IMPROVING SUPPLY CHAIN RESILIENCE

by

ELSA HIU MAN LEUNG

B.Eng., Industrial and Systems (2008)
National University of Singapore, Singapore

SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF ENGINEERING IN MANUFACTURING

AT THE

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

SEPTEMBER 2009

Signature of Author: ____________________
Department of Mechanical Engineering
August 18, 2009

Certified by: ____________________
Jérémie Gallien
Associate Professor of Operations Management
Thesis Supervisor

Accepted by: ____________________
David E. Hardt
Ralph E. and Eloise F. Cross Professor of Mechanical Engineering
Chairman, Department Committee for Graduate Students

IMPROVING SUPPLY CHAIN RESILIENCE

by

ELSA HIU MAN LEUNG

Submitted to the Department of Mechanical Engineering
on August 18, 2009 in partial fulfilment of the
requirements for Degree of Master of Engineering in
Manufacturing

ABSTRACT

Due to the global expansion of Company A's supply chain network, it is becoming more vulnerable to many disruptions. These disruptions often incur additional costs; and require time to respond to and recover from these disruptions. The base paper supply chain was identified as the most vulnerable area of the Company A Jurong and South & Southeast Asia Cluster supply chain; and a multi-stage supply chain was proposed to improve the supply chain's resilience. A statistical model was constructed to select the optimal location of the central warehouse for the proposed multi-stage supply chain. After evaluating the resilience to disruptions and the cost effectiveness of supply chains, the multi-stage supply chain with central warehouse in Tanjung Pelepas, Malaysia was found to be overall most resilient and cost effective among all the supply chains. It also incurs a lower additional cost in the event of a disruption such as changes in exchange rates and demand forecast accuracy, fuel price fluctuation, labor cost increase and shipping disruptions. As a result, establishing this multi-stage supply chain is recommended.

Thesis Supervisor: Jérémie Gallien

Title: Associate Professor of Operations Management

Table of Contents

Chapter 1 Introduction 9

1.1 Company Background 9

1.2 Company Products 10

1.2.1 Products 10

1.2.2 Base Materials 11

1.2.3 Additional Materials 11

1.3 Company A Jurong Operations 12

1.3.1 Design Department 12

1.3.2 Production Department 12

1.3.3 Planning Department 14

1.3.4 Purchasing Department 15

1.4 Supply Chain Mapping 16

1.4.1 Information Flow 17

1.4.2 Materials Flow 17

1.5 Organization of Thesis 17

Chapter 2 Problem Statement 19

2.1 Problem Description 19

2.2 Project Objective 19

2.3 Scope 20

Chapter 3 Literature Review 21

3.1 Supply Chain Resilience 21

3.2 Ways to Increase Supply Chain Resilience 23

3.2.1 Increasing Redundancy 23

3.2.2 Increasing Flexibility 24

3.2.3 Change in Corporate Culture 24

Chapter 4 Methodology 26

4.1 Project Roadmap 26

4.2 Preliminary Analysis 27
  4.2.1 Research Area 1: WIP 28
  4.2.2 Research Area 2: Additional Materials Supply 28
  4.2.3 Research Area 3: Order Management 29
  4.2.4 Research Area 4: Base Paper Supply 29
4.3 Research Area Selection 30
4.4 Base Paper Supply Chain 32
  4.4.1 Current Supply Chain 33
  4.4.2 Multi-Stage Supply Chain 34
4.5 Potential Warehouse Location Shortlist 38
4.6 Statistical Modeling 39
  4.6.1 Data Collection Method 40
  4.6.2 Statistical Procedures 43
  4.6.3 Model Verification 48
4.7 Multi-Stage Supply Chain Analysis 50
4.8 Resilience Analysis 51
Chapter 5 Results and Discussion 53
5.1 Multi-Stage Supply Chain Analysis 53
  5.1.1 Capacity 53
  5.1.2 Average Inventory 54
  5.1.3 Warehouse Cost 56
  5.1.4 Shipping Cost 57
  5.1.5 Costs and Benefits Analysis 58
5.2 Resilience Analysis 60
  5.2.1 Base Paper Commonality Increase 60
  5.2.2 Demand Forecast Accuracy Fluctuation 70
Chapter 6 Conclusion and Recommendations 73
Chapter 7 Future Opportunities 74
Appendix A – Explanation of Risk Pooling and Postponement 75

Appendix B – Illustration of Multi-stage Supply Chain Inventory 78

References 79

Table of Figures

Figure 1.1 Company A Packages (1) 10

Figure 1.2 Different Layers of a Package (1) 11

Figure 1.3 Production Process (2) 12

Figure 1.4 Supply Chain Mapping (2) 16

Figure 3.1 Enterprise Portfolios of Risks (5) 22

Figure 3.2 Vulnerability Graph adapted from *"The Resilent Enterprise"* (6) 22

Figure 4.1 Methodology Flowchart 27

Figure 4.2 Four Potential Research Areas 28

Figure 4.3 Current Single-Stage Supply Chain 33

Figure 4.4 Base Paper Warehouses in Singapore 34

Figure 4.5 Two-stage Supply Chain 35

Figure 4.6 Proposed Multi-Stage Base Paper Supply chain 36

Figure 4.7 Procedures of Potential Warehouse Location Shortlist 38

Figure 4.8 Six Shortlisted Locations for Central Warehouse 39

Figure 4.9 Procedures of Statistical Modeling 40

Figure 4.10 Single-Stage Supply Chain 48

Figure 4.11 Multi-Stage Supply Chain Model 50

Figure 5.1 Capacity of Central Warehouse 53

Figure 5.2 Total Average Inventory for All Supply Chains (rolls) 55

Figure 5.3 Total Cost of Single-Stage and Multi-Stage Supply Chains 58

Figure 5.4 Average Inventory as Base Paper Commonality is Increased (thousand rolls) 63

Figure 5.5 Percentage Decrease in Average Inventory as Base Paper Commonality is Increased (%) 64

Figure 5.6 Warehouse Capacity as Base Paper Commonality is Increased (thousand rolls) 66

Figure 5.7 Total Warehouse Costs for Increased Base Paper Commonality (thousand USD) 67

Figure 5.8 Total Shipping Costs for Increased Base Paper Commonality (thousand USD) 68

Figure 5.9 Total Costs for Increased Base Paper Commonality (thousand USD) 69

Figure 5.10 Total Warehouse Costs for σ_{fe} Variation (million USD) 70

List of Tables

Table 4.1 Definition of Ratings for Frequency of Occurrence 30

Table 4.2 Definition of Ratings for Severity of Consequences 31

Table 4.3 Evaluation of Research Areas 32

Table 4.4 Unit Shipping Cost from Suppliers to Central Warehouse (in USD) 42

Table 4.5 Warehouse Operating Cost Verification Table (in thousand USD) 49

Table 4.6: Shipping Cost Verification Table (in thousand USD) 49

Table 4.7 Total Supply Chain Cost Verification Table (in thousand USD) 50

Table 4.8 Resilience Analysis Scenarios and Input Parameter Variation 51

Table 5.1 Capacity of Central Warehouse (in thousand rolls) 53

Table 5.2 Average Inventory for Single-Stage Supply Chain (in rolls) 54

Table 5.3 Average Inventory for Multi-Stage Supply Chain (in rolls) 54

Table 5.4 Warehouse Costs for Single-Stage Supply Chain (in thousand USD) 56

Table 5.5 Warehouse Costs for Multi-Stage Supply Chains (in thousand USD) 56

Table 5.6 Shipping Cost for Multi-Stage Supply Chains 57

Table 5.7 Yearly Total Cost of Single-Stage Supply Chain and Multi-Stage Supply Chain involving Tanjung Pelepas 58

Table 5.8 CAJ Yearly Base Paper Demand (rolls) 61

Table 5.9 Pune Factory Yearly Base Paper Demand (rolls) 61

Table 5.10 CAJ Yearly Demand for Scenario 1 (rolls) 62

Table 5.11 Pune Yearly Demand for Scenario 1 (rolls) 62

Table 5.12 CAJ Yearly Demand for Scenario 2 (rolls) 62

Table 5.13 Pune Yearly Demand for Scenario 2 (rolls) 62

Table 5.14 Shipping Lead Times (months) 64

Table 5.15 Slopes of Graphs for Total Warehouse Costs (million USD/%) 71

Chapter 1 Introduction

1.1 Company Background

Company A is a multinational food processing and packaging company of Swedish origin. Committed to making food safe and available everywhere, Company A is currently one of the largest companies in this industry. Its business spans more than 150 countries with 43 packing material production plants worldwide. Due to the increased complexity of Company A's supply chain, the longer lead times and demand fluctuations subject the supply chain to disruptions such as natural disasters and accidents. Hence, competency in responding to and recovering from supply chain disruptions is important for Company A to remain competitive in the industry. This competency is known as "supply chain resilience".

Of its global network, Company A Jurong (CAJ) in Singapore and Company A Pune in India are the manufacturing plants in the South and Southeast Asia Cluster. In 2007, CAJ was honoured to receive the Manufacturing Excellence Award (MAXA) for overall excellence in innovations, operations and sustainability and its world class manufacturing (WCM) approach to ensure operational improvement and downtime minimization. Beginning its WCM campaign in 2000, CAJ has crossed the WCM Special milestone. The plant reached the Total Productive Management (TPM) Excellence milestone in 2004 and TPM Special in 2006.

Distinct from other Company A factories, CAJ operates on small and more customized orders. The customized orders requires close monitoring and scheduling of the production process as frequent set-up changes are required on the shop floor. As a consequence of continuous improvements, the customer lead time was reduced from 4 weeks to less than 2 weeks at CAJ. Even under the current economic downtime, CAJ has achieved 3-billion-pack production in the past three months.

1.2 Company Products

This section introduces company products and explains the technologies involved. The raw materials required to produce Company A packaging material will also be discussed in further detail.

1.2.1 Products

Company A offers a wide range of packaging products, processing equipment, filling machines, distribution equipment and services. Figure 1.1 shows the major packaging products of Company A.

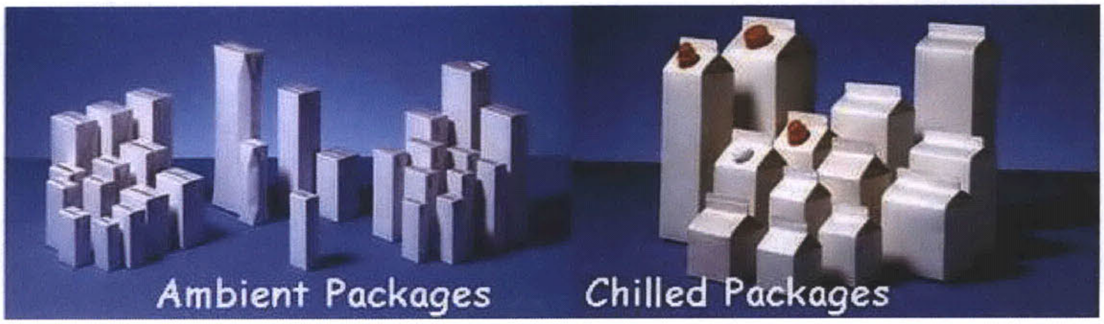


Figure 1.1 Company A Packages (1)

CAJ focuses on carton production. It manufactures carton packs, also known as Tetra packs, for food items like milk, flavoured milk, and fruit juice and soy products. Assistance is also provided to customers in designing the cartons. Each Tetra pack is made with 6 layers of aluminium, paper and polyethylene to prevent spoilage of the contents. Paper is the base material for each pack and provides structure and support to the package. The carton design is printed onto the paper. The paper is coated with a layer of aluminium foil to make the pack aseptic and preserve the flavour. In addition, there are four layers for polyethylene: one on the outside to prevent damage from moisture; an adhesive layer between the paper and aluminium foil; and two protective innermost layers to seal in the liquid. The several layers and their respective functions are shown in Figure 1.2.

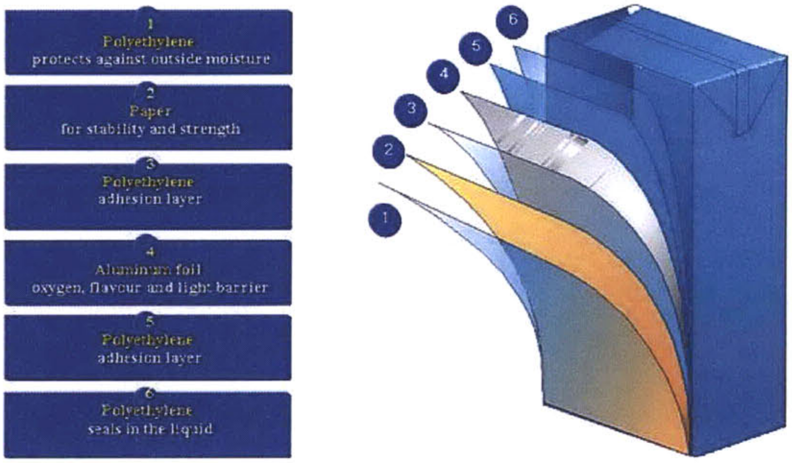


Figure 1.2 Different Layers of a Package (1)

1.2.2 Base Materials

The raw materials used in CAJ can be categorized into base materials and additional materials. The base materials refer to paper, aluminum and polyethylene (PE). The major paper suppliers are: Brazil, USA, Sweden A and B. The paper boards are categorized according to the paper grade and width. Due to the long shipping lead time from the suppliers, the planning department will place orders of the base materials in advance according to the rolling forecasts.

