simulation models.

One of the simulation models used as reference for validation by Chatfield et al. was a model developed by Chen et al at 2000. In that study, the authors developed a mathematical model to investigate the Bullwhip effect in a serial supply chain. They considered a two echelon serial supply chain with a fixed lead time L, when both firms employ periodic inventory policy with the period of one time unit and defined customer's demand as follow:

$$D_t = \mu + \rho D_{t-1} + \varepsilon_t \qquad \text{(Equation 4-1)}$$

Where μ is a nonnegative constant, ρ is correlation factor with absolute value less than one and ε_t is the error term which has a variance of σ^2. Mean $E(D_t)$ and variance $Var(D_t)$ of D are:

$$E(D_t) = \mu/(1-\rho) \qquad \text{(Equation 4-2)}$$

$$Var(D_t) = \sigma^2/(1-\rho^2) \qquad \text{(Equation 4-3)}$$

They mathematically proved that when simple moving average with P period is utilized as the forecasting method, if ε is from a symmetric distribution with mean 0 and variance σ^2, there is lower limit for Bullwhip effect as follow:

$$\frac{Var(q)}{Var(D)} \geq 1 + \left(\frac{2L}{P} + \frac{2L^2}{P^2}\right)(1-\rho^P) \qquad \text{(Equation 4-4)}$$

They showed that with a customer's demand being random and correlation factor being equal to zero, for a multi-echelon serial supply chain under the same condition stated before and with no information sharing, the Bullwhip effect is as follow:

$$\frac{Var(q_t^k)}{Var(D)} \geq \prod_{i=1}^{k}\left(1+\frac{2L_i}{P}+\frac{2L_i^2}{P^2}\right) \quad \text{(Equation 4-5)}$$

They showed that with information sharing under the same condition, Bullwhip effect can be decreased as follow:

$$\frac{Var(q_t^k)}{Var(D)} \geq 1+\frac{2(\sum_{i=1}^{k} L_i)}{P}+\frac{2(\sum_{i=1}^{k} L_i)^2}{P^2} \quad \text{(Equation 4-6)}$$

Chatfield et al. (2004) validated their proposed simulation model against this formula in two stages. First they developed a two stage serial supply chain with just a customer and a retailer. In their model at each period of time customer places the orders generated from a statistical distribution and retailer fills these orders. Retailer also places an order at each time period to update its inventory level. They obtained the mean and variance of the orders placed by retailer and used them to generate a normal distribution which they used to model wholesaler-retailer supply chain. They repeated the same process to model distributor-wholesaler and factory-distributor supply chains as well.

In their second approach, they modeled the whole five echelon serial supply chain with a customer, a retailer, a wholesaler, a distributor and a factory. They initiated the model by generating customer's orders from a statistical distribution and then they ran the simulated model and observed the variances for each echelon. They used this approach with information sharing and without information sharing.

Another model used to verify SSCS's results, was the model developed by Dejonckheere et al. (2004) who used a control engineering method to investigate the effect of information sharing on supply chain under two different inventory updating policies. They also investigated the impact of forecasting method employed by members of supply chain on Bullwhip effect. For this purpose, they considered two forecasting methods of simple moving average and exponential smoothing. The results of the model developed by Dejonckheere et al. (2004) were also used by Chatfield et al. (2004) for verification purposes.

4.3 Simphony Supply Chain Simulator's Models

Two models were developed in SSCS corresponding to both simulation models used by Chatfield et al and the model developed by Dejonckheere et al. (2004). The first model was constructed using just a "Customer" element and an "Agent" element. The "Customer" element produces orders based on a given statistical distribution. Orders placed by the "Customer" element are received by the "Agent" element. "Agent" element has a child "Inventory" element which has two child elements, an "Order" element and a "Material" element. The "Order" element has a child "Single order" element associated with the "Material" element. The orders received by "Agent" element are processed by the "Inventory" element. These orders are filled by assigning proper amount of materials from available materials in "Material" element. Before being received by "Agent" element, each order is processed by a "Data" element in the model to gather customer demand information which is later used by a "Forecasting" element to update "Inventory" element's base stock level.

To compare the developed simulation tool further with the second method employed by Chatfield et al. (2004), a full five echelon supply chain model (i.e. a customer, a retailer, a wholesaler, a distributor and a factory) has been developed. In the developed model, all four agents in supply chain act simultaneously. They all update their inventory levels and satisfy their customers' demands at the same time. The following sketches show the developed models and the values assigned to the elements' parameters.

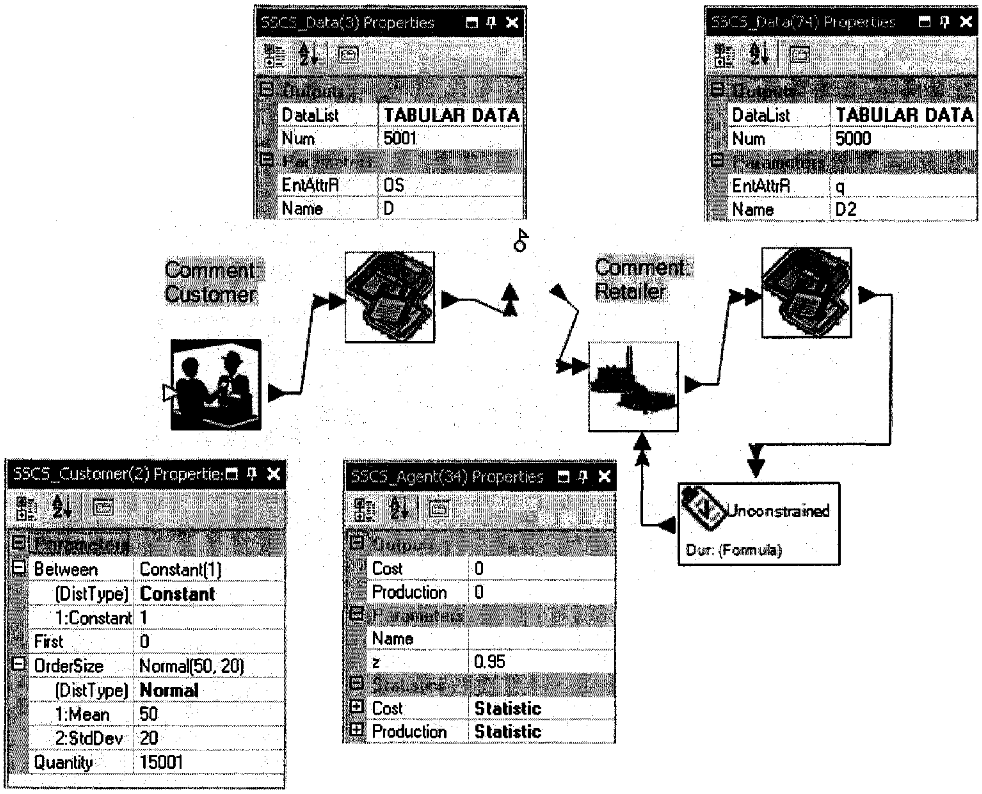


Figure 4-1 The two echelon supply chain simulation model

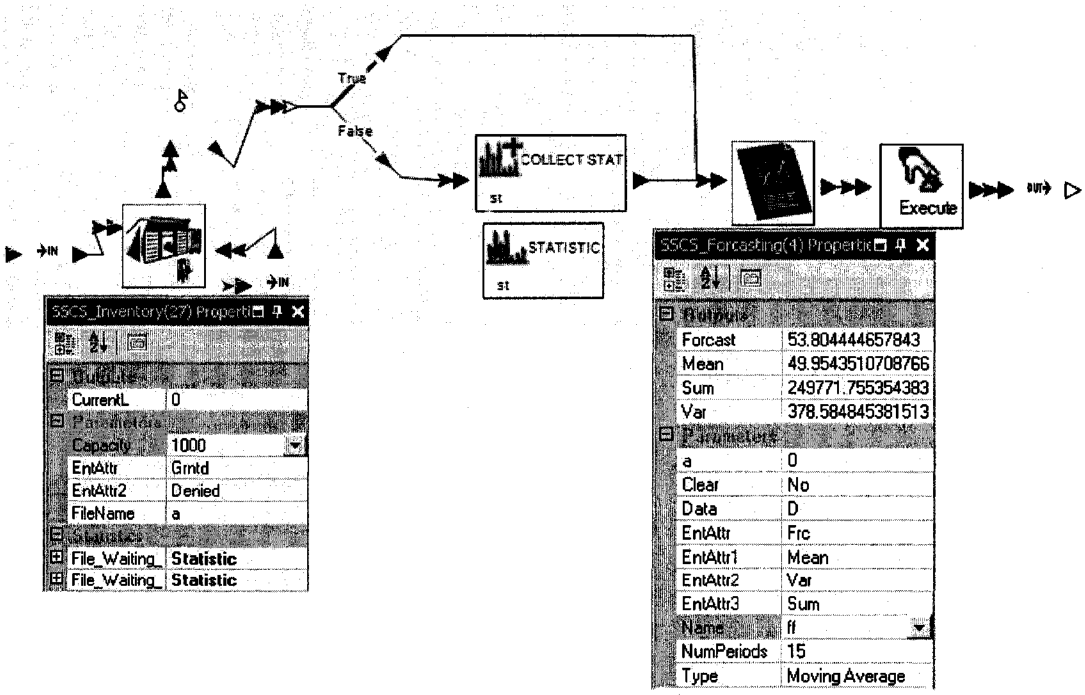


Figure 4-2 The Agent element (retailer) with Inventory and Forecasting elements

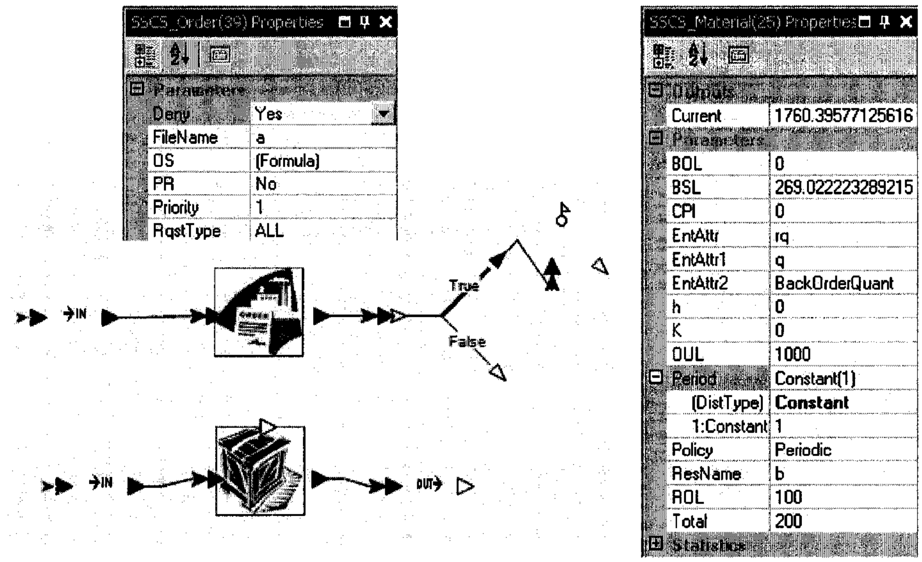


Figure 4-3 The Inventory element with Material and Order elements

The following flowcharts demonstrate how the two-echelon supply chain model works.