The aluminium foil is categorized according to width. At CAJ, aluminium foil is mainly supplied by companies from China, Malaysia and Germany. All of them supply aluminium foils in specific widths. Finally, the two largest PE suppliers are Belgium and Japan.

1.2.3 Additional Materials

The additional materials refer to materials that do not form the core components of the products but are essential for production. They include water-based inks, pallets, cores and tapes. These materials are directly managed by the purchasing department. The main characteristics of additional materials are that they are low cost and low volume. Most additional material suppliers have warehouses in Singapore. Unlike base materials, short lead time is required for additional materials. In addition, the purchasing department has sourced for alternative suppliers for most additional materials.

1.3 Company A Jurong Operations

CAJ operates with four departments: design, production, planning and purchasing. Order management and customer service are managed by the marketing company (MC), which is an independent entity from CAJ. CAJ also outsources its warehouse and delivery operations to a third party logistic company (3PL).

1.3.1 Design Department

The design department reviews and adapts customers' designs to suit CAJ's production systems. Assistance is also provided to customers in designing the carton. Once the design is confirmed, the design is broken down according to the component colours. Cyan (C), magenta (M), yellow (Y) and black or key (K) are the process colours. Apart from these, special or spot colours may be used to obtain specific shades of colour. The number of spot colours can vary from none to seven.

1.3.2 Production Department

Figure 1.3 presents the general manufacturing process to produce a typical roll of packaging material.

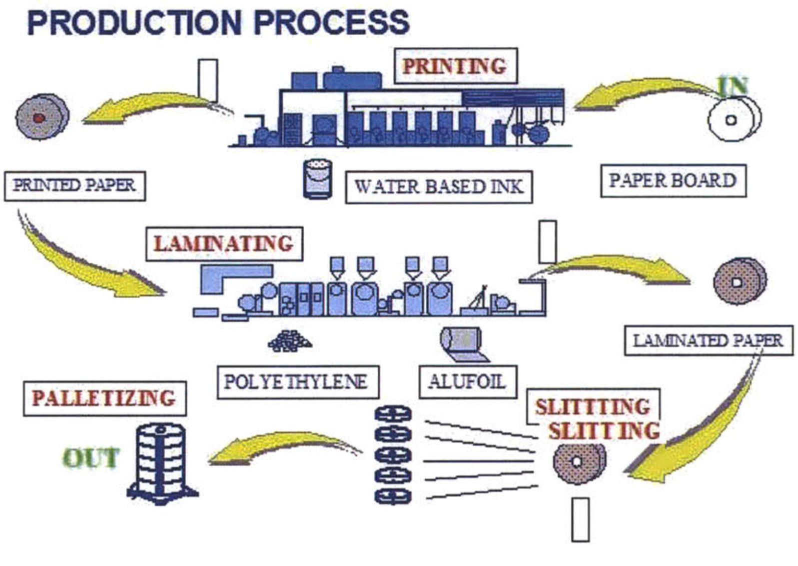


Figure 1.3 Production Process (2)

Pre-press

In the pre-press stage, the clichés for printing are prepared from the negatives. The clichés are polymeric stamps with elevated portions for the areas to be printed. One cliché is prepared for each colour used for printing. The clichés are then mounted onto the rotating spindle in the printer.

Printing

In the printing stage, the design pattern on the clichés is reproduced onto the paper board using water based ink. During the printing process, fold creases are formed onto the paper by a specific tool inside the printer. This tool also punches the holes for straws.

For routine printing, flexographic technology (flexo) is used. For higher resolution designs, CAJ uses offset printing, which is more expensive compared to flexo.

Lamination

Lamination bonds aluminium foil and PE onto the printed paper. There are three stations within a laminator. In the first station, a layer of aluminium foil with adhesives is layered onto the printed paper board. Following that, two layers of PE films are coated in the inner surface of the packaging material to prevent contamination and leakage. The last station adds another layer of PE on the outer surface of the packaging material.

Slitting

Each paper roll consists of several columns, known as webs, of packs. The slitting process cuts the entire roll into reels of a single pack width so that they can be directly fed into the filling machines at customer locations. During the slitting process, the defects are marked with a paper tab to facilitate removal at a later stage.

Doctoring

Doctoring is the process of removing the portions with defects from the reels. After the defect parts are removed, the reels are shrink-wrapped and palletized in stacks of seven. The finished stacks will be transported to the warehouse and await delivery.

Since the production is not continuous, the half-processed materials will be sent to the warehouse to be stored between all processing stages. Between printing and laminating, there is an average 4-day inventory of the work-in-process (WIP). Between laminating and slitting stages, there is an average of 2-day inventory of WIP.

1.3.3 Planning Department

The planning department at CAJ is responsible for production planning and materials planning.

Production Planning

The production system of CAJ is make-to-order. A production schedule is drafted only upon receipt of a production order from the sales department at MC. The current production lead time is around 12 days. Planning is based on due dates. The scheduling of jobs on the laminator is based on the paper width, from widest to narrowest. Since the laminator is the bottleneck, the production schedule for printing, slitting and doctoring processes are planned based on the laminator schedule.

The planning department at CAJ and the MC plan the production schedule collaboratively through the use of a block scheduling system. In this collaborative planning, the planning department generates a weekly production schedule with blocks according to width of the paper rolls. The schedule plans for production of paper rolls from the widest to the narrowest in order to reduce setup times. The MC then fits customer orders into the blocks. However, some customers tend to place last minute orders, which create disruptions to the planned production schedule. These last minute orders translates into rush orders which lower equipment efficiency.

Materials Planning

Materials Requirement Planning deals with the ordering of the raw materials needed for production. The base materials ordered are paper, polyethylene and aluminum foil with many variants in terms of grade and size. The additional materials that are used for production are ordered by the purchasing department of each converting factory as they are relatively low volume and low cost.

Company A International (CAI) as the parent body of CAJ issues the annual global forecasts for number of packs and marketing directives. For the materials common to several converting factories, e.g. the same base paper grade, CAI combines the forecasted demand of each factory and signs annual contracts with the suppliers to achieve economies of scale and to pool the variation in demand. As and when the materials are required, each converting factory then places the actual orders directly with the suppliers under the annual contracts agreed by CAI.

In addition, each converting factory updates its monthly forecasts for base materials regularly and places orders for them accordingly. The ordering for base materials is done in advance due to the long lead times. As the orders are received, the forecasts for the subsequent periods are updated.

The ordering is done on a weekly basis as this time period coincides with the frequency of dispatch. A continuous review method is used to determine the ordering quantities. The re-order point is set at approximately 40% of the monthly demand while the order up-to point is around 60% of the monthly demand.

1.3.4 Purchasing Department

The purchasing department at CAJ is responsible for the purchase of additional materials and indirect services but not base materials which is directly ordered by the planning department. Additional materials include inks, pallets, cores, straws and etc, while indirect services mainly refer to equipment maintenance, electricity, and water utilities. In terms of monetary value, base materials comprise 60% of total value while additional materials and indirect services comprise the other 40%. There are more than 10 suppliers for the additional materials and 500 providers for indirect services. The purchasing department perform regular auditions on all the suppliers. They review all the suppliers regularly and will provide assistance when the suppliers are underperforming. Suppliers who consistently underperform will be substituted. Most of the suppliers have local warehouses in Singapore. In addition, the purchasing department has a well-established system to source for alternative suppliers.

1.4 Supply Chain Mapping

The supply chain mapping of CAJ is shown in Figure 1.4. The suppliers in the figure mainly refer to base materials suppliers.

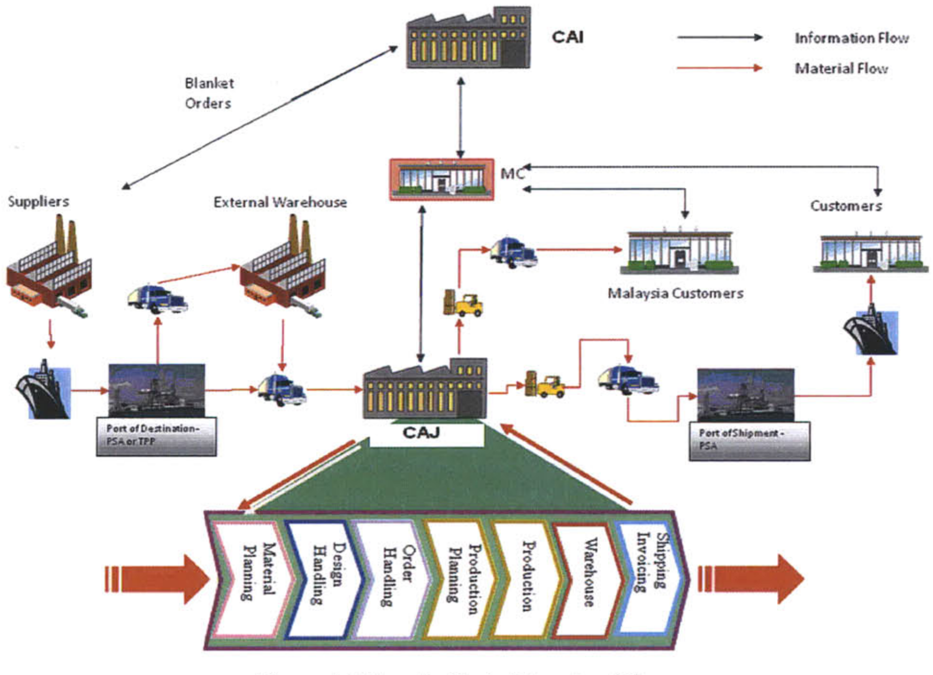


Figure 1.4 Supply Chain Mapping (2)

1.4.1 Information Flow

As the parent company of CAJ, CAI signs annual contracts with the base material suppliers according to the forecasted demands of the converting factories. The converting factories, such as CAJ, place direct orders with the suppliers under the annual contracts. Since the shipping lead times from the suppliers to the CAJ are long, CAJ places the orders with the suppliers early in advance. Using monthly demand forecasts, the planning department of CAJ breaks it down into base materials demand forecast and the orders are placed accordingly.

CAJ sources its own additional material suppliers. Since majority of them have local warehouses in Singapore, it eliminates the need for CAJ to place advance orders for additional materials. Consequently, the information flow is more direct compared with base materials.

1.4.2 Materials Flow

After an order to base materials suppliers is placed, the materials will be transported through ocean freights. They arrive at the Singapore or Malaysia port, depending on the shipping routing. Goods arriving in Malaysia may be kept at the container yard for a maximum of 30 days without incurring any additional charges. These materials are then transported to CAJ's internal warehouse by trucks. The materials are then brought to CAJ for production and finished goods are then delivered to the customers before the due date. As mentioned in section 1.3, the warehouse and transportation operations are outsourced to a logistic company. The finished goods are delivered to customers by ocean freight, or truck freight for Malaysia destinations.

1.5 Organization of Thesis

This thesis is divided into six chapters. A general background of Company A is introduced in the first chapter. Problems with the current supply chain are described in Chapter 2. Besides problem description, the objectives and scope of our project are also included in this chapter. Chapter 3 presents a literature review of studies on supply chain resilience. Chapter 4 details the methods used to identify and analyze the problem. In Chapter 5, results and discussion of this study are presented. Chapter 6 concludes this paper with findings and recommendations. Chapter 7 presents future opportunities for further research.

Chapter 2 Problem Statement

2.1 Problem Description

Due to the global expansion of Company A's supply chain network, it is becoming more and more vulnerable to many disruptions. This is due to the increased lead time involved in global sourcing, greater complexity due to a larger customer base, and improved scale of production and higher volatility in a global market. In this study, supply chain disruptions refer to any events that could disrupt the flow of goods, disturb the corporate operations or change the external business environment. These include hazard risks, operational risks, strategic risks and financial risks. In particular, Company A South and Southeast Asia Cluster experiences operational risks, such as yearly port strikes in Brazil and delayed customs clearance in India which result in materials shortage. In addition, the cluster also faces long term strategic risks, such as the ever increasing high labor cost in Singapore, and financial risks, such as high hedged fuel price in 2008. These disruptions often incur additional costs, as extra financial and human resources are required for the recovery from a short term disruption or the coping of a long term disruption. Furthermore, a substantial amount of time is required to respond and recover from these disruptions. As a result, a more resilient supply chain is desired, as it responds and recovers from disruptions faster, and minimizes the cost of disruptions.

2.2 Project Objective

In this project, the author aims to improve the supply chain resilience of CAJ and South & Southeast Asia Cluster through the following means:

- Identify the areas of the supply chain which are most vulnerable to disruptions
- Reduce the additional costs incurred in the event of disruptions
- Reduce the time to respond and recover from disruptions

2.3 Scope

This project only concerns CAJ and the South & Southeast Asia cluster, as relevant data for other clusters and CAI could not be disclosed to the author. Hence, the results of this project are only meant to benefit CAJ and South & Southeast Asia cluster.

Due to the time constraint of this project, only one area of the supply chain which is most vulnerable to disruptions was selected and investigated.

Chapter 3 Literature Review

3.1 Supply Chain Resilience

The basic purpose of a supply chain is to facilitate the delivery of the right products to the right place at the right time and in the right quantities. In current times, this seemingly simple notion is getting harder and harder to achieve due to the volatile markets and cost issues. Tough competition and demanding consumers have forced companies to make use of highly complex supply chains spanning across most continents. At the same time, supply chain management teams advocates the notion of lean to reduce wastage and to provide better response time in face of rapidly changing consumer demand. When operational performance is undisrupted, such arrangements prove to achieve efficient operation. However, as these trends in complicated supply chains and reduction of redundancy continue to escalate, supply chains also become more exposed to unexpected disruptions. (3) Hence, supply chain resilience arises as a new and relatively unexplored topic in the manufacturing industry in recent years.