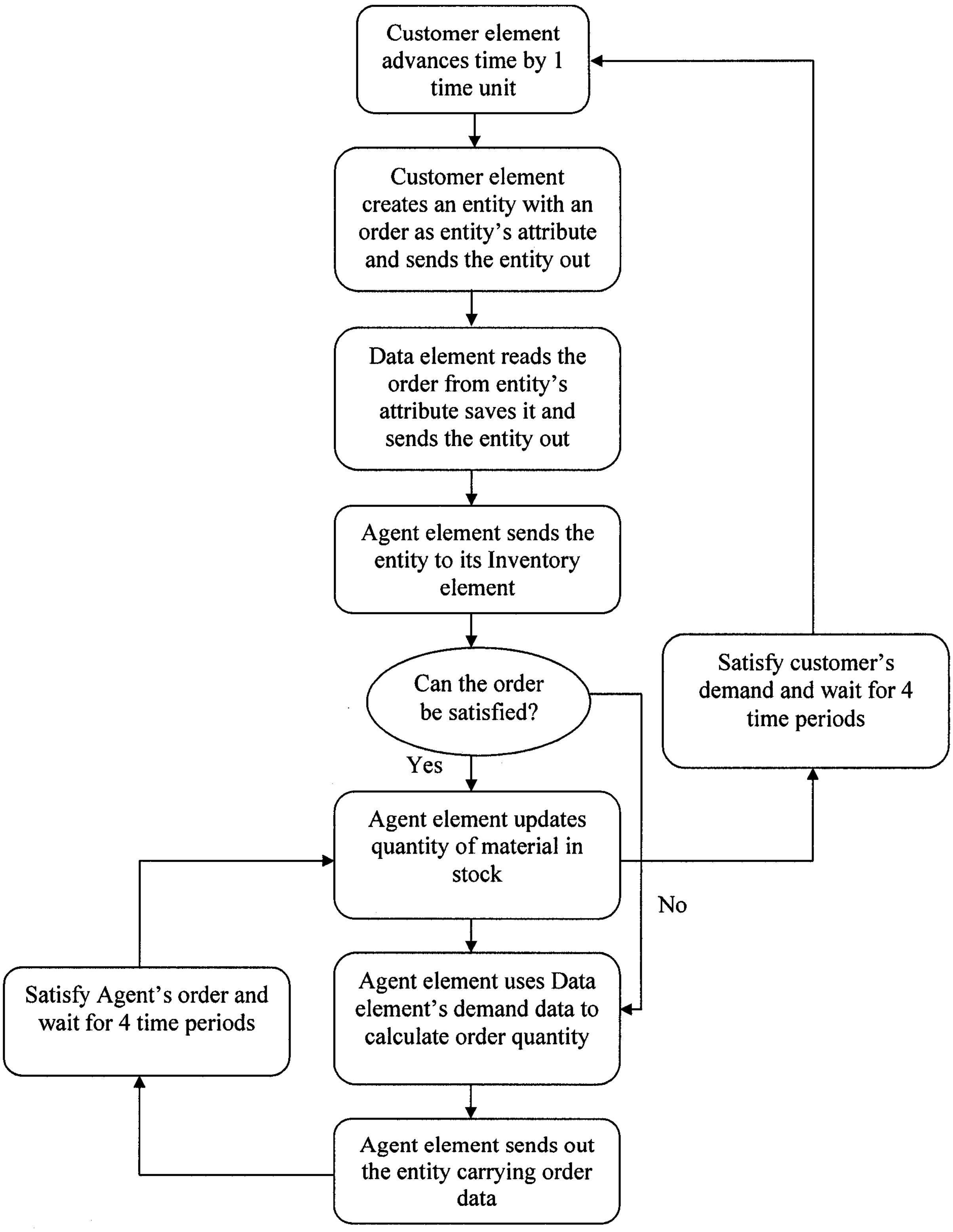


Figure 4-4 Flowchart of the processes of the two–echelon supply chain

4.4 Moving Average Forecasting

4.4.1 No Information Sharing

By running the simulated model of the two echelon supply chain for sequential pairs of upstream supplier and downstream customers for four times and introducing the mean and variance of supplier's orders in each step as the mean and variance of customer's orders in the next step, the model produced the following values for variance ratios:

Table 4-1 Chen and Chatfield (2nd method) results vs. SSCS results (NIS)

	Customer	Retailer	Wholesaler	Distributor	Factory
Chen et al.	1	1.89	3.57	6.74	12.73
Chatfield	1	1.90	3.59	6.70	12.84
SSCS	1	1.895	3.61	6.88	12.98

Simulation model of the supply chain was run just once for 5000 time periods with 500 periods to warm up.

The five echelon serial supply chain simulation model developed and shown in Figure 4-4, was validated against Chen's model and Chatfield's model. The parameters of the model, number of simulation replication and simulation run time are presented accordingly at the bottom of Figure 4-5.

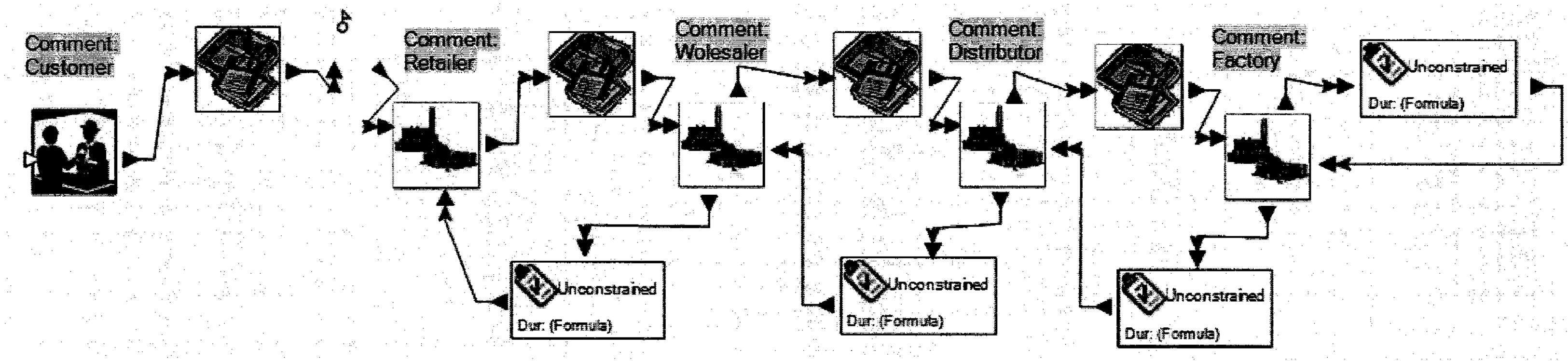


Figure 4-5 The five echelon supply chain simulation model

- Supply chain participants: Customer, Retailer, Wholesaler, Distributor, Factory
- Customer's demand: Normal distribution with mean 50 and standard deviation 20
- Inventory policy: periodic review policy (for all supply chain members)
- Inventory review period: 1 time unit (for all supply chain members)
- Lead time: 4 (orders placed at time t will be received at time t+5)
- Forecasting method: Simple moving average (for all supply chain members)
- Forecasting span: 15 periods (for all supply chain members)
- Simulation replication: 1 replication
- Simulation time: 5000 periods (500 periods was used to initialize the model)

The following table compares the outcome of the simulation performed to the outcomes of the models developed by Chen et al. (2000) and Chatfield et al. (2004):

Table 4-2 Chen and Chatfield (1st method) results vs. SSCS results (NIS)

	Customer	Retailer	Wholesaler	Distributor	Factory
Chen et al.	1	1.89	3.57	6.74	12.73
Chatfield	1	1.90	4.01	9.09	21.70
SSCS	1	1.88	3.95	8.96	21.40

To further verifying the results generated by models constructed by SSCS's elements, the same five echelon supply chain model was set with the attributes Chatfield et al. used to compare their model with that of Dejonckheere et al. (2004).

First, all the members of the supply chain were supposed to employ order up to level policies with simple moving average forecasting method to update their base stock level. Customer's demand rate was assumed to be generated from a normal distribution with mean of 100 and variance of 100. All lead times were assumed to be 4 and review periods used by all chain members were all set to 1. Review period for all chain members was set to 1 with 4 time periods as lead time. Under all these assumptions and assuming safety factor of zero, with all chain participants using 19 periods simple moving average forecasting with no information sharing, the developed model was run once for 2000 time periods with first 500 time periods for initialization. The following table shows the comparison between the results generated from SSCS model with the results of Chatfield and Dejonckheere's models.

Table 4-3 Dejonckheere and Chatfield (1rst method) results vs. SSCS results (NIS)

	Customer	Retailer	Wholesaler	Distributor	Factory
Dejonckheere	1	1.67	2.99	5.72	11.43
Chatfield	1	1.67	2.99	5.72	11.43
SSCS	1	1.68	3.04	5.84	11.72

4.4.2 Analyzing the Difference

Tables 4-1 and 4-3 show that the results of SSCS supply chain model are very close to the results of Chen's model, Chatfield's model and Dejonckheere's model. However, in table 4-2, the results of SSCS model show a good proximity with the outputs of Chatfield's simulation model while they do not agree with the outputs of Chen's simulation model. Chatfield et al. (2004) argued that the inconsistency is the result of not considering stock-out at different levels of supply chain by Chen's model.

Because the process of filling orders in Chen's model has no effect on the process of updating inventory, stock out events can not have much contribution to the difference of the results. The reason of such difference can be related to the fact that Chen's model shows the lower limit on Bullwhip effect under several different assumptions one of which is that the orders being place by the customer are independent and identically distributed.

As can be seen from Table 4-2, the ratios of variances in retailer-customer level are not different in both cases, but the difference of variance ratios grows by moving upstream the supply chain. This can be attributed to the fact that moving upstream the supply chain the orders being placed by different agents are not from a symmetric distribution anymore and the skewness of the orders being generated increases going farther upstream. To investigate this theory, the model was run for 2000 time periods, using the exact same parameters and features but with different number of time periods for initialization (the first run with no initialization and the second run with 400 time periods for initialization). The results are presented in the following table. As using the early time periods of simulation can result in more skewness of orders, it can be expected that the less initializing periods are, the more the difference between the results of SSCS model and those of Chen's model is.

Table 4-4 Chen results vs. SSCS results with and without initialization (NIS)

	Customer	Retailer	Wholesaler	Distributor	Factory
Chen et al.	1	1.89	3.57	6.74	12.73
SSCS (1st)	1	2.09	5.62	16.26	45.23
SSCS (2nd)	1	1.88	3.98	9.04	21.60

4.4.3 Information Sharing

One of the remedies suggested for Bullwhip effect is to use centralized demand information or information sharing. Information sharing is suggested to be an effective method in reducing Bullwhip effect. This is based on the managerial insight that by sharing customer's demand information with all parties involved in the supply chain and by using that information for forecasting, the variance ratio between two successive echelons can be reduced. The reduction in variance ratio is the direct consequence of using customer's demand data which have less variance for forecasting.

As shown in section 4-2, Chen et al. (2000) presented a formula for the variance ratios for a supply chain under information sharing situation. The formula was developed based on the assumption of having identically distributed, non-correlative demand data in supply chain.

To verify the SSCS's capability of modeling a supply chain with centralized demand information, a simulation model of a five echelon supply chain was developed. As in Chen's model, at each time period, the customer places an order which is consequently received by the retailer. Retailer processes the order placed by the customer and updates its inventory by placing an order to the wholesaler. Retailer also provides wholesaler with its forecast of customer's demand for the next time period. Wholesaler uses retailer's order quantity and the forecast of customer's demand provided to update its inventory level. In the same way, each member of the supply chain provides the information regarding forecasted customer's demand to its supplier. The main point in this process suggested by Chen et al. (2000) is using the real time demand of the downstream customer by its direct upstream supplier for updating inventory level.

The result of the simulation model developed using SSCS elements is compared to the results of Chen and Chatfield's models in the following table. The developed model was run once for 5000 time periods with the first 500 periods for initialization.

Table 4-5 Chen et al. and Chatfield et al. results vs. SSCS results (IS)

	Customer	Retailer	Wholesaler	Distributor	Factory
Chen et al.	1	1.89	3.22	5.00	7.22
Chatfield et al.	1	1.90	3.26	5.08	7.36
SSCS	1	1.89	3.23	5.01	7.28

The same model developed for validating against Dejonckheere's model under no information sharing with the exact same parameters is also used under information sharing condition. The results are compared to those of Charfield's and Dejonckheere's models in table 4-6. It was assumed in all models that all members of the supply chain use the real time data of their customer's demand rate in order to update their inventory base stock level.