Supply chain resilience is an emerging term that relates to the amount of risk and the vulnerability of a company. In this paper, the definition of resilience with regards to supply chains is taken to be referring to "the ability of a system to return to its original state or move to a new, more desirable state after a disruption occurred." (4)

Disruptions to a supply chain can take many forms. The article *"A Managerial Framework for Reducing the Impact of Disruptions to the Supply Chain"* published by the Supply Chain Resource Cooperative suggests a framework that categorizes disruptions into four areas: financial risks, strategic risks, hazard risks and operational risks. (5) Figure 3.1 shows the Enterprise Portfolio of Risks proposed in the article.

Figure 3.1 Enterprise Portfolios of Risks (5)

Natural disasters such as earthquakes and floods are just a few examples of hazard risks while man-made events such as sabotage, terrorist attacks, customs delays, and accidents are some operational risks. Financial risks may include currency and foreign exchange rate fluctuations; labor costs increases while strategic risks may include contracts withdrawals, planning inefficiencies and unexpected customer demand changes.

In addition, any single disruption may also be categorized accordingly to the probability of occurrence and its associated consequences as suggested in the book *"The Resilient Enterprise"*. (6) The graph depicted in Figure 3.2 shows some examples of how different disruptions can be categorized.

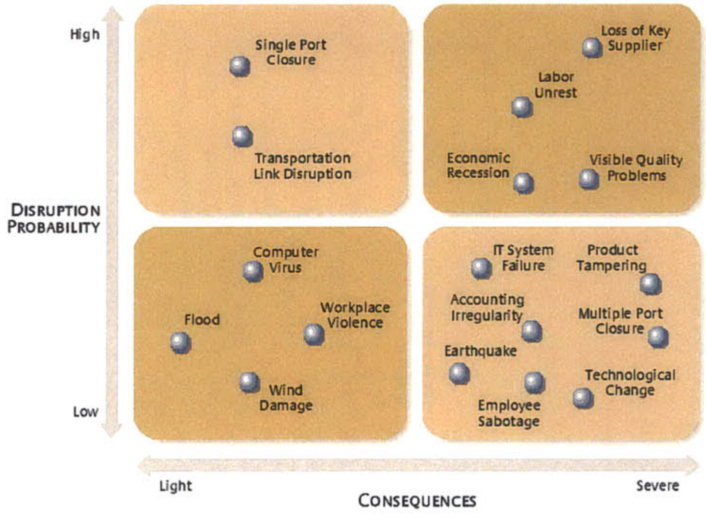


Figure 3.2 Vulnerability Graph adapted from *"The Resilent Enterprise"* (6)

For instance, a technological change is categorized as low frequency with severe consequences. This is because such a change is usually not abrupt and occurs over an extended period of time. At the same time, it can bring about much impact on the company such as a change in the raw materials requirements and demand patterns. On other hand, a transportation link disruption is categorized as high frequency with light consequences. This is because such a disruption often occurs regularly but its impacts are not severe as the issue can usually be resolved within a short period of time, without much additional costs incurred. An economic recession happens regularly in different countries and its impacts are often include drop in customer demand and changes in foreign exchange rates, leading to huge loss in revenues. Hence, it is categorized as high frequency with severe consequences in Figure 3.2.

On top of that, the author Sheffi advocates that vulnerability of a supply chain or part of a supply chain should be viewed in two regards: the probability of disruption and the severity of the consequences. He suggests the quantification of vulnerability as (6):

$$\text{Vulnerability} = \text{Probability of Disruptions} \times \text{Severity of Consequences}$$

3.2 Ways to Increase Supply Chain Resilience

In the article *"Building a Resilient Supply Chain"* published in the Harvard Business review, Sheffi describes three main ways through which companies can develop resilience: increasing redundancy, building flexibility and changing the corporate culture. (7) While other concepts are also discussed in academic articles, most of the topics discussed typically belong to one of these three strategies.

3.2.1 Increasing Redundancy

In theory, the most convenient way to increase supply chain resilience is by increasing redundancy across the entire supply chain. Increasing inventory levels, increasing the types of inventory held, lowering capacity utilization and increasing the number of suppliers can doubtlessly increase the company's ability to bounce back after a disruption since the company would have more space to continue operations while recovering from a disruption.

However, this option is undesirable as it involves high costs, low efficiency and often results in sloppy work and lowered quality. Furthermore, it is in direct conflict with the notions of contemporary lean manufacturing and Six Sigma concepts that advocate the use of low inventory and work-in-process levels and the reduction of waste to increase the efficiency of operations. (7)

3.2.2 Increasing Flexibility

Sheffi advocates increasing supply chain flexibility to improve supply chain resilience. (6) Flexibility allows a supply chain to recover faster from disruptions and respond faster to demand variation. Supply chain flexibility can be achieved through a combination of various actions including standardizing processes and replacing sequential processes with concurrent processes. A classic example could be a clothing company which, instead of doing it the traditional way ie. produce all the finished products before the selling phase, produces generic clothes that are undyed and colors them just before selling according to the latest customer demands at every outlet. This postponement strategy greatly increases flexibility of the supply chain and hence also increases its resilience since it can respond faster to any shifts in customer demand, with minimum additional costs incurred.

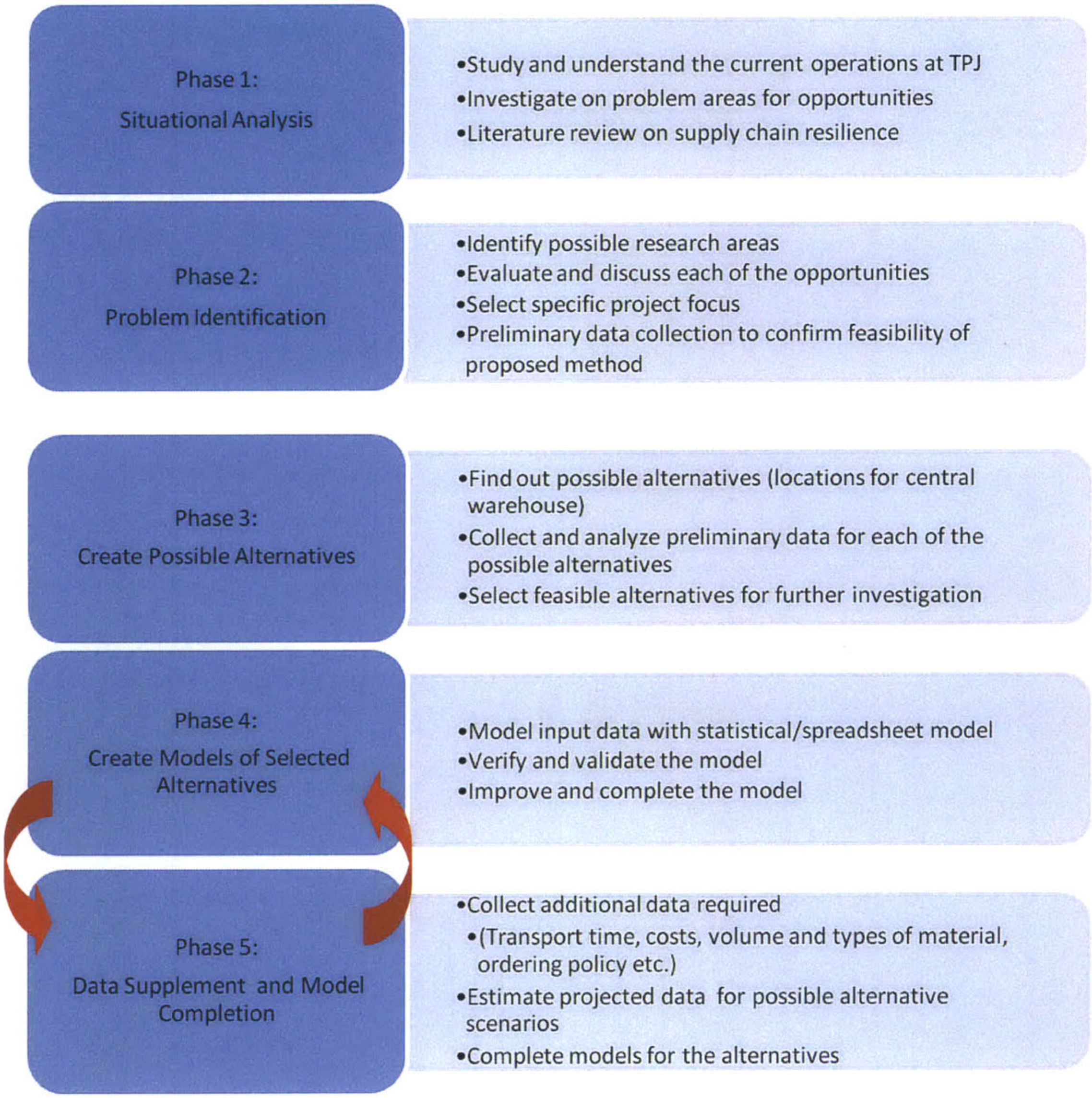
3.2.3 Change in Corporate Culture

Historical experience shows that corporate culture plays a major part in accelerating the recovery process after a disruption. Corporate practices such as continuous communication among employees, high employee empowerment and anticipating for disruptions are among the best practices that help to improve supply chain resilience. For instance, consider a company with a spontaneous corporate culture, in which employees are rewarded when they take it upon their personal responsibility to alert the upper management to any possible risks. Such a company is often better able to anticipate and recover from risks and is more resilient as compared to another company in which there is a passive corporate culture where all employees deal only with their direct responsibilities.

Chapter 4 Methodology

4.1 Project Roadmap

The entire project will be divided into seven phases as presented in the following flowchart (Figure 4.1). The phases are basically sequential except for Phase 4 and Phase 5 which may be iterative.



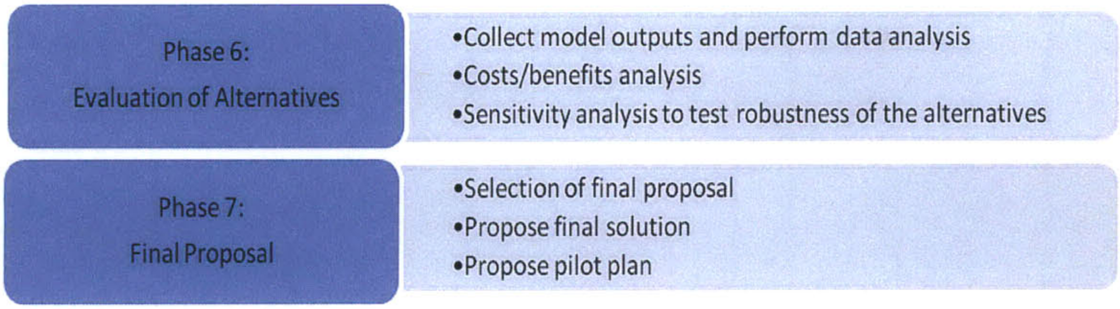


Figure 4.1 Methodology Flowchart

4.2 Preliminary Analysis

During the first two phases of the project, the existing operational policies and supply chain organization were studied in detail. For the purpose of this extensive research, discussions were held across all departments at CAJ including the supply chain pillar, purchasing department, planning department, production department and warehousing department. Background information of the existing supply chain system is presented in Chapter 1. Interviews with relevant persons in all the departments revealed most of the supply chain risks that CAJ was aware of. In addition, CAJ's records of contingency plans and near-misses analyses were studied to further quantify and list out the common supply chain risks faced at CAJ. Historical data from the past five years were also collected to study customers and supplier trends, as well as CAJ's ordering patterns to identify any possible disruptions that might have occurred before. (8) From the study of the organization, four potential supply chain risk areas were identified for supply chain resilience improvement: WIP, additional materials supply, order management and base paper supply. These areas were verified with the various departments to be the most important risks that CAJ currently faced. These four research areas are summarized in Figure 4.2 with their relevant supply chain issues.

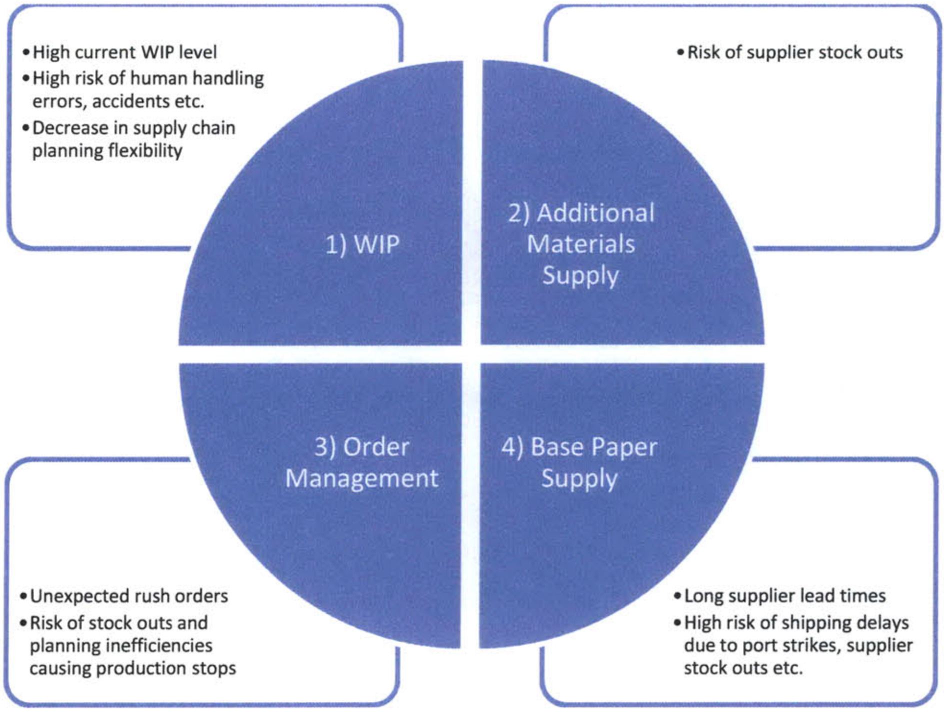


Figure 4.2 Four Potential Research Areas

4.2.1 Research Area 1: WIP

The production at CAJ consists of four major processes in sequence: printing, laminating, slitting and doctoring. Between each process, buffers exist to maintain machine efficiency. The buffers exist as WIP stored in the CAJ warehouse next to the production floor. As a result, the WIP is moved out of the production floor after each process and moved into the production floor again at the beginning of the next process. This WIP movement implies a high risk of human errors and handling accidents as WIP is moved around frequently. A high level of WIP also increases the supply chain's response time when a disruption occurs and the supply chain planning becomes less flexible since capacity is being used by the WIP.

4.2.2 Research Area 2: Additional Materials Supply

Occasionally, the supply of additional materials can be disrupted due to a supplier shortage for various reasons. The purchasing department has adopted a number of practices to protect CAJ's operations from such disruptions. All the consumables and indirect materials are sourced locally and CAJ has alternative local suppliers for most of the additional materials. When a supplier shortage occurs, CAJ usually negotiates with an alternative supplier to procure the items at a higher cost, hence incurring additional costs to keep the operations running. Since the alternative suppliers are located locally, the response time is usually short.

4.2.3 Research Area 3: Order Management

Sometimes, customers place rush orders for various reasons, for example, in anticipation of a demand surge during a festive season. Such orders are not expected and cause inconveniences to the order management process since the planning department needs to make changes to the previously planned production schedule. Rescheduling incurs additional set-up costs, extra materials resource planning and creates potential problems for human resource planning. In worst cases, production may have to stop due to material stock outs or planning issues because of rush orders.

4.2.4 Research Area 4: Base Paper Supply

Base materials, consisting of paper, aluminium foil and polyethylene pellets, are shipped from overseas, typically involving long supplier lead times. Among the three types of base materials, base paper supply poses the most problems as base paper is replenished most frequently and demand is hard to predict because of the large number of different paper grades.

As Company A International places strict standards on base paper supply, the number of approved suppliers is very limited. As result, supplier lead times are very long as the approved suppliers are located far away from South and Southeast Asia. Occasionally, base papers may run out of stock in the required paper grade and width due to any disruption such as port strikes, sudden demand changes and accidents. When that happens, high costs are incurred to replenish the supplies by air freight or long response time is required due to the long supplier lead times.

4.3 Research Area Selection

Considering the four research topics described above, a comparison was made to select the research topic that potentially achieves the most improvement in terms of supply chain resilience.

As defined by Sheffi (6):

Vulnerability = Probability of Disruption x Severity of Consequences

The potential impact of each research topic can thus be evaluated according to the vulnerability of the corresponding portion of the supply chain.

A rating method was used to evaluate "vulnerability". After interviewing expert personnel from the relevant departments and collecting relevant historical data, the probability of disruption occurrence and severity of its consequences were rated on a scale of 1 to 5 (1 being the least important) for each of the research topic based on the background information obtained. Probability of occurrence was taken as the frequency of typical problems/delays occurring in relation to the research topic. Severity of the consequences was defined to consider the effect on the customer service level, costs, length of time delayed and the ease of recovery. The rating points for each category are given in Tables 4.1 and 4.2.

Table 4.1 Definition of Ratings for Frequency of Occurrence

Rating	Frequency
1	Yearly
2	Quarterly
3	Monthly
4	Weekly
5	Daily

Table 4.2 Definition of Ratings for Severity of Consequences

Rating	Severity of Consequences
1	Production is not affected but overall, additional costs incurred.
2	Management framework available. Production efficiency reduced ie OEE.
3	Multiple alternative plans at higher costs. Production stops but resumes when alternative plans are taken.
4	Single alternative plan at significantly higher costs. Production stops but resumes when alternative plan is taken.
5	No solution readily available. Production stops until problem solved, unable to deliver, high costs to recover quickly

For Research Area 1, the high WIP level is a reoccurring issue since the current production stages requires a high level of WIP to achieve high machine efficiency. As a result, WIP handling errors and accidental movements are occurring on a daily basis, causing short delays in production. Hence, the probability of disruption is rated as 5. However, production is seldom completely stopped for substantial periods of time because of this and therefore, a rating of 1 is given in terms of severity of consequences.

With regards to Research Area 2, the supply of additional materials is seldom disrupted since they are not used in large quantities and not used frequently. As the materials are mostly sourced locally, the supplier lead times are short. Furthermore, stock outs only happen a few times per year since suppliers are usually required to keep inventory on-hand. As there are multiple suppliers for the materials, there are alternative sources available at a higher cost. This accounts for the ratings of 3 and 2 allocated to this research area with regards to probability of disruption and severity of consequences.

As for order management, the most frequent disruptions are caused by the rush orders which occur almost on a weekly basis. This gives a rating of 4 for frequency of occurrence. However, the planning department could prepare in advance for some of the rush orders and hence a rating of 2 is given to this research area in terms of severity of consequences.

Base paper is sourced from suppliers that are located in Americas and Europe. Therefore, long lead times are involved. Even so, base paper runs out of stock only a few times per year because orders are placed for the base paper in advance according to the materials requirement plan and demand forecasts. However, consequences of stock outs are very severe as the long supplier lead times imply long response time and high costs involved to maintain the customer service level. There is usually no solution readily available and the planning department has to seek contingency plans such as using higher paper grade paper as substitute etc. This accounts for the high ratings allocated to this research area.

From the above analysis, it can be seen that Research Area 4 potentially gives the most impact as the base paper material supply is the most vulnerable among the four research areas. Hence, it was decided that this project should work on the issue of base paper in order to give the most significant improvement in terms of supply chain resilience. The assigned ratings to individual research areas are presented in Table 4.3.

Table 4.3 Evaluation of Research Areas

	Research Area 1 WIP	Research Area 2 Additional Mat'ls	Research Area 3 Rush Orders	Research Area 4 Base Paper
Probability of Disruption	5	2	4	2
Severity of Consequences	1	3	2	5
Vulnerability	**5**	**6**	**8**	**10**

4.4 Base Paper Supply Chain

The main reason for the vulnerability of the supply of base paper is due to the long supplier lead times involved. Long supplier lead times imply that orders must be placed very early in advance. This decreases forecast accuracy as the forecast period is long. Furthermore, when a disruption occurs, the time required for the system to recover is long since a long lead time is required for any new orders to be delivered. To illustrate this point, consider the case when a sudden surge in demand requires more base paper to be ordered. The response time to the surge in demand is greatly constrained by the supplier lead time. On a separate note, if there is a disruption in the supply of base paper for any reason, a long supplier lead time is required to obtain the materials from alternative suppliers.

The second major contributing factor to the vulnerability of the supply of base paper is the high costs involved in recovery. Stock outs result in decrease in machine efficiency and increase in machine downtime as changeovers are required. These translate to downtime costs on top of the additional costs incurred to maintain the customer service level. For instance, air freight might be used instead to shorten the supplier lead time required or base paper of higher grade may be used as substitute instead.

4.4.1 Current Supply Chain

A single-stage supply chain is used to supply base paper to CAJ as depicted in Figure 4.3, with four major base suppliers.

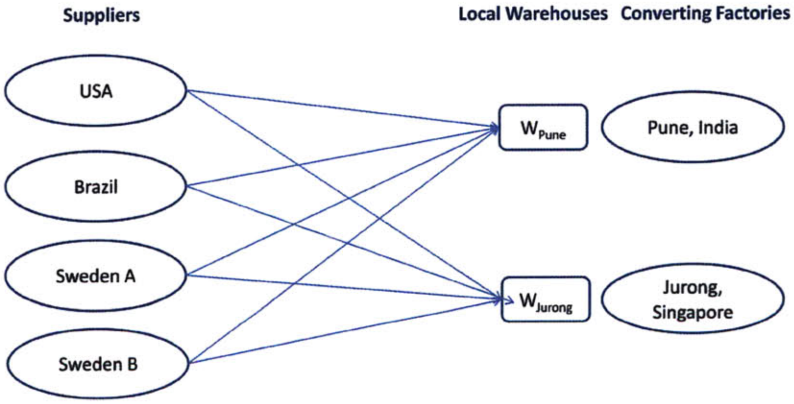


Figure 4.3 Current Single-Stage Supply Chain

Suppliers ship base paper to the local warehouses in Jurong, Singapore and in Pune, India. For CAJ, rolls of base paper are typically stored at three locations: CAJ warehouse, Singapore external warehouse and at the local container ports on consignment basis. Figure 4.4 gives an overview of the average inventory levels and capacity of the warehouses in Singapore. The arrows indicate the material flow from the suppliers to each of the warehouses.

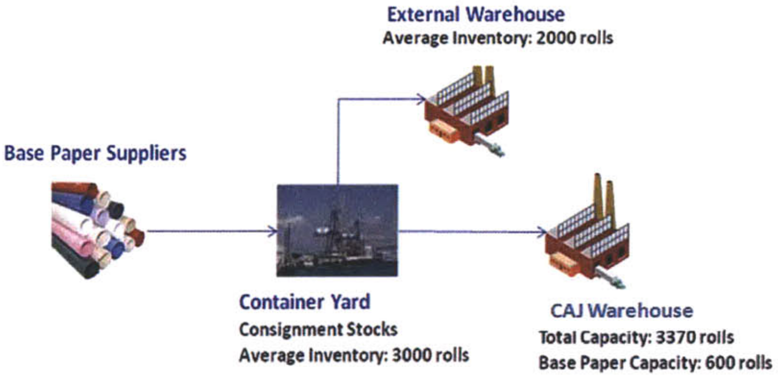


Figure 4.4 Base Paper Warehouses in Singapore

4.4.2 Multi-Stage Supply Chain

A multi-stage supply chain was proposed to improve the resilience of base paper supply. A multi-stage supply chain supports the concept of risk pooling and postponement with regards to demand variations. Risk pooling in supply chain terms typically refers to the notion of reducing risk for each individual entity by aggregating risk for all the entities as a whole while postponement concept in supply chain terms refers to the strategic delay of decision making point to minimize risk. Appendix A gives a detailed discussion on these on two concepts.

A multi-stage supply chain stems from the notion of using an aggregate warehouse and proposes the use of additional central warehouses (CW) on top of the original warehouses that cater to individual markets. The simplest form of a multi-stage supply chain is illustrated in Figure 4.5 where a single central warehouse is used as a cross-dock to give a two-stage supply chain. $W_{central}$ refers to the central warehouse.

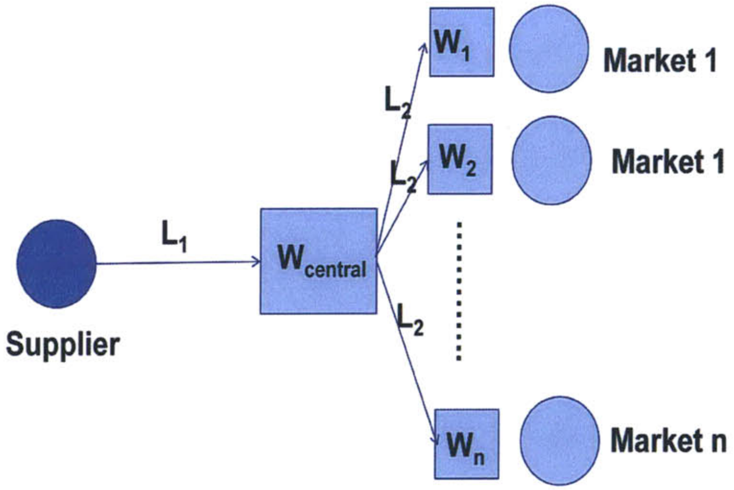


Figure 4.5 Two-stage Supply Chain

A multi-stage supply chain gives various potential benefits such as shorter response time to the markets, better service from regional locations, transportation economies and risk pooling over supplier lead time. (9)

With regards to supply chain resilience, multi-stage supply chains potentially increase resilience to various supply chain risks by allowing the supply chain to respond faster and reducing the costs incurred due to disruptions. For instance, in face of short term risks that may result in materials shortage, such as sudden demand changes and delays in shipping lead times, a multi-stage supply chain is expected to respond faster to the changes as compared to a single-stage supply chain. Because of risk pooling at the central warehouses, when there is materials shortage in any market, there is a higher chance that the materials may be supplied by the central warehouses since there is a larger quantity of stocks shared by all the markets, as compared to the single-stage supply chain case where each market keeps its own stock. Furthermore, in single-stage supply chains, high costs are often inccurred to obtain the materials from alternative suppliers or by air-freighting. On the other hand, these costs may be avoided if the materials can be easily obtained from the central warehouses.

In addition, the choice of locations for the central warehouses may also potentially increase the supply chain's resiliences to long term risks such as strategic and financial risks, including increasing labor costs, increasing fuel prices and decreasing foreign exchange rates etc. For instance, multi-stage supply chains with central warehouses in locations which have lower operating costs or are less sensitive to economic changes may result in less additional costs incurred as the business environment evolves, often resulting in increased labor costs and fuel prices.