Table 4-6 Dejonckheere and Chatfield (1st method) results vs. SSCS results (IS)

	Customer	Retailer	Wholesaler	Distributor	Factory
Dejonckheere	1	1.67	2.61	3.83	5.32
Chatfield	1	1.67	2.61	3.83	5.34
SSCS	1	1.69	2.67	3.94	5.50

4.5 Exponential Smoothing

4.5.1 No Information Sharing

To verify the results generated by the five echelon supply chain model using exponential forecasting, those results were compared to the results of the analytical model constructed by J. K. Ryan (1997). In her model, Ryan calculated the ratio of variances in a two echelon supply chain when the customer places its order to the retailer and retailer uses exponential forecasting to update its inventory. According to the analytical model developed by Ryan, in such a supply chain when the customer's demands are not correlated and drawn from a symmetric distribution, the lower bound for the ratio of variances of retailer and customer can be obtained using the following analytical formula:

$$\frac{Var(q)}{Var(D)} \geq 1 + 2L\alpha + \frac{2L^2\alpha^2}{2-\alpha} \qquad \text{(Equation 4-7)}$$

α : parameter of exponential smoothing

L: lead time

Although Ryan has not addressed the variance ratio for other members of a supply chain with more than two echelons under information sharing and no information sharing conditions, it can be logically assumed that for no information sharing condition the variance ratio of each firm in the chain can be analytically calculated as follow:

$$\frac{Var(q_t^k)}{Var(D)} \geq \prod_{1}^{k}\left(1 + 2L_i\alpha_i + \frac{2L_i^2\alpha_i^2}{2-\alpha_i}\right) \qquad \text{(Equation 4-8)}$$

The following table shows the comparison made between the outcomes of the above formula and the results obtained from the simulation model of a five echelon supply chain constructed by SSCS elements. The model was designed for all members of supply chain to use exponential smoothing with the same value for α. The developed model then was run once for each α value for 2000 time periods with 500 periods for initialization.

Table 4-7 Analytical results vs. simulation results (NIS)

	Customer	Retailer	Wholesaler	Distributor	Factory
Analytical (α=.1)	1	2.26	5.10	11.54	26.09
Simulation (α=.1)	1	2.23	5.09	11.74	27.06
Analytical (α=.2)	1	4.11	16.89	69.45	285.34
Simulation (α=.2)	1	4.05	17.24	74.52	323.20

The results in the above table show an increasing difference moving upstream between simulation outcomes and outcomes of the analytical formula. This difference can be caused by the fact that by going toward upstream in supply chain, the demand data gets skewed and having demand data from a symmetric statistical distribution is not a valid assumption anymore.

4.5.2 Information Sharing

The main purpose of choosing the model developed by Dejonckheere et al. (2004) as the reference was the formula presented by the authors for calculating variance ratios in supply chain under information sharing situation when all participants in the chain practice exponential forecasting method to update their inventory periodically. They developed the formula via an analogy with the lower bound of variance ratios for bullwhip effect presented by Chen at al. for simple moving average forecasting method. The formula is as follow:

$$\frac{Var(q)}{Var(D)} \geq 1 + 2\sum_{1}^{k} L_i \alpha + \frac{2(\sum_{1}^{k} L_i)^2 \alpha^2}{2-\alpha} \qquad \text{(Equation 4-9)}$$

For verification of the developed SSCS model, the exact same aforementioned parameters were used. For exponential smoothing forecasting method, α was set to be 0.1. The model was set first under assumption of no information sharing and then with the assumption of information enrichment. At each case, the developed model was run once for 5000 time periods with 500 periods of initializing. The outcomes in both cases are presented in the following tables along with the reference results.

Table 4-8 Dejonckheere and Ryan results vs. SSCS results (NIS)

	Customer	Retailer	Wholesaler	Distributor	Factory
Dejonckheere	1	2.26	5.16	11.84	27.22
Analytical	1	2.26	5.10	11.54	26.09
SSCS	1	2.23	5.09	11.74	27.06

Table 4-9 Dejonckheere results vs. SSCS results (IS)

	Customer	Retailer	Wholesaler	Distributor	Factory
Dejonckheere	1	2.26	4.05	6.37	9.21
Analytical	1	2.26	4.05	6.37	9.21
SSCS	1	2.26	4.05	6.36	9.20

4.6 Effect of Real Time Demand Data

4.6.1 Moving Average Forecasting

As mentioned before one of the principal underlying assumptions of the formula presented by Chen et al. (2004) for supply chain under centralized demand information, is using of real time demand data. In Chen's model, each member of the supply chain uses its direct customer's demand at time t to update its inventory level for the same time period. By replacing this assumption by another assumption according to which, the customer's demand at time t-1 is used by any member of supply chain for updating inventory at time t, both analytical and simulation models generate different outcomes. To compare the effect of these two assumptions on Bullwhip effect, the ratio of variances of two successive members of supply chain is calculated analytically for both cases in below:

- Using real-time demand data, assuming safety factor of zero and no correlation:

$$q_t^1 = y_t^1 - y_{t-1}^1 + D_{t-1} \qquad \text{(Equation 4-10)}$$

q_t^1 = Retailer's demand rate at time t

$y_t^1 = \frac{L_1 \sum_1^P D_{t-i}}{P}$ =Retailer's BSL at time t

D_{t-1} = Customer's demand rate at time t-1

P = the number of time periods being used for forecasting

For other members of supply chain, the equation is as follow:

$$q_t^k = y_t^k - y_{t-1}^k + q_t^{k-1} \qquad \text{(Equation 4-11)}$$

$$= y_t^k - y_{t-1}^k + y_t^{k-1} - y_{t-1}^{k-1} + q_t^{k-2}$$

$$= y_t^k - y_{t-1}^k + y_t^{k-1} - y_{t-1}^{k-1} + y_t^{k-2} - y_{t-1}^{k-2} + q_t^{k-3}$$

$$= \dots\dots\dots$$

$$= (1 + \frac{L_1 + \dots + L_k}{P}) D_{t-1} - \frac{L_1 + \dots + L_k}{P} D_{t-p-1}$$

The variance of q_t^k can be calculated then as follow:

$$Var(q) = (1 + \frac{\sum_1^k L_i}{P})^2 Var(D) + (\frac{\sum_1^k L_i}{P})^2 Var(D) \qquad \text{(Equation 4-12)}$$

$$= \left(1 + \frac{2\sum_1^k L_i}{P} + \frac{2\sum_1^k L_i^{\;2}}{P^2} \right) Var(D)$$

Assuming the same lead time L for all members of the supply chain ($L_1 = L_2 = \ldots = L_k = L$), the variance of q_t^k is:

$$Var(q) = \left(1 + \frac{2kL}{P} + \frac{2k^2L^2}{P^2}\right)Var(D) \qquad \text{(Equation 4-13)}$$

- Using demand date from last time period, assuming safety factor of zero and no correlation with lead time L for all supply chain participants:

$$q_t^1 = y_t^1 - y_{t-1}^1 + D_{t-1} \qquad \text{(Equation 4-14)}$$

$$\begin{aligned} q_t^k &= y_t^k - y_{t-1}^k + q_{t-1}^{k-1} \\ &= y_t^k - y_{t-1}^k + y_{t-1}^{k-1} - y_{t-2}^{k-1} + q_{t-2}^{k-2} \\ &= y_t^k - y_{t-1}^k + y_{t-1}^{k-1} - y_{t-2}^{k-1} + y_{t-2}^{k-2} - y_{t-3}^{k-2} + q_{t-3}^{k-3} \\ &= \ldots\ldots \\ &= y_t^k - y_{t-k}^1 + D_{t-k} \end{aligned}$$

The variance of q_t^k can be calculated then as follow:

$$Var(q) = \left(\frac{L(D_{t-1} + D_{t-2} + \ldots + D_{t-k} - (D_{t-P-1} + \ldots + D_{t-P-k}))}{P}\right) + D_{t-k}$$

(Equation 4-15)

$$= (1 + \frac{L}{P})^2 Var(D) + (2k-1)\frac{L^2}{P^2} Var(D)$$

$$= (1 + 2k\frac{L^2}{P^2} + 2\frac{L}{P})Var(D)$$

Using the formula developed above for a five echelon supply chain under centralized demand information by using previous time period demand data, variance ratios for each tire of the supply chain were calculated. The following table shows the calculated variance ratios compared to the same ratios resulted from simulation model constructed by SSCS elements. The simulation model was run once for 5000 time periods with 500 periods of initialization.

Table 4-10 Analytical results vs. simulation results (IS)

	Customer	Retailer	Wholesaler	Distributor	Factory
Analytical	1	1.89	2.11	2.33	2.55
Simulation	1	1.91	2.16	2.39	2.65

By comparing ratios of variances of the two models developed with and without using real-time information to update inventory base stock level, it becomes clear that using last time period demand data is more effective in reducing Bullwhip effect than using real time demand data.

4.6.2 Exponential Smoothing

In the case of employing exponential smoothing forecast technique, to demonstrate the effect of using real time customer's demand rate data on Bullwhip effect, the results of the simulation model under information sharing condition with the assumption that all members of the supply chain update their inventory level with their immediate customer's real time demand rate versus the results of the same model with all chain members using last time period data instead are presented in the following table. In both cases α was set to 0.1.

Table 4-11 Real time updating results vs. not real time updating results (IS)

	Customer	Retailer	Wholesaler	Distributor	Factory
Real time	1	2.26	4.05	6.36	9.20
Not real time	1	2.26	2.38	2.53	2.69

4.7 Conclusions

Comparison of the results produced by models constructed using SSCS (SSCS) with the results of other simulation tools and analytical formulas for different scenarios shows the functionality of the developed supply chain toolkit in modeling coordination and information sharing problems in supply networks. Also validating the models built by elements of SSCS template with well known analytical formulas for serial supply chains shows the degree of accuracy of the developed template.

An analysis in the later part of this chapter shows that using the real time demand information from downstream customer to update the parameters of the upstream supplier produces Bullwhip effect of higher magnitude. On the other hand this analysis shows that using the demand data available from the last period of time to update the parameters results in a Bullwhip effect of lower magnitude. This difference is observed in either cases of using moving average forecasting or exponential smoothing forecasting technique. The result of having last time period demand data used for updating the parameters are compared with the results of a developed analytical formula. This comparison shows the accuracy and reliability of the developed supply chain modeling toolkit.

5 Construction Supply Chain Case Study

5.1 Introduction

As mentioned in the previous sections, one of the main design goals of SSCS was compatibility. According to compatibility goal, SSCS was designed to work easily with other specific purpose simulation tools developed for construction processes. Since there are many construction processes simulated in Simphony environment, choosing Simphony as the simulation environment for developing SSCS toolkit was an important step toward achieving compatibility.

Supply chain management as a concept has been long of interest of construction researchers and practitioners. However, most studies conducted in the area of construction supply chain have investigated the subject from a common sense or intuitional perspective. Just a handful number of literatures can be found which have tried to model and formulate a construction supply chain problem and accordingly quantify the benefits of implementing such a concept in construction industry.

Construction as an industry has a tremendous amount of material flow, information flow and financial flow for each and every project undertaken. This provides the interested researchers with a wide variety of supply chain problems. However, the complexity of construction processes, their one of a kind nature, and high degree of uncertainty involved in each process hinder the development of the proper models to address construction supply chain issues.

Simulation is one of the most effective techniques for analyzing construction processes and problems. It enables researchers and practitioners to capture the uncertainties and complexities involved in a construction project and therefore it is reliable choice to investigate and study construction supply chain problem.

This chapter includes presentation of a case study developed to demonstrate the use of SSCS toolkit with other Simphony-based construction simulation tools in modeling a construction project's supply chain.

In this chapter a tunneling project's pre-cast liner supply chain is presented as a case study for construction supply chain simulation. The tunneling project is modeled using Simphony Tunneling Template while the supply chain concepts are applied using SSCS toolkit. A series of different scenarios are investigated and some conclusions are made based on the simulation results.

Section 5.2 of this chapter introduces a typical tunneling project's supply chain. Section 5.3 elaborates on the characteristics of the problem addressed in this chapter. Section 5.4 discusses the simulation model developed to perform sensitivity analysis using SSCS. Section 5.5 present the result of the conducted sensitivity analysis and section 5.6 summarizes the conclusions made based on the results of the performed simulation study.

5.2 Tunneling Supply Chain Case Study

Tunneling projects are common in construction industry. Many tunnels have been constructed through years and a great amount of experience has been accumulated. Despite the similarity in the methods of construction of different tunnels, there are still a lot of uncertainties involved in each individual tunneling project. Such uncertainties prevail even in projects undertaken by the same contractor and constructed using the exact same method.

Because of such complexity, high risk and uncertainties involved in tunneling projects, simulation tools and techniques are used to model tunneling projects (AbouRizk S., Ruwanpura J., Fernando S., 1999).

Although Tunneling Simulation tools help to capture most problems and uncertainties associated with tunneling construction, they mostly lack the ability to provide a wider perspective to consider supply chain related issues in tunneling construction.

In order to complete a tunneling project several sections should be constructed including the main tunnel. The most important processes of the main tunnel construction are excavation, liner installation and dirt removing. The sequence of events in a typical tunneling project is as follow:

- Excavation: A certain length of the tunnel is bored either by hand or by tunnel boring machine (TBM). The dirt produced in this process is dumped into muck cars carried by a train.
- Liner installation: After the boring for a certain length of the tunnel is done, the boring machine installs the concrete liners from a muck car carried by a train.
- Dirt removing: The muck cars containing dirt are transferred to the other end of the tunnel by a train. The dirt can be taken out of the tunnel using a crane.

All these processes should be accomplished in order to continue boring another section of the tunnel. Therefore, any problem in any of these processes can affect the whole tunneling productivity and the desired project duration and cost accordingly.

The concrete liner segments installed in a tunnel can be either pre-cast segments or cast in place. Using pre-cast segments accelerates all processes significantly. However this means the concrete segments should be cast and cured in another location before being transferred to the tunneling site and being installed. This forms a major material flow in tunneling construction process which is the flow of pre-cast liner segments.

The need of considering simulation modeling of the pre-cast concrete liner segments' flow in a tunneling project can be realized from the significant effects that liners' supply can have on a tunneling project's productivity. Not having the right amount of concrete liners at the right time in the right place can cease the whole boring operation and therefore delay finishing of the project.

5.3 Problem Statement

The project selected to be modeled as a case study for construction supply chain is Glencoe tunnel project in Calgary, Canada. This project is being constructed by the City of Edmonton and the supplier for the pre-cast concrete liner segments is a company named Lafarge. The liner segments are cast, cured and stored in Lafarge yard and then transferred to the tunneling site according to the orders being place by the Glencoe tunnel project team. The liners are stockpiled in the tunneling site and being used as needed according to the tunnel advancement rate.

Lafarge considers its in-site storage area as a resource and it is not willing to produce and hold all the liners in advance before the start of the project. Lafarge production capacity of the pre-cast concrete liner segments is also limited. On the other hand, in many occasions especially when the tunnel under construction is in a crowded area of a city which is the case with Glencoe tunnel, tunneling site does not have enough room to accommodate more than a certain number of concrete liners. Furthermore, a quality control process is in place by the Glencoe tunneling project team which can affect the production by rejecting a produced batch of concrete liners.

The objective of the study conducted in this section is to model the supply chain of pre-cast concrete liner segments for Glencoe tunnel using Simphony Tunneling Template and SSCS and to investigate the effect of the different parameters on the tunneling construction productivity by means of comparing the duration of the project under different scenarios and assumptions. The parameters considered in this study are:

- Liners' production rate: Lafarge has a capacity constraint in its pre-cast segmental liner production line. This production capacity is determined by the number of moulds owned by Lafarge and used to produce the liner segments. There is a negotiation in place between City of Edmonton and Lafarge to increase the number of the moulds however, because of high cost of acquiring new moulds, the effect of increasing production capacity on the tunneling project productivity should be investigated.

- Storage capacity: Storage capacity on Lafarge site or on tunneling site is believed to be the most important factor affecting the tunneling productivity. To know the extent of this effect, different scenarios with different storage capacities should be simulated.
- Quality control: City of Edmonton places a high value on the quality of the produced concrete liners. The Glencoe tunnel project team also has rigid requirements for the quality of the produced segments and rejects any unqualified segment. Because the liners are being produced in batches, any rejection affects the whole batch. The importance of quality control is a known fact but its affect over tunneling project productivity is to be quantified by simulating different scenarios.
- Quantity of liners ready: Lafarge starts producing the liners for each tunneling project after receiving the order from the City of Edmonton. In order to have the desired number of liners ready before the start of a project, it is crucial for the City of Edmonton to take into account the lead time needed for production when placing the order. Otherwise, the tunneling project starts with less than the appropriate amount of liners ready which can affect the tunnel construction productivity.

5.4 Simulation Model

The simulation modeled developed for the problem includes two major components: Tunneling component and Lafarge component.

Tunneling component is used to model the processes taken place in a tunneling project. This part has been constructed using Simphony Tunneling Template. Interested readers are referred to Tunneling Template User's Guide to review the features and characteristics of this template. The parameters of the elements of this template are set to those of Glencoe tunnel. An Inventory element is also used to simulate the storage area at tunneling site.

Lafarge component is developed to model the liner production processes. The three main processes simulated in this part are production, storage and quality control. The production part is designed to accommodate the capacitated liner production process due to the limited number of moulds available in Lafarge site. The storage area is modeled using an Inventory element with periodic Inventory policy with period of one day and a constant base-stock level. Quality control part of the model is simulated by incorporating a constant rejection percentage for the produced liners.

For validation purposes, the developed model was run under the assumption of having enough storage capacity and liners. The obtained project duration then was compared to the project duration of the tunneling simulation model without Lafarge component. The proximity of the results validates the simulation process.

Tunneling storage capacity is limited and at any given time the quantity of liners held on the tunneling site can not exceed that capacity. The delivery time of the liners from Lafarge Site to tunneling site is two hours if the requested number of liners is available. Considering the negligible delivery time, in order to cope with both constraints of batch delivery policy and limited storage area, the orders are being placed in batches which have the same size as delivery batches.

In the process of tunneling whenever a quantity of liners equal to the ordering batch size is consumed, an order is placed for the same number of liners to replace the consumed ones. The order is then received by Lafarge with no delay and is processed immediately. Upon the availability of the quantity of liners requested, replenishment takes place and the requested number of liners is delivered to the tunneling site. The ordering batch size is equal to delivery batch size or a full truck load.

At the end of each working day, the total amount of liners requested by the tunneling site in that day is reviewed by Lafarge and is used as a quantity of liners that should be produced. Using the periodic review policy with the constant base-stock level helps meeting the capacity constraint of Lafarge storage area. The liners then are produced in Lafarge capacitated production line constrained by the number of moulds.

The production starts with pouring the mixture of concrete, water and aggregate into the moulds. The forms are removed after a working day and the curing process of the produced liners starts. Seven days after removing the forms, a strength test is performed and according to the result the produced batch of liners is either rejected or accepted. Upon achieving the acceptable strength the batch of liners is added to the finished product inventory and can be delivered to tunneling site accordingly. On the other hand if one of the segments fails the test, the produced batch of liners should be held in work-in-process inventory for another fourteen days. After this period another test is performed on the liners. If the acceptable strength is achieved, the liners are added to the finished product inventory but if the liners fail the strength test, the whole batch should be produced again.

Components of the simulated model of Glencoe tunnel's liner supply chain are demonstrated in the following figures:

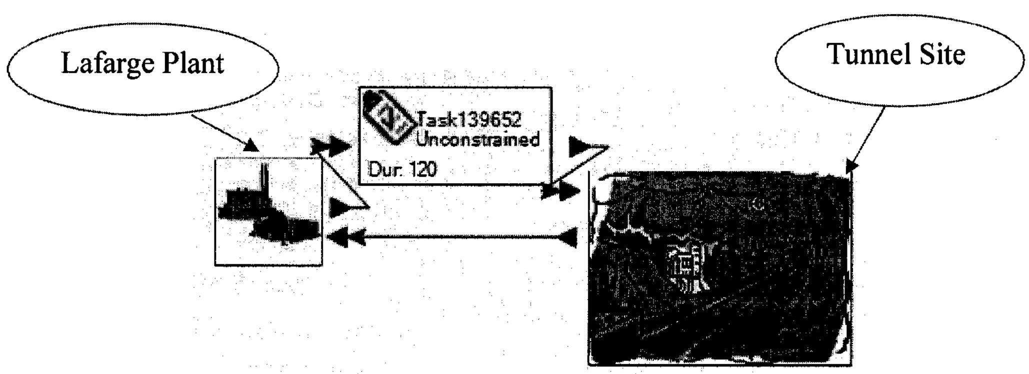


Figure 5-1 Tunneling and Lafarge sites

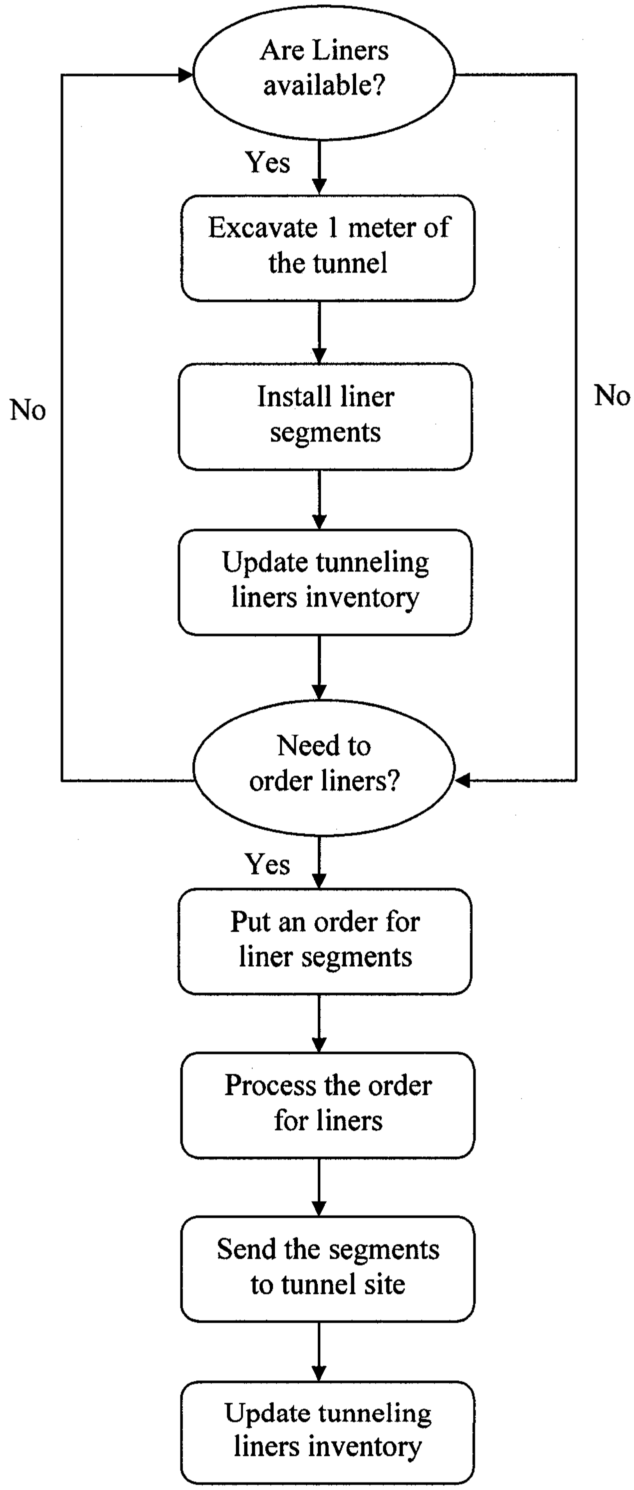


Figure 5-2 Flowchart of processes at tunneling and Lafarge sites

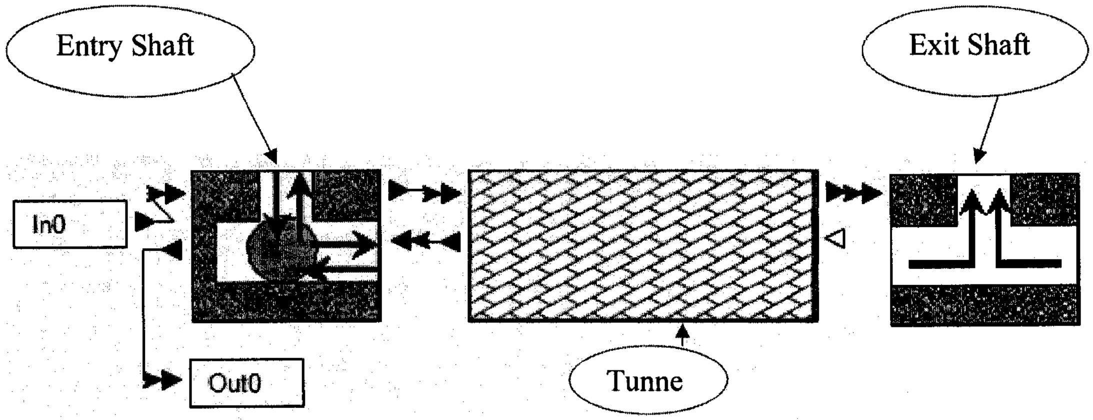


Figure 5-3 inside tunneling root element, entry shaft, soil segment and exit shaft