For a multi-stage supply chain, it is expected that the total amount of inventory for the system may be increased accordingly as compared to a single-stage supply chain. However, as the number of markets involved (N) increases, a multi-stage system would require fewer inventories as compared to a single-stage system. This is illustrated through an example given in Appendix B. In view of the various benefits of a multi-stage system, costs-benefits analysis should be done to evaluate its usefulness.

CAJ Application

The proposed network involves an additional central warehouse that is shared between all the converting factories within a Company A cluster. Converting factories refer to factories that primarily produce printed and laminated rolls of paper to cater for customers' filling facilities. CAJ belongs to the South and Southeast Asia cluster which is shared with the converting factory located at Company A, Pune. The original supply for base paper and proposed two-stage supply chain are presented in Figure 4.3 and Figure 4.6 respectively.

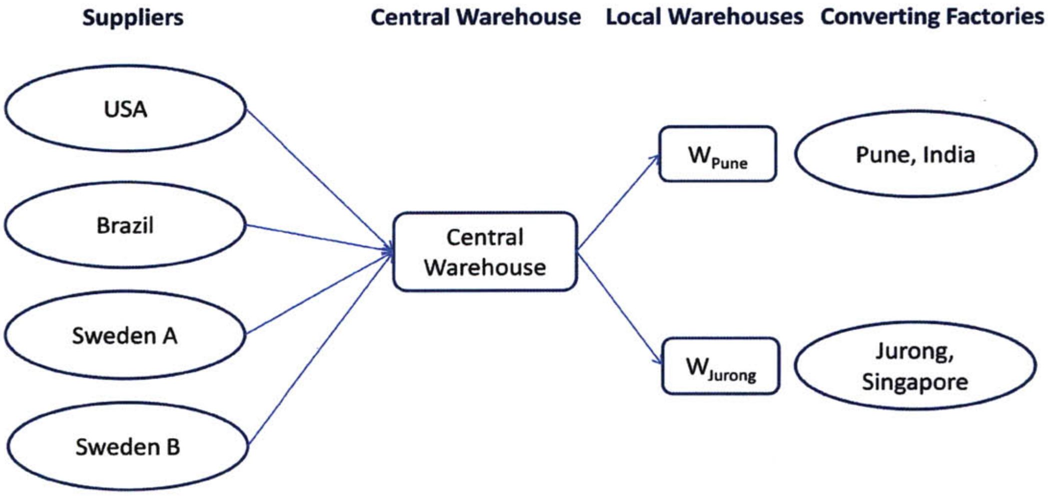


Figure 4.6 **Proposed Multi-Stage Base Paper Supply chain**

The central warehouse is meant to be located closer to the two converting factories than the base paper suppliers. By holding base paper at the central warehouse, the lead time required to deliver base paper from the central warehouse to the converting factories, L2, is much shorter than the original supplier lead time, L. This increases resilience of the supply chain significantly since response time is reduced proportionally to the lead time reduction. At the same time, costs of recovery from disruptions are also significantly reduced with regards to air freight costs and costs of maintaining the same customer service level. Since inventory at the central warehouse is shared between the two factories, when there is a sudden requirement for a certain base paper grade, there is a higher chance that it is available at the central warehouse as compared to the single-stage supply chain case.

On a further note, additional reduction in costs can occur if the central warehouse is placed strategically at a location that is cheaper to maintain than at the converting factories. Considering the high labor and facility costs in Singapore, it is highly possible that a central warehouse at a nearby region would give significant costs savings immediately and also in future when the business environment evolves. In addition, the current stock level at CAJ often requires the use of an external warehouse on top of the use of the complimentary storage of 30 days at the ports of import. The rental costs of the external warehouse may be saved if the central warehouse eliminates the need for the external warehouse. Furthermore, if inventory level at the CAJ warehouse is reduced, this can free up space in the CAJ warehouse for other items such as WIP and finished goods and translate into costs savings with regards to holding costs of base materials.

A preliminary observation shows that by volume, about 30% of India's demand is in common with paper grades used in CAJ and about 30% of CAJ's demand is in common with paper grades used at Pune. Even though this percentage is not huge, the Company A management team has indicated substantial plans to shift Pune's operations in the near future such that base paper demand would be very similar between Pune and CAJ. Hence, this demonstrates the high potentiality of a multi-stage supply system that caters to both converting factories and CAJ management was involved in verifying this before the methodology is further carried out.

4.5 Potential Warehouse Location Shortlist

In order to find an optimal central warehouse location for a resilient multi-stage supply chain, a few potential warehouse locations were shortlisted. First of all, all major container ports within close proximity of South and Southeast Asia cluster were listed. Subsequently, the ports were evaluated based on the four criteria indicated in Figure 4.7. Those ports which cannot meet these criteria were eliminated. As a result, six locations were shortlisted for further investigation.

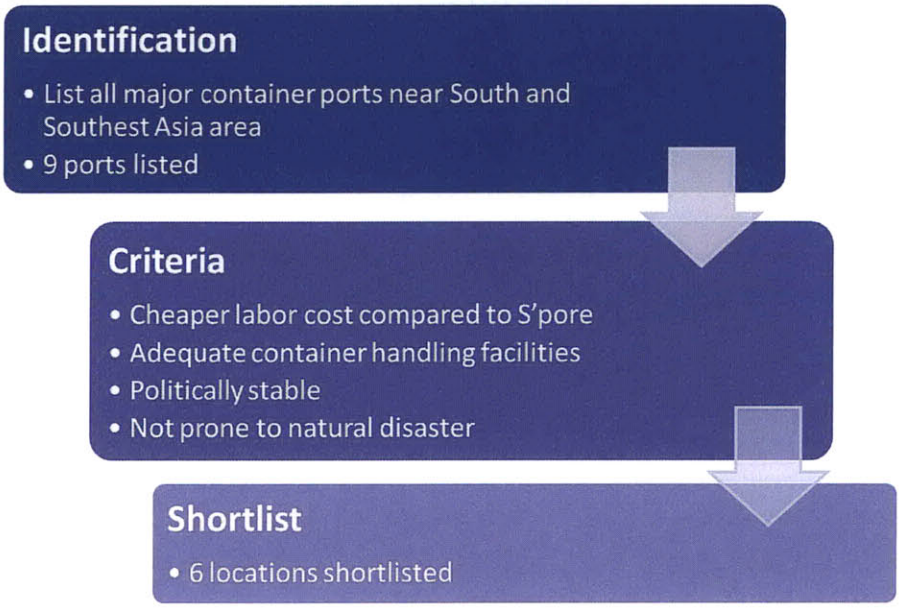


Figure 4.7 Procedures of Potential Warehouse Location Shortlist

Figure 4.8 shows the geographical locations of the six shortlisted locations for consideration.

Figure 4.8 Six Shortlisted Locations for Central Warehouse

4.6 Statistical Modeling

To select the optimal central warehouse location among the shortlisted locations, a statistical model was constructed. Model outputs included two main components: the shipping cost and warehouse operating cost. They were summed as the total supply chain cost which was used to evaluate the resilience and cost effectiveness of the supply chains.

As shown in Figure 4.9, all relevant data was first collected. A number of statistical procedures were carried out to estimate both the shipping cost and the warehouse cost. These estimated costs were then compared to the actual costs involved in CAJ base paper supply chain to verify the accuracy of the statistical model.

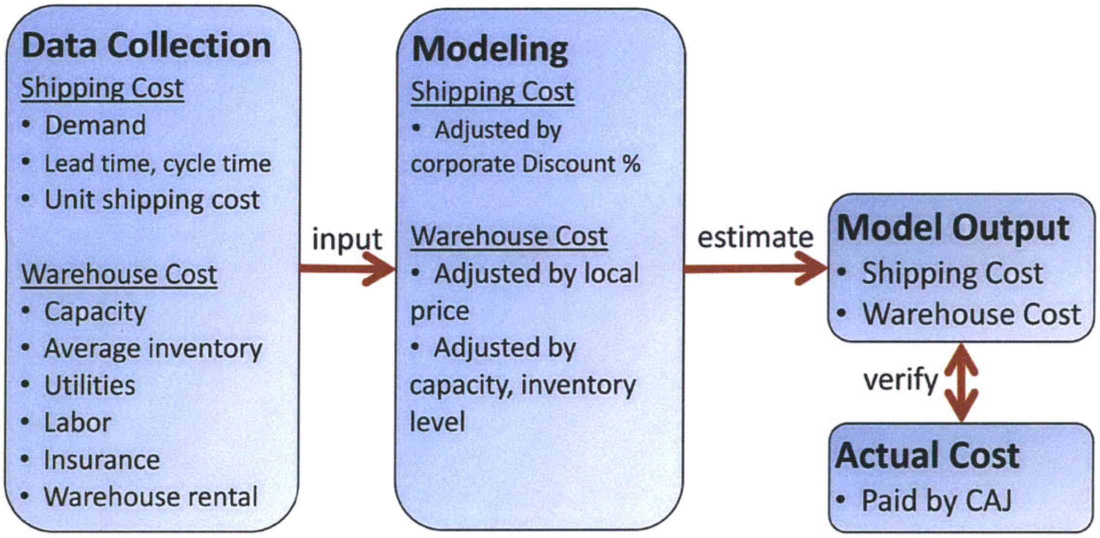


Figure 4.9 Procedures of Statistical Modeling

In the model verification process, the actual costs involved in the CAJ base paper supply chain were obtained and used for comparison with the estimated costs. The actual costs involved in the Pune supply chain were not used in the verification process as these costs not disclosed for this project.

4.6.1 Data Collection Method

Data relevant to base paper supply chain was collected for the cost estimation of the multi-stage supply chain. This data was divided into four categories: demand data, shipping data, warehouse operation data and miscellaneous data. The detailed data collection methods are explained below.

Demand Data

Demand data consists of actual demand and forecasted demand for all paper grades used in both converting factories. It was used for the calculation of overall shipping volume and safety stocks.

For both converting factories, the actual demand and the forecasted demand for each paper grade of the past 12 months was obtained from the SAP system. Demand data is measured in number of paper rolls. Since it was a common practice to pack 9 rolls of paper into a 40-foot standard container to utilize the container space, the number of paper rolls can be directly translated into number of containers.

Shipping Data

Shipping data consists of unit shipping cost, shipping lead time, shipping cycle time and customs clearing time. Unit shipping cost was used in estimation of the total shipping cost, while shipping lead time, shipping cycle and customs clearing time were used in safety stock calculation.

The unit shipping cost was quoted from Maersk Line, a major shipping partner with Company A. The price was quoted based on one 40-foot standard container for packing paper materials (non-hazardous materials). The quotation was made in US dollars and inclusive of pick-up and delivery, so no additional transportation costs would be involved. The unit shipping costs for shipping from all suppliers to all potential warehouses were tabulated into a spreadsheet as shown in Table 4.4 and a similar table was formulated for unit shipping costs from all potential warehouses to converting factories. However, two exceptions were considered, i.e. transportations within India and from Tanjung Pelepas to Singapore. In these two cases, truck freight was proven to be more economical, thus the quotations were obtained from the third party logistics partner (3PL) of Company A instead. Unit shipping costs for shipping directly from suppliers to CAJ were also collected for model verification. The actual unit shipping cost paid by CAJ was obtained from the planning department to calculate the corporate discount percentage.

Table 4.4 Unit Shipping Cost from Suppliers to Central Warehouse (in USD)

Unit Shipping Cost From Suppliers to Central Warehouse (USD)

To from	USA	Brazil	Sweden A	Sweden B
Laem Chabang, TH				
Yantian, CN				
Ho Chi Minh City, VN				
Tanjung Pelepas, MY				
Chennai, IN				
Jakarta, ID				
Singapore, SG				

Similarly, the shipping lead times (in days) and shipping cycles (in days) were obtained from Maersk Line, and were tabulated respectively. The same truck freight exceptions were considered.

The typical customs clearing times of CAJ products in relevant countries were found to be negligible and largely overlapped with the shipping lead time. Thus they were not included in our model.

Warehouse Operation Data

Warehouse operation data consists of labor costs, utility data, equipment rentals, insurance, and warehouse rentals. All the data was used for the estimation of inventory holding costs for the central warehouse and the converting factory warehouses. All these costs were translated into US dollars for easy comparison.

The capacity and head count of labor in CAJ warehouse were obtained from the 3PL. The unit labor costs were extracted from *"The Labor Cost Report of 40 Developing Countries"* compiled by Jassin-O'Rourke Group. (10) This labor cost data includes wages, bonuses, insurance, and employee welfare. Thus, these elements would not be further collected separately.

The utility usage of CAJ warehouse was obtained from the purchasing department and the unit cost of electricity (in kWh) was extracted from the *"ASEAN Electricity Tariff Database"* (11). The

Liquified Petroluem Gas (LPG) unit cost (in tanks) was obtained from the latest update LPG suppliers in relevant countries.

The equipments such as forklifts and stacking pallets used in CAJ warehouse were rented from UMW group. Hence, the total rental cost of these equipments was obtained from UMW.

The insurance cost covering the building of CAJ warehouse and stored goods were obtained from the CAJ purchasing department.

The warehouse lease price was quoted from the largest property agent of each relevant country; the physical size of CAJ warehouse was measured by the authors.

The respective total warehouse operating costs for CAJ warehouses were obtained from the respective cost pillars, they were needed for verification of our model.

Miscellaneous Data

The other data such as import and export taxes, the availability of tax free (free trade) zones was enquired from the CAJ purchasing department.