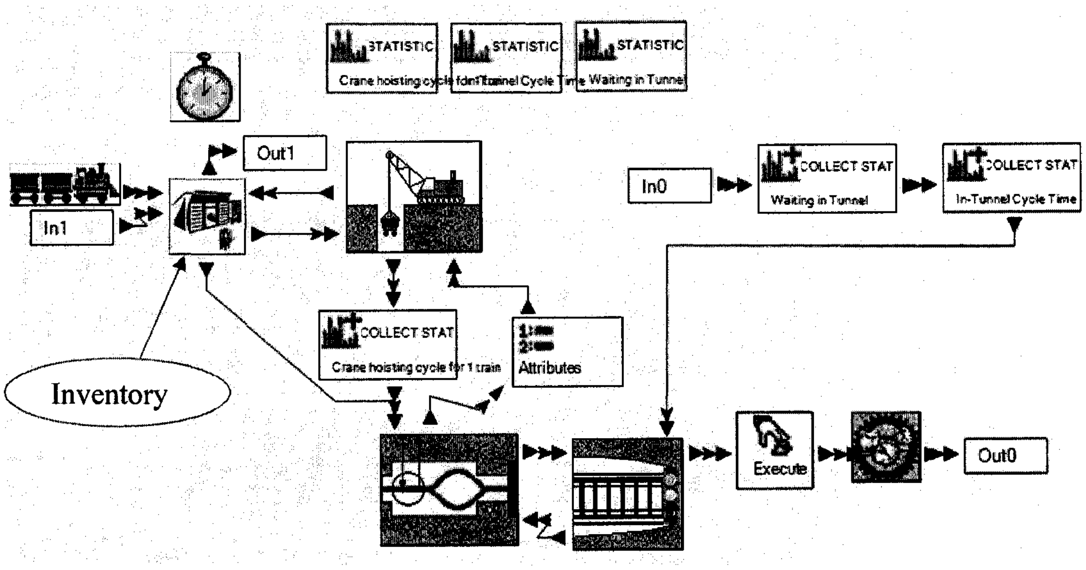


Figure 5-4 Processes inside entry shaft element including Inventory

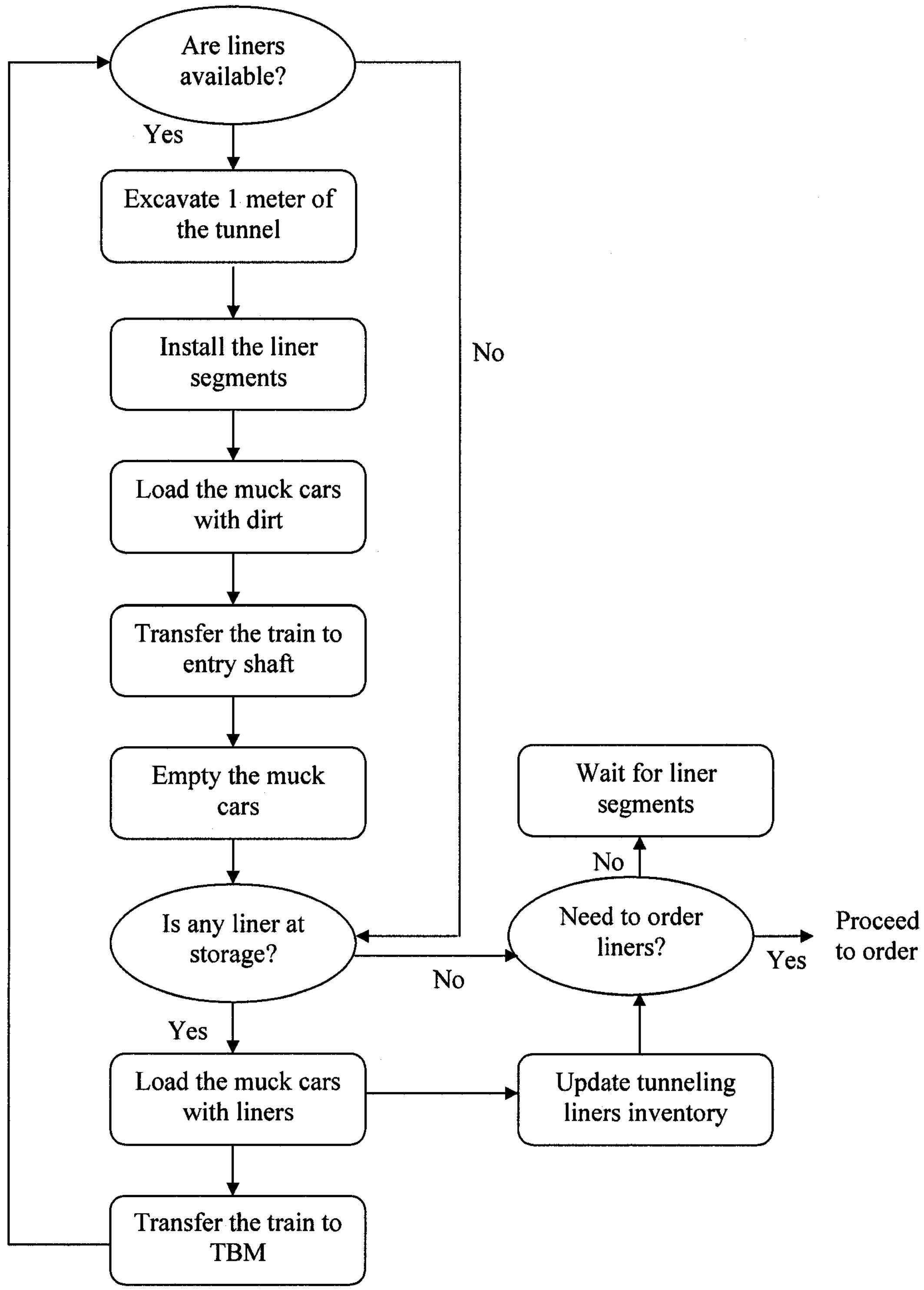


Figure 5-5 Flowchart of processes at tunneling site

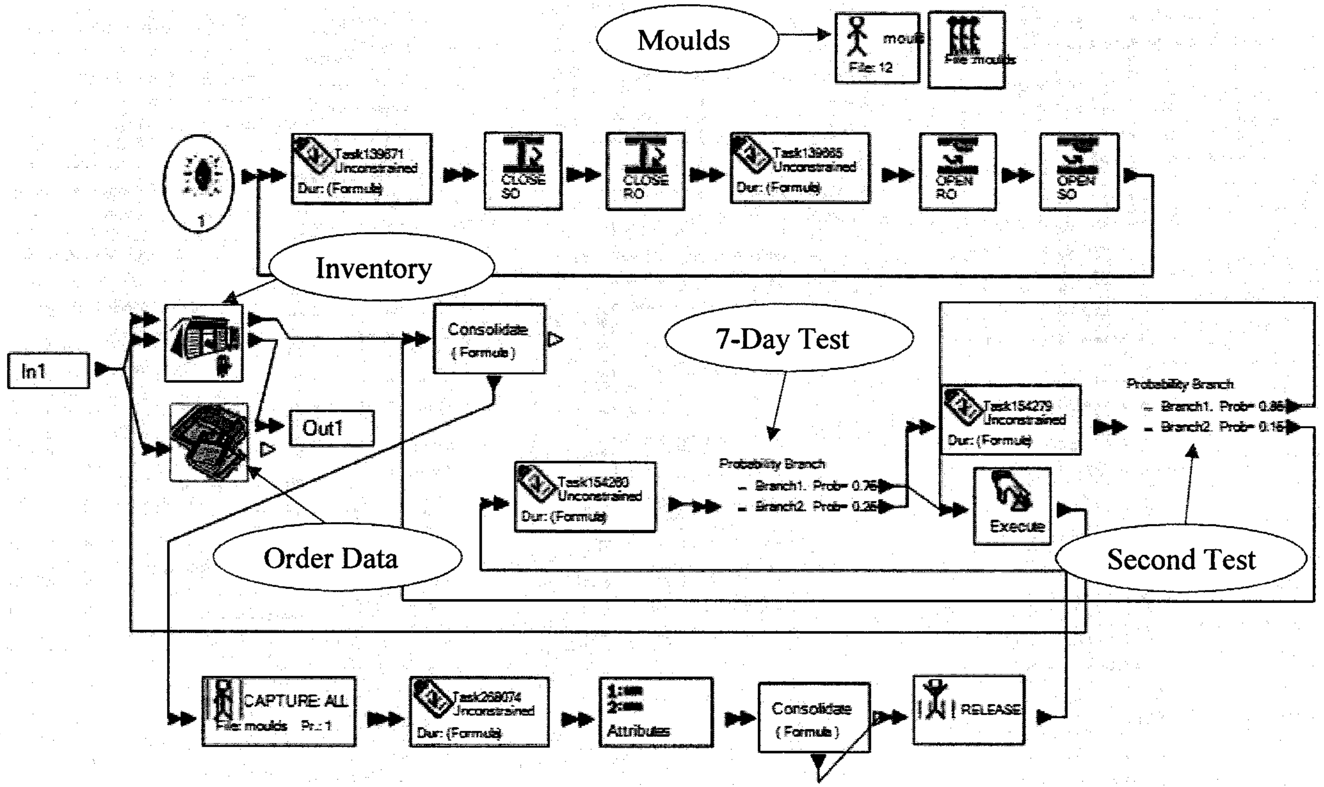


Figure 5-6 Processes inside Lafarge site element

5.5 Sensitivity Analysis

After developing the simulation model of the liner supply chain for the tunneling project, a sensitivity analysis should be performed in order to determine the factors that can affect the productivity of the tunneling project and also to quantify the effect of each of those factors. This sensitivity analysis was performed by changing the model attributes and running the simulation. Time of simulation run in all cases was less than 15 minutes.

5.5.1 Storage Capacity

The first two factors to be investigated are the storage capacity of the tunneling site and the storage capacity of Lafarge site. To conduct a sensitivity analysis with respect to these two variables, four different scenarios are considered, each scenario with a different number of shifts per day and different shift duration. The original scenario is set to a ten-hour shift per day. Other scenarios are considered with a twelve-hour shift per day, two eight-hour shifts per day and two ten-hour shifts per day.

For each scenario, the capacity of storage area on Lafarge site changes while the capacity of tunneling storage area is fixed and equal to its original value of fourteen meters of liners. After this stage, the Lafarge storage capacity is set to one hundred which is its original value while the tunneling storage capacity is set to different values.

In order to have an analytical reference for comparison purposes, a simplified analytical formula for the total storage capacity in the model needed to avoid any delay in tunneling project is formulated. This analytical formula is calculated based on the equation employed for calculating the amount of inventory needed when utilizing periodic review policy. The underlying equation used is as follow (Simchi-Levi et al., 2003):

$$S_p = L\mu + z\sigma\sqrt{L} \qquad \text{(Equation 5-1)}$$

Where L represents lead time, z is the safety factor, μ is the mean daily demand and σ is the variance of daily demand.

Assuming zero percentage of failure in the second strength test, no capacity constraint for liner production and a normally distributed daily demand, the storage capacity required for liners is:

$$S.C. = \mu_{PR} * SD * (8 * FP + 29 * (1 - FP)) + z * \sigma_{PR} * SD * \sqrt{(8 * FP + 29 * (1 - FP))}$$

(Equation 5-2)

Where μ_{PR} and σ_{PR} are mean and standard deviation of the production rate in meter per day. FP is the failure percentage of the first test and z is the safety factor associated with the desired confidence interval. SD represents tunneling shift duration.

The simulation results for each scenario and the analytical storage capacity level are presented in tables 5-1 to 5-4 and figures 5-7 to 5-14. In all scenarios, for calculating the analytical value of the required storage capacity, Lafarge storage capacity and tunnel site storage capacity were set to 100 and 14 respectively.

5.5.1.1 Scenario 1

Table 5-1 Model properties for scenario 1

Tunnel Shift Duration	Shifts/Day	Lafarge Shift Duration	Failure in 7-Day	Failure in 28-Day	Moulds
10	1	8	0.15	0.15	12

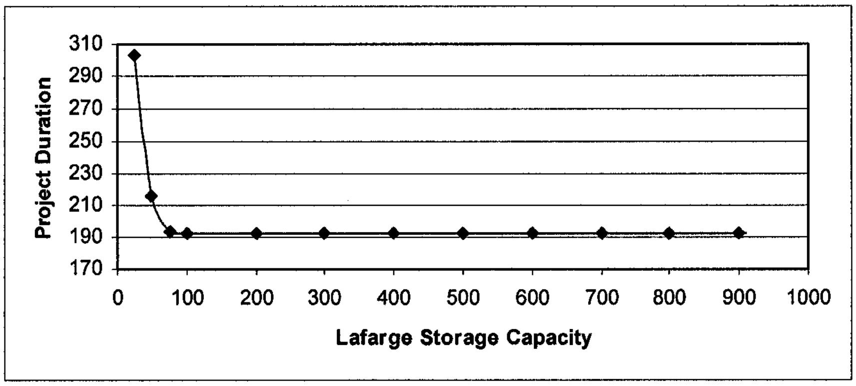


Figure 5-7 Project duration in days vs. Lafarge storage capacity (meters of liner) (Scenario 1)

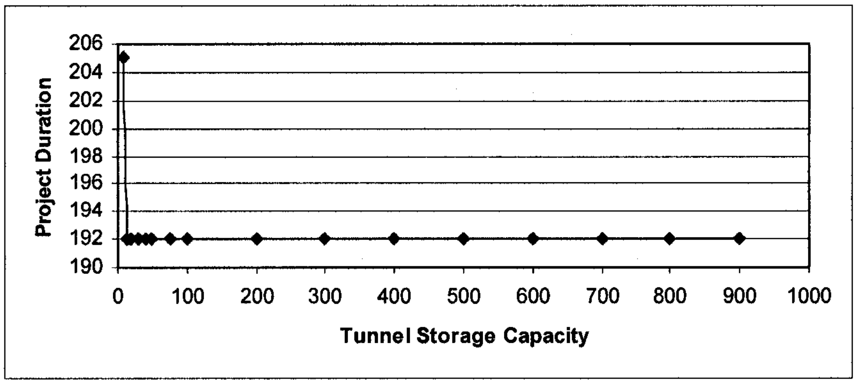


Figure 5-8 Project duration in days vs. tunneling site storage capacity (meters of liner) (Scenario 1)

5.5.1.2 Scenario 2

Table 5-2 Model properties for scenario 2

Tunnel Shift Duration	Shifts/Day	Lafarge Shift Duration	Failure in 7-Day	Failure in 28-Day	Moulds
12	1	8	0.15	0.15	12

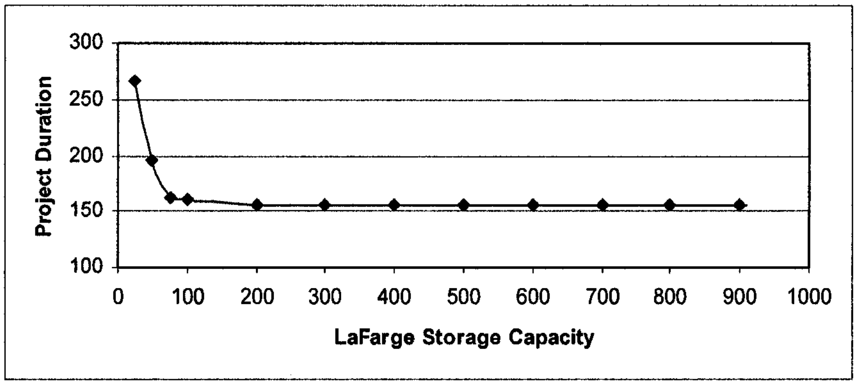


Figure 5-9 Project duration in days vs. Lafarge storage capacity (meters of liner) (Scenario 2)

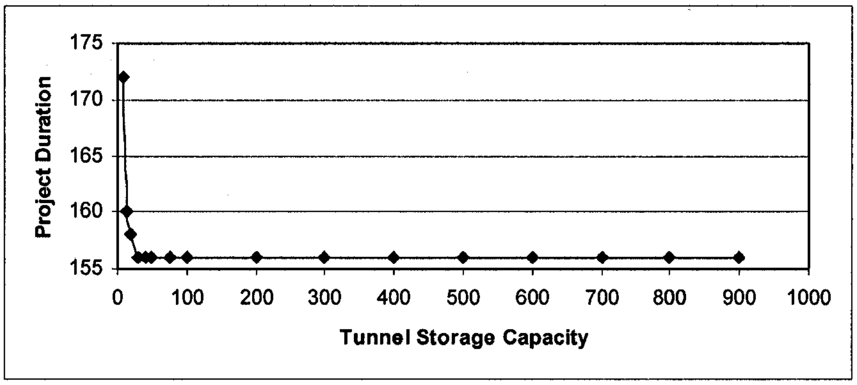


Figure 5-10 Project duration in days vs. tunneling site storage capacity (meters of liner) (Scenario 2)

5.5.1.3 Scenario 3

Table 5-3 Model properties for scenario 3

Tunnel Shift Duration	Shifts/Day	Lafarge Shift Duration	Failure in 7-Day	Failure in 28-Day	Moulds
8	2	8	0.15	0.15	12

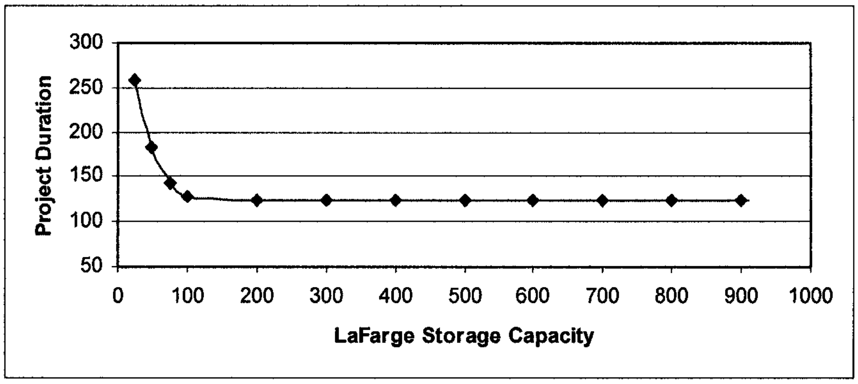


Figure 5-11 Project duration in days vs. Lafarge storage capacity (meters of liner) (Scenario 3)

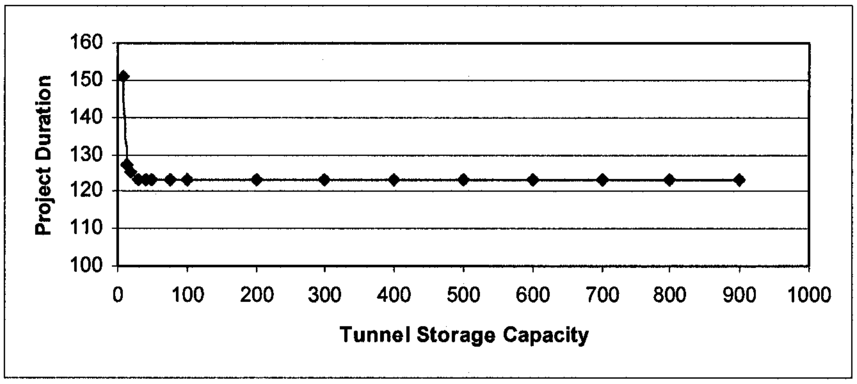


Figure 5-12 Project duration in days vs. tunneling site storage capacity (meters of liner) (Scenario 3)

5.5.1.4 Scenario 4

Table 5-4 Model properties for scenario 4

Tunnel Shift Duration	Shifts/Day	Lafarge Shift Duration	Failure in 7-Day	Failure in 28-Day	Moulds
10	2	8	0.15	0.15	12

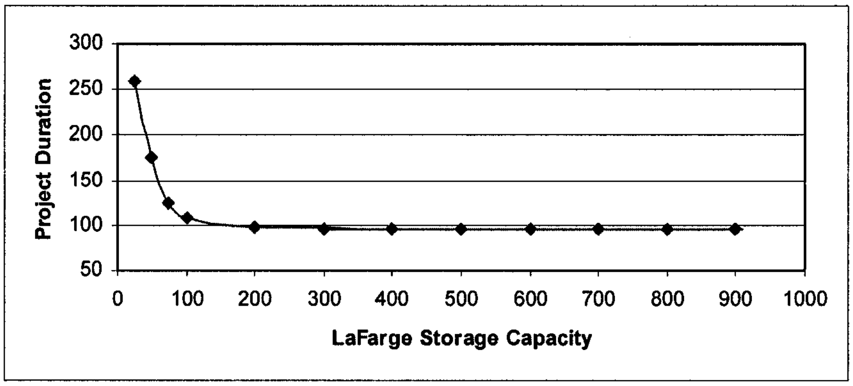


Figure 5-13 Project duration in days vs. Lafarge storage capacity (meters of liner) (Scenario 4)

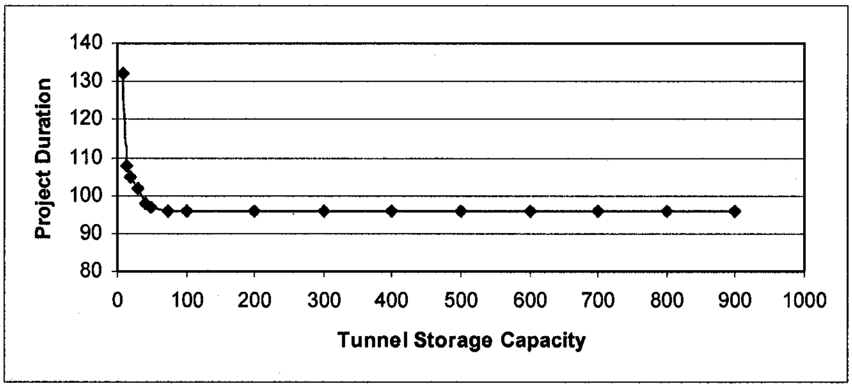


Figure 5-14 Project duration in days vs. tunneling site storage capacity (meters of liner) (Scenario 4)

All the simulation results for all scenarios with different storage capacities for Lafarge and tunneling sites are presented in tables 5-5 and 5-6 and figures 5-15 and 5-16. The underlined values of project duration correspond to the thresholds where reducing storage capacity starts affecting the duration of the tunneling project. These values are important in order to make a comparison with the analytically driven values for the necessary quantity of liners in meters needed before starting of the project which represent the desirable storage capacity.