4.6.2 Statistical Procedures

Shipping Costs Calculation

Frequent shippers like Company A usually pay a lower shipping cost than the quoted price. After obtaining the actual unit shipping cost of CAJ from Maersk Line, a corporate discount percentage was calculated based on Equation 4.1. Corporate discount percentages for different shipping routes were calculated, they were subsequently used to adjust shipping costs for various routes.

$$D=\frac{u_{quoted\ shipping}-u_{actual\ shipping}}{u_{quoted\ shipping}}\times 100\% \qquad (4.1)$$

where D is the corporate discount percentage, $u_{\text{quoted shipping}}$ is the quoted unit shipping cost, and $u_{\text{actual shipping}}$ is the actual unit shipping cost paid by Company A.

The author assumes Company A will receive the same percentage of discount for similar shipping routes from Maersk Line. Then the quotations were adjusted according to Equation 4.2 for more accurate estimation of the actual shipping cost for Company A. Different routings are discounted separately, e.g. Intra-Asia, South American to Asia, Europe to Asia and etc.

$$u_{adjusted\ shipping} = u_{quoted\ shipping} \times (1-D) \tag{4.2}$$

where $u_{\text{adjusted shipping}}$ is the adjusted unit shipping cost, $u_{\text{quoted shipping}}$ is quoted unit shipping cost, and D is the corporate discount percentage.

The shipping volume is the aggregated annual forecast demand of all paper grades for a particular shipping route. The total shipping cost for that route was calculated based on Equation 4.3. The shipping volume was divided by 9 to translate directly into number of containers.

$$C_{shipping} = \frac{V_{shipping}}{9} \times u_{adjusted\ shipping} \tag{4.3}$$

where C_{shipping} is the total shipping cost for a shipping route, V_{shipping} is the shipping volume for that route, and $u_{\text{adjusted shipping}}$ is the corresponding adjusted unit shipping cost.

Equation 4.3 is applicable for all shipping routes including those from the suppliers to central warehouse and from central warehouse to converting factories. It is also used in calculating the direct shipping cost from suppliers to converting factories in model validation.

Safety Stock Estimation

Forecast error variance of each base paper grade was estimated from the variance within the historical data by Equation 4.4. (12)

$$\sigma_{fe}^2 = E\,[(y_d - y_f)^2\,] \tag{4.4}$$

where σ_{fe} is the standard deviation of forecast error, E is the *mean* operator, y_d is the historical actual demand and y_f the historical forecasted demand.

Standard deviation of forecast error was then used as the expected variation to calculate the amount of safety stock of each paper grade by Equation 4.5. (13)

$$S_{fe}=\sigma_{fe}\times Z_p\times\sqrt{L+t_{cyc}} \tag{4.5}$$

where S_{fe} is the safety stock, σ_{fe} is the standard deviation of forecast error, Z_p is the Z-score at service level P, L is the shipping lead time and t_{cyc} is the shipping cycle time.

Warehouse Operating Cost Calculation

The capacity of the central warehouse was estimated by the sum of maximum inventory of all base paper grades. The maximum inventory of each base paper grade is made up of the lead time demand, safety stock for demand fluctuation and safety stock for forecast error. The details are expressed in Equation 4.6. (13)

$$W_{cw}=\sum\left[\mu_d(L+t_{cyc})+Z_p\sigma_{df}\sqrt{L+t_{cyc}}+Z_p\sigma_{fe}\sqrt{L+t_{cyc}}\right] \tag{4.6}$$

where W_{cw} is the capacity of central warehouse, μ_d is the forecasted average demand rate, L is the shipping lead time, t_{cyc} is the shipping cycle time, Z_p is the Z-score at service level P, σ_{df} is the standard deviation of forecasted demand fluctuation.

The average inventory in the warehouse covers the lead time demand and the safety stock for forecast error for all base paper grades, while the demand fluctuation is averaged out. The formula for this estimation is Equation 4.7. (13)

$$\bar{I}=\sum\left[\frac{\mu_d(L+t_{cyc})}{2}+Z_p\sigma_{fe}\sqrt{L+t_{cyc}}\right] \tag{4.7}$$

where $\bar{I}$ is the average inventory of base paper in a warehouse. One exception is for the average inventory of CAJ base paper, the consignment inventory on the shipping yard is subtracted away from the calculated $\bar{I}$, and this adjusted average inventory is used for subsequent calculation. This consignment inventory does not incur any additional cost to CAJ.

The author assumes the physical area of the warehouse is directly proportional to its capacity. Thus, it was estimated based on the physical area of CAJ warehouse and calculated by Equation 4.8. The warehouse rental cost for the central warehouse was then quoted based on this calculation.

$$A_{cw} = \frac{W_{cw}}{W_{CAJ}} x\, A_{CAJ} \tag{4.8}$$

Where A_{cw} is the physical area of central warehouse, W_{cw} is the capacity of central warehouse capacity, W_{CAJ} is the capacity of CAJ warehouse, and A_{CAJ} is the physical area of CAJ warehouse.

For the operating cost of warehouses, the author assumes the utility usage, headcount of labor, equipment rental and insurance are all directly proportional to the average inventory of the warehouses. The electricity cost was also multiplied by the local unit utility cost, while the labor cost was multiplied by the local unit labor cost. The LPG unit cost and unit equipment rental price is believed to be the same in the region. A substantial portion of the insurance costs is for insuring the base paper, which has the same value globally. Thus the insurance costs are also considered to be directly proportional to the average inventory.

These costs are calculated by the following equations, Equation 4.9 to Equation 4.13. Since the CAJ warehouse is used to store other materials beside the base paper, any empty space is utilized immediately thus it is always full. Therefore the average inventory of CAJ warehouse is the same as the warehouse capacity.

$$c_{elec} = \frac{\bar{I}}{\bar{I}_{CAJ}} \times N_{CAJ\ elec} \times u_{local\ elec} \tag{4.9}$$

where c_{elec} is electricity cost, $\bar{I}$ is the average inventory of base paper in a particular warehouse, $\bar{I}_{CAJ}$ is the total average inventory of CAJ warehouse, $N_{CAJ\ elec}$ is the electricity usage of the CAJ warehouse, $u_{local\ elec}$ is the local electricity unit cost.

In this analysis, all workers were expected to work 8 hours per day, and 5 days per week, no additional holidays were considered.

$$c_{labor} = \frac{\bar{l}}{\bar{l}_{CAJ}} \times N_{CAJ\ labor} \times u_{local\ labor} \qquad (4.10)$$

where c_{labor} is labor cost, $N_{CAJ\ labor}$ is the head count of labor in CAJ warehouse, and $u_{local\ labor}$ is the local labor unit cost.

$$c_{LPG} = \frac{\bar{l}}{\bar{l}_{CAJ}} \times c_{CAJ\ LPG} \qquad (4.11)$$

where c_{LPG} is LPG cost, $c_{CAJ\ LPG}$ is the LPG cost of CAJ warehouse.

$$c_{equipment} = \frac{\bar{l}}{\bar{l}_{CAJ}} \times c_{CAJ\ equipment} \qquad (4.12)$$

where $c_{equipment}$ is equipment rental cost, and $c_{CAJ\ equipment}$ is the equipment rental cost of CAJ warehouse.

$$c_{insurance} = \frac{\bar{l}}{\bar{l}_{CAJ}} \times c_{CAJ\ insurance} \qquad (4.13)$$

where $c_{insurance}$ is insurance cost, and $c_{CAJ\ insurance}$ is the insurance cost of CAJ warehouse.

A summation of these costs is the estimated total warehouse operating cost for base paper. The calculation is shown in Equation 4.14. This estimation is applicable for both central warehouse and converting factory warehouses.

$$c_{estimated\ paper} = c_{elec} + c_{labor} + c_{LPG} + c_{equipment} + c_{insurance} \qquad (4.14)$$

where $c_{estimated\ paper}$ is the estimated total warehouse operating cost for base paper in a particular warehouse.

The CAJ warehouse is used to store other goods as well, including WIP and finished goods. Hence, when the base paper inventory is reduced, the extra space could be utilized by other goods. Thus the author can assume the warehouse is always full. As a result, the actual CAJ warehouse operating cost for base paper was calculated as a fraction of the total operating cost of the CAJ warehouse. The details of the calculation are shown in Equation 4.15. This actual warehouse operating cost for CAJ paper was used to verify the model accuracy subsequently.

$$c_{actual\ CAJ\ paper} = \frac{\bar{I}_{actual\ CAJ\ paper}}{\bar{I}_{CAJ}} \times c_{actual\ CAJ\ warehouse} \tag{4.15}$$

where $c_{\text{actual CAJ paper}}$ is calculated actual warehouse operating cost of base paper in CAJ warehouse, $\bar{I}_{\text{actual CAJ paper}}$ is the actual average inventory of base paper in CAJ warehouse, $\bar{I}_{\text{CAJ}}$ is the total average inventory in CAJ warehouse which is also the warehouse capacity of CAJ, and $c_{\text{actual CAJ warehouse}}$ is the actual warehouse operating cost of CAJ warehouse.

4.6.3 Model Verification

In order to verify the accuracy of the proposed statistical model, a comparison between the estimated costs by the model and the actual costs was made using CAJ supply chain costs.

In Figure 4.10, the single-stage supply chain is illustrated. The red arrows indicate the shipping costs while the light green boxes indicate the relevant warehouses that make up the warehouse costs.

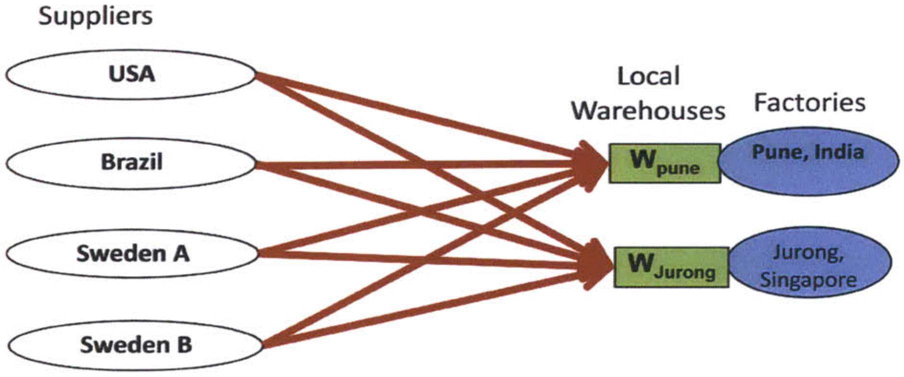


Figure 4.10 Single-Stage Supply Chain

As shown in Table 4.5, all the estimated warehouse operating cost components appear to be very accurate. The estimated total warehouse operating cost for CAJ base paper is only 1.37% less than the actual cost.

Table 4.5 Warehouse Operating Cost Verification Table (in thousand USD)

Cost Elements	Actual Cost	Estimated Cost	% Difference
Labor Cost	573	564	-1.67%
Electricity	35	35	-0.51%
Insurance	32	32	-0.50%
Equipment Rental	21	21	-0.50%
LPG	108	107	-0.50%
Total	**769**	**758**	**-1.37%**

In Table 4.6, the estimated shipping costs from different suppliers are fairly accurate as all of them are within 11% of estimation error. The estimated total shipping cost for CAJ base paper is only 0.36% more than the actual cost.

Table 4.6: Shipping Cost Verification Table (in thousand USD)

Suppliers	Actual Cost	Estimated Cost	% Difference
Sweden A	3,759	3,654	-2.79%
Sweden B	1,949	1,835	-5.84%
USA	3,941	4,350	10.37%
Brazil	2,034	1,886	-7.28%
Total	**11,682**	**11,724**	**0.36%**

Table 4.7 presents the total supply chain costs of CAJ base paper. From the total percentage difference of 0.25% between the actual and estimated cost of the supply chain, it can be seen that the model is more than 99% accurate.

On a further note, it can be noted that shipping cost is a major part of the total supply chain cost, since it is about fifteen times of the warehouse operating cost. Therefore, an accurate estimation of the shipping cost is important to give a good estimation of total supply chain cost.

Table 4.7 Total Supply Chain Cost Verification Table (in thousand USD)

	Actual Cost	Estimated Cost	% Difference
Warehouse Operating Cost	769	758	-1.37%
Shipping Cost	11,682	11,724	0.36%
Total Supply Chain Cost	**12,451**	**12,482**	**0.25%**

4.7 Multi-Stage Supply Chain Analysis

In order to evaluate the proposed multi-stage supply chain, a model was made of the proposed supply chain with an added central warehouse, based on the statistical model illustrated earlier. Figure 4.11 depicts the proposed multi-stage supply chain with a central warehouse that aggregates base paper from the suppliers.

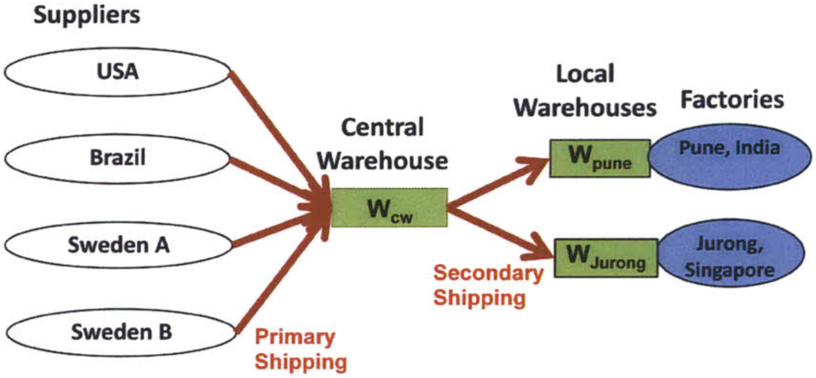


Figure 4.11 Multi-Stage Supply Chain Model

A total of six statistical models were built to simulate each of the six shortlisted locations as the central warehouse location. The models were then evaluated with respect to the total cost of the supply chain, including shipping and warehouse costs. Warehouse cost included the operating costs of all three warehouses while the shipping cost included the primary and secondary shipping costs involved. The results of the model would be presented and discussed in Section 5.1.