Table 5-5 Lafarge storage capacity and tunneling working hours vs. project duration (Tunnel Storage capacity was set to 14)

Lafarge Storage	Working Hours/Day			
	10	12	16	20
25	303	267	258	258
50	216	196	182	176
75	193	163	142	125
100	192	160	127	108
200	192	156	123	97
300	192	156	123	96
400	192	156	123	96
500	192	156	123	96
600	192	156	123	96
700	192	156	123	96
800	192	156	123	96
900	192	156	123	96

Table 5-6 Tunnel storage capacity and working hours vs. project duration (Lafarge storage capacity was set to 100)

Tunnel Storage	Working Hours/Day			
	10	12	16	20
7	205	172	151	132
14	192	160	127	108
20	192	158	125	105
30	192	156	123	102
40	192	156	123	98
50	192	156	123	97
75	192	156	123	96
100	192	156	123	96
200	192	156	123	96
300	192	156	123	96
400	192	156	123	96
500	192	156	123	96
600	192	156	123	96
700	192	156	123	96
800	192	156	123	96
900	192	156	123	96

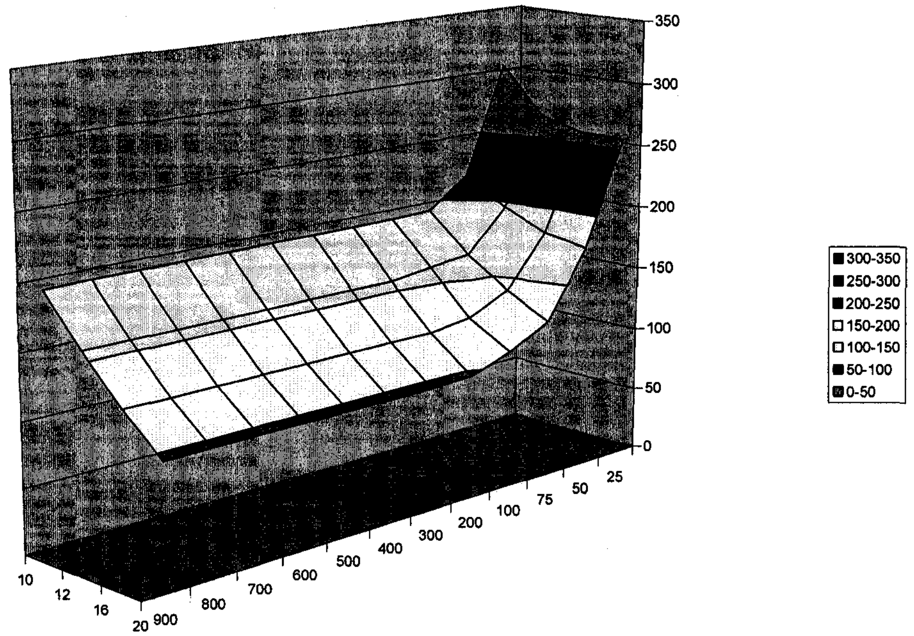


Figure 5-15 Total tunneling project duration (days) as a function of working hours per day and Lafarge liner storage capacity (meters of liner)

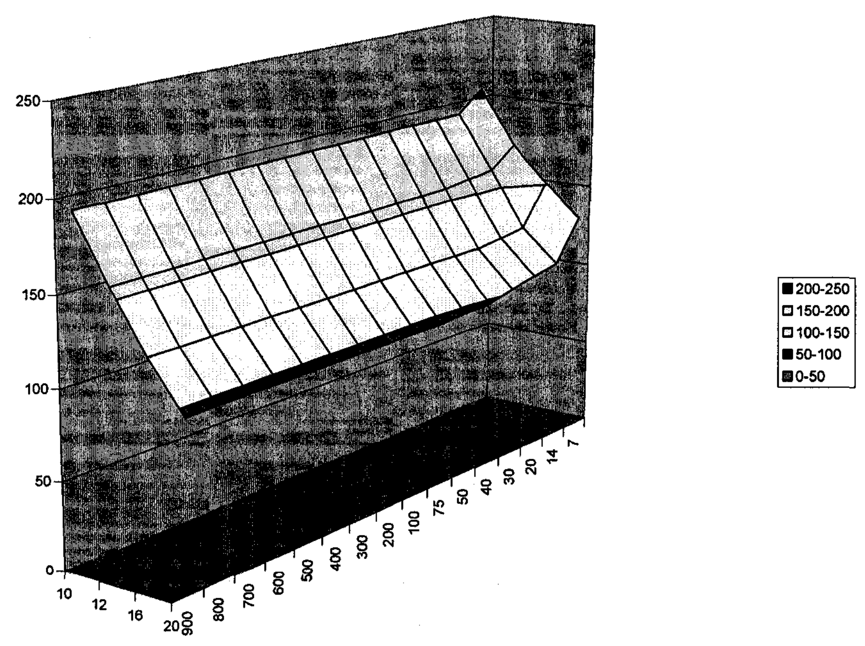


Figure 5-16 Total tunneling project duration (days) as a function of working hours per day and tunneling site liner storage capacity (meters of liner)

The delivery time of the liners from Lafarge site to tunneling site upon availability of the liners is negligible. This means that the two storage areas form a single storage system with the capacity equal to the sum of the capacities of both of them. for example with Lafarge storage capacity equal to 25 meters of liner and tunnel storage capacity of 14 meters of liner, there is an inventory system with the capacity of 25+14=39 meters of liner in the supply chain.

As shown in the tables 5-5 and 5-6 and graphs 5-15 and 5-16, reducing the capacity of storage area in either Lafarge site or tunneling site can increase the duration of the tunneling project to some extent. In theory, the duration of the tunneling project goes toward infinity as the system storage capacity gets closer to zero. This means that without storage capacity, liner segments can not be produced and project can be completed. On the other hand as the network storage capacity increases, the total duration of the project reaches a constant value. This is an expected behavior of the total tunneling duration as a function of supply chain storage capacity. It means if there is no storage capacity, the project duration would be infinite and if there is more than a threshold available storage capacity, the duration would be equal to the duration of the project when all liners are available in the tunneling site and there is no supply chain issue.

The duration escalating effect of capacity reduction is close to nothing unless the capacity is reduced to a certain threshold. These thresholds are highlighted in the tables 5-5 and 5-6 for any given value of working hours per day. As an expected result, the thresholds values increases as the working time per day increases. Increasing working time per day translates into increased demand rate in supply chain which results in the need for a larger storage capacity and a larger threshold value. Tables 5-7 and 5-8 present the threshold values for different working time durations. The first table is based on the result from changing Lafarge storage capacity while the second table is based on the results from changing tunneling site storage capacity. The projected analytical values for storage capacity are also presented in both tables.

Table 5-7 Storage capacity thresholds based on Lafarge storage capacity (meters of liner)

Storage Threshold	Working Hours/Day			
	10	12	16	20
Simulation	89-114	114-214	114-214	214-314
Analytical	82	94	125	155

Table 5-8 Storage capacity thresholds based on tunneling site storage capacity (meters of liner)

Storage Threshold	Working Hours/Day			
	10	12	16	20
Simulation	107-114	120-130	120-130	150-175
Analytical	82	94	125	155

As can be seen, the threshold value is presented as an interval rather than a fix number for simulation results. This is the direct consequence of running simulation for discreet values of storage capacity (i.e. 114, 214, 314 …). By comparing the simulation results for thresholds with the analytically estimated values, the analytical results are found to be not accurate. This means that although the analytically calculated values for the required storage capacity can provide some insights and be considered as an initial guess, they needs to be justified by simulation results. The required justification of the analytically estimated values is the result of the simplifying assumptions made in deriving the analytical formula (i.e. normally distributed demand, unlimited production capacity, no quality control …).

5.5.2 Production Capacity

The next variable which can affect the result of the simulated model and should be considered for sensitivity analysis is Lafarge's production capacity. Lafarge owns and operates certain number of moulds enough for producing twelve meters of liner per day. This means that Lafarge's production capacity is twelve meters of liner per day without considering the curing procedure and quality tests. There is a negotiation in progress between City of Edmonton and Lafarge to increase the number of moulds which results in increasing of production capacity. However, due to the high cost of acquiring new moulds, a sensitivity analysis is required to investigate the benefits of increasing production capacity in terms of reduction in tunneling project duration. Lafarge storage capacity and tunnel site storage capacity were set to 100 and 14 respectively.

Table 5-9 Model properties for sensitivity analysis of production capacity

Tunnel Shift Duration	Shifts/Day	Lafarge Shift Duration	Failure in 7-Day	Failure in 28-Day
10	2	8	0.15	0.15

Table 5-10 Project duration (days) vs. production capacity (meters of liner) per day

Production Capacity	6	8	10	12	14	16
Project duration	151	117	110	108	106	105

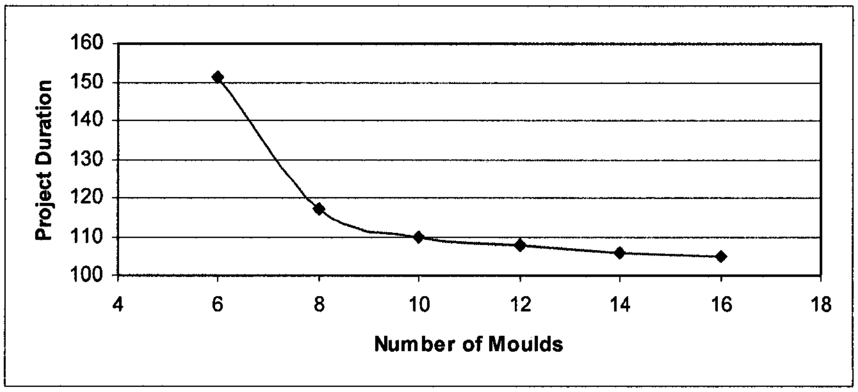


Figure 5-17 Project duration (days) vs. production capacity (meters of liner) per day

The project duration as a function of production capacity also shows an expected behavior. Decreasing production capacity increases the tunneling project duration and as the production capacity gets close to zero, the project duration approaches infinity which means that the project can not be accomplished without having the capability of producing liners. On the other hand, as the production capacity increases, the project duration reaches a fixed value which is the duration of the tunneling project with having all the liners ready on tunneling site.

The shape of the function demonstrated in the previous graph also suggests that by increasing the production capacity more than a certain value, the reduction rate decreases. It means that the reduction in project duration caused by increasing production capacity by one unit decreases substantially by passing a certain point which divides the whole function into two parts. The value of this dividing point alongside the axis associated with production capacity directly depends on the average daily demand of the liners. If the liners average daily demand is less than the production capacity, increasing the capacity has almost no effect on the duration of the tunneling project; conversely, if the average daily demand for liners is more than the production capacity, increasing the capacity can noticeably reduce the project duration. The average daily demand for liners can be determined as a function of average hourly productivity of tunneling project and the working hours per day.

5.5.3 Quality Control

One of the procedures affecting the supply chain of the segmental liners is the quality control practice. The quality control process is embedded into the simulated model through incorporating two concrete strength tests and the percentage of rejection associated with each test. A better quality practice throughout the production of the liners translates to lower rejection percentage of liners in either test especially in the first one which takes place after 7 days of curing.

To investigate the degree of importance of maintaining good quality control and quality assurance practices and to quantify the magnitude of the effect of the quality issues on the tunneling project in terms of either decreasing or increasing the duration of the project, a sensitivity analysis should be performed.

To capture the effect of quality control over the total tunneling project duration, the developed simulation model is run with different values of rejection percentage representing liner's production quality. The following table and graph demonstrate the results of different rejection percentage in the first test on the total duration of the project. Lafarge storage capacity and tunnel site storage capacity were set to 100 and 14 respectively.