4.8 Resilience Analysis

To investigate on the resilience level of the multi-stage supply chains compared to single-stage supply chain, a resilience analysis was carried out to compare the impact of certain common disruptions on the supply chains. A list of scenarios was generated based on the historical data of CAJ since 2003 and the expert opinions of CAJ management team. (8) This list includes the disruptions that occur most frequently and are the most costly to CAJ. For this analysis, only disruptions which can be quantified as a change in input parameters were discussed. Non-quantifiable disruptions, such as environmental legalization, supplier loss and labor unrest were not analyzed, since accurate estimation of costs and consequences cannot be obtained and cannot be reflected in the statistical model.

In addition, different quantifiable disruptions could lead to changes of the same input parameters and hence have the similar impact on the supply chain. For example, hazard risks such as natural disasters and operational risks such as port strike both result in a longer shipping lead time. Thus, these disruptions were discussed together, e.g. the case of natural disasters and port strikes were discussed under the scenario of shipping disruptions. A total of seven scenarios were found to be representative of the most supply chain risks that CAJ faces. Furthermore, other scenarios which are not discussed explicitly in this article often result in changes of the same input parameters, thus the similar results could be inferred. These seven scenarios and their corresponding input parameter variations are presented in Table 4.8.

Table 4.8 Resilience Analysis Scenarios and Input Parameter Variation

Scenarios/Disruptions		Input Parameter Variation
1	Stock commonality increase	Paper grades, Supplier change
2	Demand forecast accuracy fluctuation	Forecast errors
3	Currency exchange rate fluctuation	Currency exchange rate
4	Demand surge	Actual & forecasted demand
5	Fluctuation in fuel price	Shipping cost
6	Shipping disruptions	Shipping lead time
7	Labor cost increase	Labor cost

To evaluate the impact of each scenario on the supply chain, the relevant input parameters were varied across a range and the model outputs were collected. Resilience analysis was then carried out on each set of model outputs. The results and discussion are presented in Section 5.2. Scenarios 1 and 2 are discussed in Elsa Leung's thesis, scenarios 3 and 4 are discussed in Jingxia Yang's thesis while scenarios 5 to 7 are discussed in Jie Xu's thesis.

Chapter 5 Results and Discussion

5.1 Multi-Stage Supply Chain Analysis

5.1.1 Capacity

The estimated required capacity of the central warehouse (CW) relates directly to the physical size, which determines the rental fees. Therefore, a small estimated capacity is desirable to minimize costs. Equation 4.6 is used to obtain the capacity required at the central warehouses. Table 5.1 presents the results on capacity for each of the six central warehouse locations. Figure 5.1 plots the values in a bar-chart for comparison.

Table 5.1 Capacity of Central Warehouse (in thousand rolls)

Location	CW Capacity
Tanjung Pelepas, MY	19.8
Laem Chabang, TH	20.5
Yantian, CN	19.6
Ho Chi Minh City, VN	20.0
Chennai, IN	20.5
Jakarta, ID	20.4

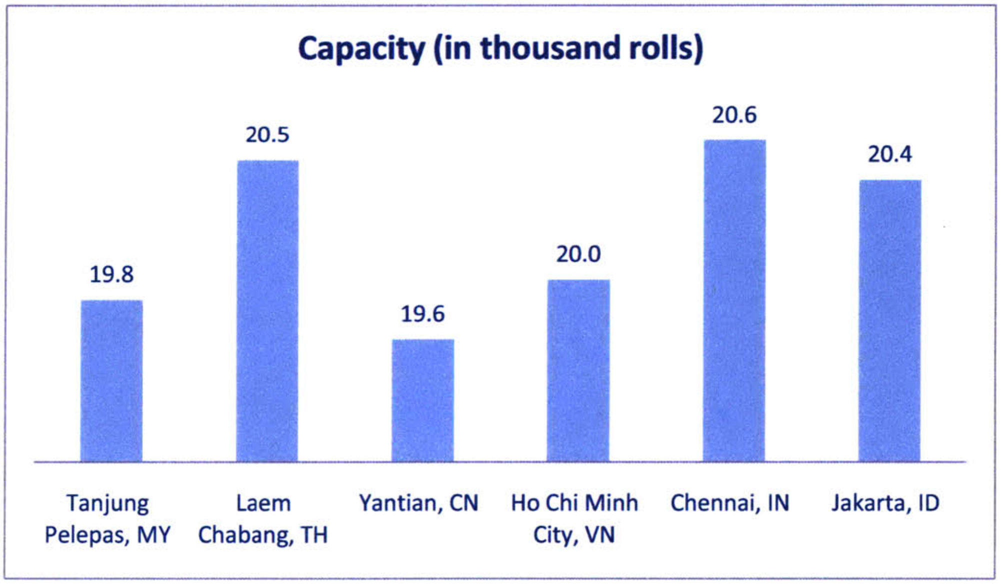


Figure 5.1 Capacity of Central Warehouse

From the results, it can be seen that building a central warehouse at Tanjung Pelepas and Yantian would require the lowest capacity. This is mainly because of the shorter shipping lead times from the suppliers, L, involved as compared to the other central warehouse options. Hence this signifies lower warehouse rental cost as compared to the other locations.

5.1.2 Average Inventory

The average inventory at each of the warehouses is used to estimate the warehouse cost components such as labor, equipment, insurance, LPG and electricity costs. Hence, a low total average inventory of the supply chain would be desirable. Equation 4.7 is used to evaluate the average inventory required at all the warehouses and Table 5.2 presents the average inventory levels of the warehouses in the current single-stage supply chain. The average inventory corresponding to the Singapore location considers all three warehouses in Singapore: the CAJ warehouse, external warehouse and the inventory stored at the container ports.

Table 5.2 Average Inventory for Single-Stage Supply Chain (in rolls)

Location	Average Inventory	Total
Singapore	5,587	6,357
Pune	770	

Table 5.3 illustrates the average inventory levels for the multi-stage supply chain, for each of the six potential warehouse locations.

Table 5.3 Average Inventory for Multi-Stage Supply Chain (in rolls)

CW Location	Average Inventory			Total Average Inventory
	CW	Singapore	Pune	
Tanjung Pelepas, MY	6,384	306	290	6,979
Laem Chabang, TH	6,984	1,906	392	9,282
Yantian,CN	6,106	2,193	407	8,706
Ho Chi Minh City, VN	6,426	1,761	392	8,580
Chennai, IN	7,054	2,193	79	9,326
Jakarta, ID	6,811	2,193	378	9,382

Figure 5.2 gives an illustration of the total overall average inventory for the entire supply chain for each of the different central warehouse locations and the single-stage supply chain. The different color blocks further illustrate the corresponding level of average inventory at each of the three warehouse components: Singapore, Pune and central warehouse.

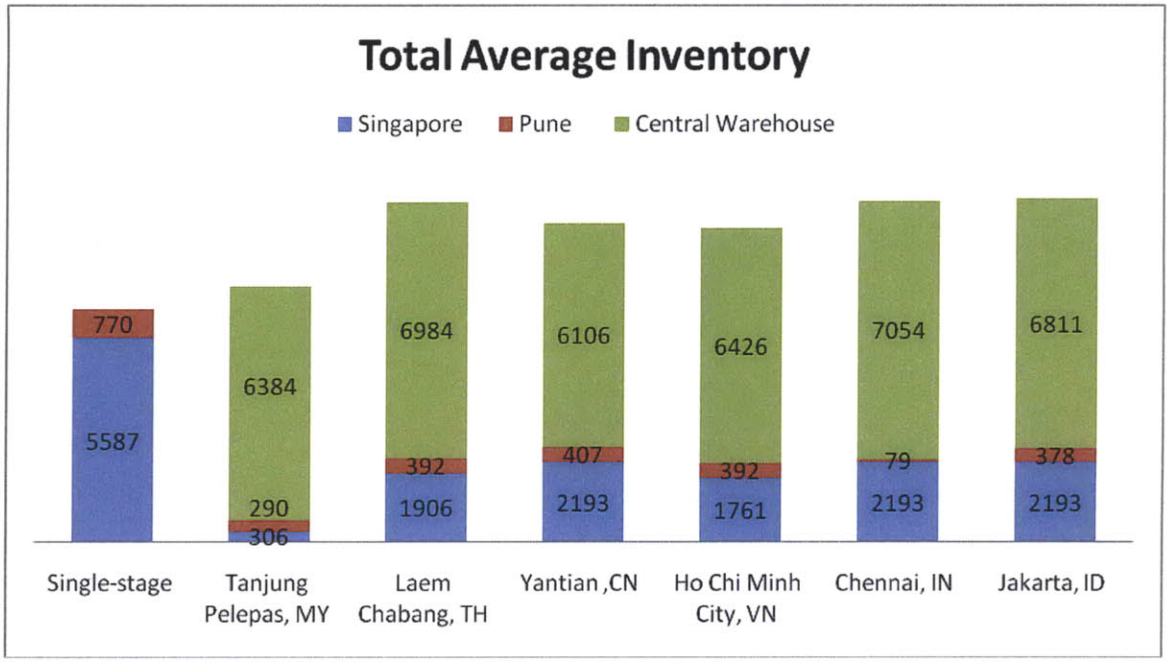


Figure 5.2 Total Average Inventory for All Supply Chains (rolls)

From Figure 5.2, it can be seen that the multi-stage supply chain with a central warehouse at Tanjung Pelepas results in the lowest total average inventory among the six central warehouse locations. From Equation 4.7, it can be inferred that the low total average inventory for the multi-stage supply chain with central warehouse in Tanjung Pelepas is mainly due to the shorter shipping lead times from the suppliers, L, as compared to the other locations since all other components are same for the other locations. Comparing with the single-stage supply chain, the total average inventory level is only increased by about 600 rolls of base paper.

Focusing on the local warehouse in Pune, it can be seen that the average inventory level is reduced from 770 rolls to 290 rolls. For Singapore, the reduction is more significant from 5587 rolls to just 306 rolls. This reduction in average inventory is mainly due to the reduction in secondary shipping lead time as compared to the shipping lead time required for the single-stage supply chain. Bearing in mind that the capacity available within the CAJ internal warehouse is around 600 rolls, this reduction in average inventory for CAJ would eliminate the need for the external warehouse in Singapore and hence potentially reduce the cost involved.

However, the total average inventory of the whole system is larger for the multi-stage supply chains than the single-stage supply chains. This is because the multi-stage supply chains involve an additional warehouse in comparison and requires an additional shipping segment. Hence, more safety stock is required overall. This concept is also explained in Appendix B.

5.1.3 Warehouse Cost

Warehouse costs for each of the cases were calculated according to the capacity and average inventory obtained from the models. Equations 4.8 to 4.14 are thus used to evaluate each component of warehouse operating costs and the total warehouse operating costs. Table 5.4 presents the warehouse costs for the single-stage supply chain.

Table 5.4 Warehouse Costs for Single-Stage Supply Chain (in thousand USD)

Location	Warehouse Cost	Total
Singapore	769	834
Pune	65	

Table 5.5 presents the warehouse costs for the multi-stage supply chains for each of the six central warehouse locations.

Table 5.5 Warehouse Costs for Multi-Stage Supply Chains (in thousand USD)

CW Location	Warehouse Cost			Total Cost
	CW	Singapore	Pune	
Tanjung Pelepas, MY	770	90	25	885
Laem Chabang, TH	875	564	33	1,472
Yantian,CN	785	648	34	1,468
Ho Chi Minh City, VN	605	521	33	1,159
Chennai, IN	693	648	7	1,349
Jakarta, ID	587	648	32	1,267

All the multi-stage supply chains cost more than the single-stage supply chains in terms of the total warehouse costs. As explained earlier, the total overall capacity and average inventory are more than that of the single-stage supply chains due to the additional central warehouse involved. Since the total warehouse costs are proportional to the total capacity and average inventory, the total warehouse costs are hence higher for the multi-stage supply chains than for the single-stage supply chains. From the results, it can be seen that having a central warehouse at Tanjung Pelepas would cost around USD 50,000 per year more than the single-stage supply chain.

5.1.4 Shipping Cost

The total shipping cost involved for the single-stage supply chain amounts to around USD 12.9 million per year. The total shipping costs for the multi-stage supply chains are obtained though the use of Equation 4.2 and 4.3 and presented in Table 5.6.

Table 5.6 Shipping Cost for Multi-Stage Supply Chains

CW Location	Shipping Cost (in million USD)	% Increase compared to Single-Stage Supply Chain
Tanjung Pelepas, MY	14.8	14.2
Laem Chabang, TH	16.8	22.3
Yantian,CN	15.8	14.3
Ho Chi Minh City, VN	13.8	2.7
Chennai, IN	19.9	48.6
Jakarta, ID	18.6	29.3

It can be seen that the supply chain with a central warehouse at Tanjung Pelepas would result in a 2.7% increase in total shipping cost as compared to the single-stage supply chain. Total shipping cost is expected to be higher for the multi-stage supply chains than the single-stage supply chain since there is an additional shipping segment involved. The difference in shipping costs for each of the central warehouse locations are justified by the different unit shipping costs involved for the different central warehouse locations.

5.1.5 Costs and Benefits Analysis

This section discusses about the costs and benefits of the proposed multi-stage supply chain as compared to the single-stage supply chain.