Table 5-11 Model properties for sensitivity analysis of quality control

Tunnel Shift Duration	Shifts/Day	Lafarge Shift Duration	Failure in 28-Day	Moulds
10	2	8	0.15	12

Table 5-12 Project duration (days) vs. rejection percentage in the first quality test

Rejection percentage	0.05	0.1	0.15	0.2	0.25
Project duration	104	105	108	115	122

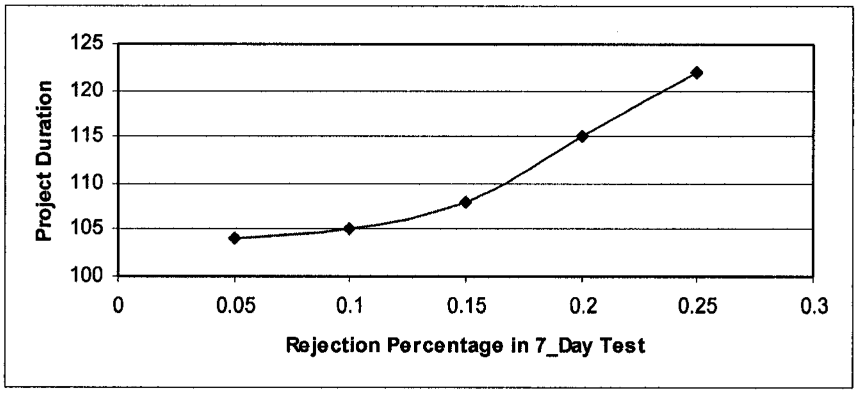


Figure 5-18 Project duration (days) as a function of quality of liner production

As it is expected, improving the quality of liner's production and reducing the failure percentage in the tests result in reduction of the project duration. The resulted reduction however, decreases as the quality improves. It means decreasing failure percentage from 0.1 to 0.05 has less reduction effect than decreasing failure percentage from 0.15 to 0.1.

5.5.4 Quantity of Liners Available

The last variable considered for sensitivity analysis in this study is the quantity of the segmental liners ready and in stock before the start of the project. In the previous sections, the effect of storage capacity was considered and analyzed. The objective of this section is to determine the effect of not starting the project with a full storage capacity of liners.

This is a situation which can be caused by City of Edmonton's not considering the time required for producing the required initial quantity of the liners equal to the available storage capacity. In such a situation, Lafarge is supposed to continue producing liners in full capacity until it reaches its limit in storing liners. To quantify the effect of such problem on the total project duration, the model is modified so that by starting the simulation the production of liners continues to be in full capacity until the inventory is full. Not having a full storage at the start of the project can be modeled as an early order being placed by the project team for a quantity of liners equal to the capacity of the inventory minus the amount of the liners available. The following table and figure show the outcomes of the simulation model. Lafarge storage capacity and tunnel site storage capacity were set to 100 and 14 respectively.

Table 5-13 Model properties for sensitivity analysis of quantity of liners ready

Tunnel Shift Duration	Shifts/Day	Lafarge Shift Duration	Failure in 7-Day	Failure in 28-Day	Moulds
10	2	8	0.15	0.15	12

Table 5-14 Project duration (days) vs. quantity of liners ready (meters)

Quantity of liners	20	40	60	80	100	120	130	140	150	175
Project duration	116	115	113	111	108	105	102	98	97	96

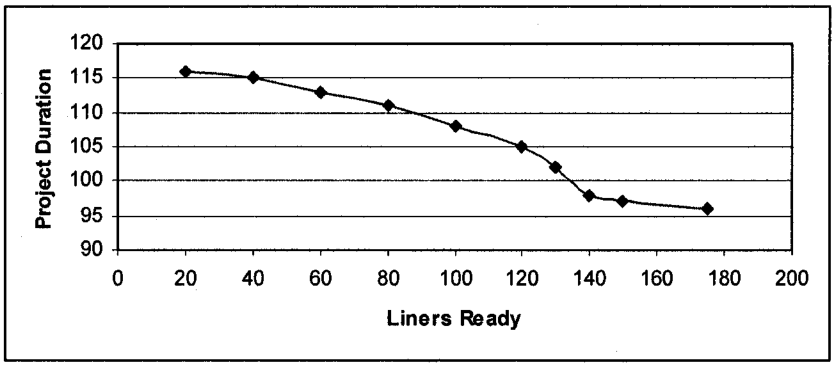


Figure 5-19 Project duration (days) as a function of number of liners ready in meters

As can be interpreted from the results, having just 60 meters of liners at the start of the Glencoe tunnel project can result in 5 days increasing of the project duration which is equal to a working week. The curve representing the project's duration is descending as expected. This means that the project duration will decrease by increasing the quantity of liners in hand. Also the graph shows that project duration curve approaches a horizontal line as the number of the liners ready increases. On the other hand as the number of the liners ready approaches zero, the increasing in project duration decreases and it does not approaches infinity. That is because, the storage capacity is available and the project can start after enough quantity of liners is produced.

This analysis shows the importance of considering the lead time in placing the first order by City of Edmonton in order to provide Lafarge with adequate time to produce enough quantity of liners before the start of the project. The developed simulation model can also be used to determine the lead time required to place the first order for each individual tunneling project.

5.6 Conclusions

By determining variables of interest and designing different scenarios the impact of each variable over the system-wide performance was investigated. The system-wide performance was measured by the total duration of the tunneling project as one of the most important criterion in performance measurement of such construction projects. Performing such a sensitivity analysis in this chapter provides a good insight into the importance and the magnitude of the effect of each of the variables under study.

The result of studying the effect of the chosen variables on the project's total duration proves the importance of considering the whole supply chain of a project in assessing project's performance under any given condition.

The sensitivity analysis showed that total storage capacity of the supply chain and production quality of liners can have substantial impacts on the project's duration while the effects of production capacity and quantity of liners ready are less severe. It was observed that working double-shift and increasing duration of shifts can only improve productivity if enough quantity of liners and enough storage capacity are available. Also having an effective quality control process was proved to be very important as high failure percentage dramatically increase the duration of the project. The result of sensitivity analysis also revealed that increasing production capacity can just marginally improve the productivity while it requires a sizeable investment.

The magnitude of the impact of each variable studied in this chapter is directly based on the properties of the tunneling project. Each new tunneling project should be modeled and analyzed individually for the extent of the influence of each variable over the project's duration to be realized.

An even more critical situation with regard to tunneling supply chain which requires being modeled and analyzed is the situation when several tunneling project are being constructed simultaneously. Having several tunneling projects placing orders for the same type of segmental liners can increase the demand level in the supply chain significantly. Considering the capacitated liner production line of Lafarge and the fact that Lafarge is the only supplier of the liners, such shift in the demand can cause substantial delays on some of the projects' estimated delivery time.

Having an effective quality control in place, considering the shortage of storage area and knowing the required lead time in placing the first order in order to have a full storage capacity of liners before the start of the project are some practices that can be employed by City of Edmonton to address supply chain issues for the tunneling projects.

6 Conclusions and Recommendations

6.1 Research Summary

This thesis is an endeavor to introduce the concept of supply chain management to the researchers and practitioners especially in the field of construction engineering and management and to provide them with an environment for supply chain's policy evaluation and sensitivity analysis. The content of the thesis presents the process and outcomes of the research performed in four consequent phases.

The first phase of the research presented in chapter one of the thesis, focuses on introducing the ideas and concepts regarding supply chain management. The definition of the concepts, research areas contributed to the emergence of supply chain idea and different research fields within the area of supply chain management are reviewed in this phase. Supply chain modeling approaches with emphasis on supply chain simulation are also reviewed in this phase of the research. "Information Sharing and Coordination in Supply Chain" is introduced as the special area of interest of this research in this phase of the thesis. Then "Bullwhip effect" literatures as the main stream of research in information sharing and coordination in supply chain are reviewed. This is followed by a review conducted of the state of the art in information sharing and coordination literature in supply chain which concludes with a through review of supply chain related researches in construction engineering and management area.

The second phase presented in the second chapter of the thesis focuses on the development of the special purpose simulation toolkit as a template in Simphony for modeling and simulating information sharing and coordination problems in the supply networks. The elements of the developed template and their features introduced in this phase are designed to represent main supply chain coordination concepts including inventory, production, distribution, forecasting, transportation, information sharing and demand.

The third phase of the research focuses on validating the simulation toolkit developed in the second phase. In this stage, a five-echelon serial supply chain is simulated. The model parameters are adjusted for different scenarios with moving average forecasting, exponential smoothing forecasting, information sharing and no information sharing. The results of the simulated model in each case are validated against the results of another simulation model and the ones of an analytical model. Comparison of the results shows an acceptable accuracy of the outputs of the model developed using SSCS template. Finally the impact of using real time demand information is investigated. In both cases of moving average and exponential smoothing forecasting methods, using real time demand data with information sharing shows greater magnitude of Bullwhip effect moving upstream the supply chain.

In the last phase of this thesis, a case study of construction supply chain supply chain is conducted. Following the construction supply chain literature survey in the first phase and observing the area's lack of analytical and quantitative approaches, the study carried out in this section tries to initiate a structured analytical and quantitative approach toward assessing the benefits or losses of employing different supply chain policies in construction industry. The result of the case study shows the functionality of the suggested modeling approach for analyzing the supply chains of the construction processes and also for providing insights into the supply chain issues of construction projects.

6.2 Research Contributions

After an extensive review of supply chain management literatures, "Information Sharing and Coordination in Supply Chain" was selected as the focal area of the presented study. The main stream of research in this area however is inspired by the phenomenon named "Bullwhip effect"

By choosing information sharing and coordination in supply chain as the topic of interest in supply chain management field, the research presented in this thesis was dedicated to the task of developing a supply chain simulation toolkit with regards to design goals of flexibility, extendibility and compatibility. The main objective of developing such a simulation toolkit was to provide researchers and practitioners dealing with supply network problems with a modeling environment which enables them to analyze the results of adopting different policies and strategies in supply chain coordination and information sharing related problems.

As a result of the conducted research presented in this thesis, a powerful supply chain simulation toolkit was developed and validated against other simulation models and analytical formulas. In spite of most analytical formulas capable of dealing with serial supply chains or a certain aspect of a supply network with a specific topology, the developed simulation toolkit provides supply chain modelers with the ability of modeling more complicated problems, considering different policies and looking at different features of supply networks varying in size and shape.

Furthermore, SSCS was shown to have the potential to be employed in investigating real life supply chain problems especially in construction industry. Modeling a real construction supply chain case study and capturing the uncertainties and complexities associated with such a real life problem can be considered as one of the very first efforts to introduce an analytical method to quantify the gains and losses of adopting different supply chain strategies in construction industry

6.3 Future Research

Simulation of a supply chain is mainly the task of modeling the behavior of each agent involved in the chain and also modeling the interactions between the involved agents. In the real life supply networks, every firm makes daily decisions regarding how to adopt new policies, employ different strategies and interact with other parties involved in the network. The decisions made by each firm are based on the information available to the firm at the time and are the result of an optimization process run by the firm with the objective of maximizing the benefit or minimizing the cost either locally or globally.

The extent to which a supply chain can be simulated is directly depends on the extent to which a firm's behavior can be modeled. In all analytical formulas or simulation tools currently in practice, some basic assumptions regarding the policies employed by different agents in supply chain are being made. These policies are the results of the same optimization process performed locally. However to model a more complicated supply network with acceptable accuracy, there is a need to move from introducing such policies to the simulation model to allowing the simulation agents to perform the optimization in the real time.

A major breakthrough in supply chain simulation can be achieved by trying to model a firm enable to optimize a user introduced objective function with regard to predefined constraints in real time. In order to achieve such a goal, the simulation parts modeling the optimization processes should be separated from the rest of the simulation model with respect to time. In the other word, upon obtaining new information form the surrounding environment, an agent in the simulation model should be given time to perform an optimization process and adjust itself to the new situation. During the optimization process performed by each agent, all other simulation processes should be paused and simulation time should not be advanced. Such a complicated modeling behavior is just attainable trough using high level architecture simulation environment which should be the main stream of any further development of this research.

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