Costs

Combining the shipping costs and the warehouse costs for each supply chain, the total cost of the supply chains are calculated. Figure 5.3 depicts the total costs for each supply chain together with the proportion of shipping and warehouse costs.

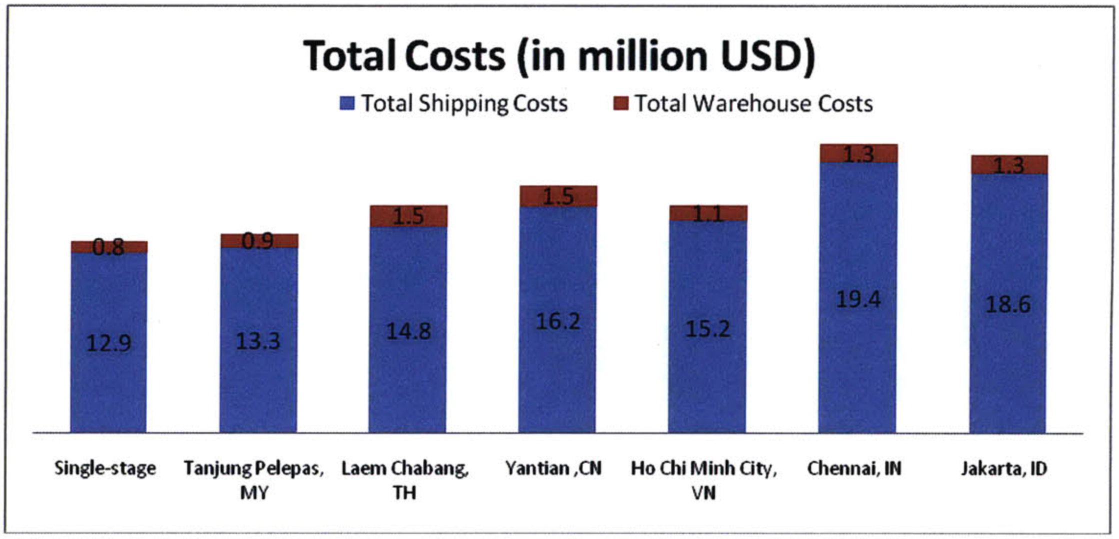


Figure 5.3 Total Cost of Single-Stage and Multi-Stage Supply Chains

It can be seen that the total cost for the supply chain with central warehouse at Tanjung Pelepas is less than half a million USD more than the single-stage supply chain. The actual cost difference is presented in Table 5.7.

Table 5.7 Yearly Total Cost of Single-Stage Supply Chain and Multi-Stage Supply Chain involving Tanjung Pelepas

Single-Stage Supply Chain	USD 13.8 M
Multi-Stage Supply Chain (with Tanjung Pelepas)	USD 14.2 M
Difference in Cost	**USD 465 K**

Benefits

As discussed in Section 5.1.2, having a central warehouse at Tanjung Pelepas reduces the average inventory to just around 300 rolls. Since the capacity for base paper at the CAJ warehouse is currently 600 rolls, this means that all the 300 rolls of inventory base paper would be able to fit into the CAJ warehouse. Thus, the need for the use of the Singapore external warehouse is eliminated. Currently, CAJ stores an average of 2000 rolls of base paper at the external warehouse, amounting to 524 thousand USD per year.

Comparing this value with the difference in cost between the single-stage supply chain and the multi-stage supply chain involving Tanjung Pelepas, there is an overall savings of about 60,000 USD per year for the multi-stage supply chain. This cost benefit acts on top of the benefit of having increased supply chain resilience.

Another benefit of using a multi-stage supply chain is that the decision point of what paper grade to order and in what quantity is delayed. With a single-stage supply chain, the lead time for base paper is around 9 weeks from supplier to CAJ. But with a multi-stage supply chain, the time required to ship from the central warehouse to CAJ is reduced to just half a day. This implies that it is possible to make the decision to order the base paper much later than before.

This idea of postponement increases supply chain resilience in terms of response time and the cost of recovery. When a disruption occurs, CAJ can be expected to be able to respond quicker due to the short lead from the central warehouse. Furthermore, as the decision point is delayed, the supply chain acts as if it is already in anticipation of any possible changes that may occur before the day before production, hence reducing any potential cost of recovery such as machine downtime, additional planning and air freight costs etc.

The proposal of a central warehouse provides potential for the future expansion of CAJ and the South and Southeast Asia cluster. As operating costs in the central warehouse locations are significantly lower than in Singapore, it would be more economical to expand the warehouse at central warehouse.

5.2 Resilience Analysis

After analyzing the base scenario, the model was evaluated with disruptions taken into consideration. Seven scenarios of disruptions were modeled and discussed in three separate theses as mentioned in Section 4.8. In Sections 5.2.1 and 5.2.2, the results of the analysis regarding an increase in base paper commonality and fluctuations in demand forecast accuracy are presented.

For each of the scenario, the resilience of the various supply chains is discussed according to quantifiable benefits, mainly in terms of costs. Since supply chain resilience is defined by the ability to recover or shift to a better state after a disruption, in the following discussions, resilience is evaluated generally by the rate of response to the disruption in terms of additional costs incurred.

5.2.1 Base Paper Commonality Increase

Since risk pooling is one of the major benefits of a multi-stage supply chain, there is a need to investigate its actual effect for the case of CAJ and Pune converting factories. In terms of the base paper multi-stage supply chains, potential risk pooling at the central warehouses are achieved when paper rolls stored there can be used by both CAJ and Pune. This is only possible for the paper grades and suppliers that are in common for both CAJ and Pune. Since CAJ and Pune only share the same paper grades and suppliers for certain products currently, there is still much room for improvement in terms of increasing base paper commonality so as to increase risk pooling effects. The effect on the supply chain as that happens will be discussed in this section.

The current level of commonality can be evaluated by comparing the demand for different paper grades from different suppliers at the two converting factories. Table 5.8 and 5.9 list the yearly demand of paper used at CAJ and Pune.

Table 5.8 CAJ Yearly Base Paper Demand (rolls)

Supplier	Paper Grade	Demand
USA	1612	8,233
USA	1617	1,971
Sweden A	1501	291
Sweden A	1621	10,223
Sweden A	1622	5,838
Sweden A	1625	8,765
Sweden A	1626	9
Sweden A	1659	1,721
Sweden B	1645	7,435
Sweden B	1647	14,973
Brazil	1621	25,089
Brazil	1622	26
Brazil	1626	6
Brazil	1627	0
Brazil	1899	158
	Total:	84,738

Table 5.9 Pune Factory Yearly Base Paper Demand (rolls)

Supplier	Paper Grade	Demand
USA	1607	1,480
USA	1617	24
Sweden A	1621	606
Sweden A	1622	224
Sweden A	1625	1,416
Sweden A	1626	47
Sweden B	1122	407
Sweden B	1136	4,425
	Total:	8,630

In fact, the Pune converting factory's existing technology is very much behind CAJ's. In addition, they serve a different set of customers, mainly domestic, as compared to the diverse customers that CAJ serves. As such, the paper grades and suppliers used are much different from CAJ. In Tables 5.8 and 5.9, the paper grades highlighted in red depict the paper grades and suppliers that are in common between the two factories, amounting to just over 30% of the total yearly demand volume for both factories. For each factory, the common paper grades and suppliers with the other factory is also around 30% of its own total annual demand. Hence, the original base paper stock commonality is considered to be around 30%.

There are future plans to improve the Pune factory such that its technology and complexity would be able to match that of CAJ. As such, top management from CAJ has advised that stock commonality between CAJ and Pune would be expected to increase, with the Pune factory using CAJ as the benchmark for improvements. Hence, this analysis would test the resilience of the supply chain when Pune factory's base paper requirement shifts to become more similar to CAJ.

Currently, the suppliers Sweden A and Brazil both supply paper of the same grade. However, the paper from Brazil is cheaper than Sweden A. As such, there are plans in CAJ to gradually shift the usage of paper from Sweden A to Brazil instead. In addition, for risk pooling to be increased, one future target for

CAJ is to reduce the number of different paper grades used as paper grades are better streamlined to cater for both customers' and the supply chain's needs.

To simulate the future situation of increased base paper commonality and the shift of base paper supplier from Sweden A to Brazil, this research investigates two scenarios in which the overall base paper commonality between the two factories will be increased to 60% and 100% respectively.

Scenario 1 simulates a 60% base paper commonality by combining all the Brazil paper grades to a single paper grade and replacing all Sweden A paper grades by the single combined Brazil paper grade. This scenario is desirable as it greatly reduces the different types of paper grades handled by CAJ and Pune. The demand of paper required is kept the same. Table 5.10 and 5.11 shows the base paper demand including the paper grades and suppliers for CAJ and Pune based on Scenario 1. From the quantity of paper that is common between the two factories, highlighted in red, it can be seen that there is around 60% of the total annual paper demand common between CAJ and Pune.

Table 5.10 CAJ Yearly Demand for Scenario 1 (rolls)

Supplier	Paper Grade	Demand
USA	1612	8,233
USA	1617	1,971
Sweden B	1645	7,435
Sweden B	1647	14,973
Brazil	Combined	52,054
	Total:	84,738

Table 5.11 Pune Yearly Demand for Scenario 1 (rolls)

Supplier	Paper Grade	Demand
USA	1607	1,480
USA	1617	24
Sweden B	1122	407
Sweden B	1136	4,425
Brazil	Combined	2,293
	Total:	8,630

Scenario 2 represents the case of 100% base paper commonality: all paper grades are to be replaced by a single paper grade from the same supplier (Brazil) for the same total annual demand for each factory. Although this scenario is unfeasible and unrealistic in the near future, it can give insights to the supply chain's resilience as the stock commonality between Pune and CAJ and within each factory is optimized fully. This scenario is depicted by Tables 5.12 and 5.13 for both converting factories.

Table 5.12 CAJ Yearly Demand for Scenario 2 (rolls)

Supplier	Paper Grade	Demand
Brazil	Combined	84,738

Table 5.13 Pune Yearly Demand for Scenario 2 (rolls)

Supplier	Paper Grade	Demand
Brazil	Combined	8,630

In the following sections, the estimated average inventory and warehouse capacity of each locations will be discussed, followed by the costs discussion, consisting of the warehouse and shipping costs. Finally, the total cost of the supply chain will be discussed.

Average Inventory

Figure 5.4 depicts the estimated average inventory at the three locations for each of the three scenarios evaluated, as obtained by using Equation 4.7.

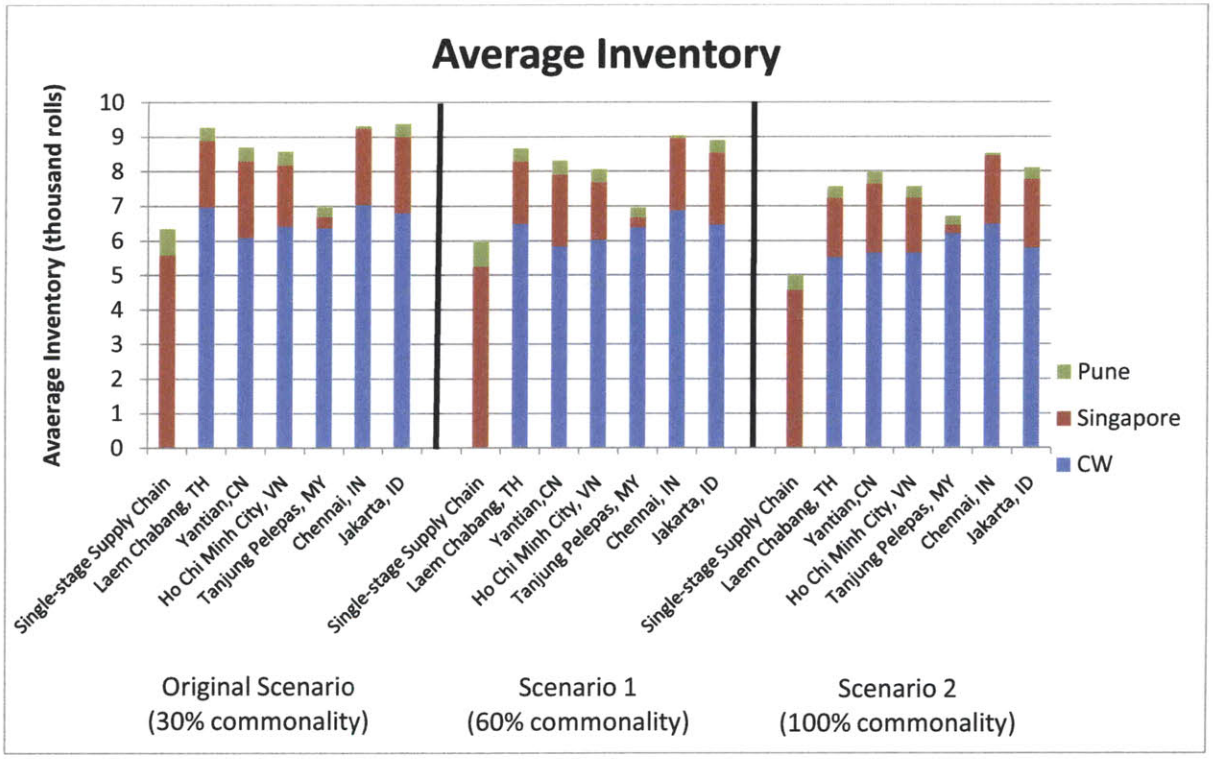


Figure 5.4 Average Inventory as Base Paper Commonality is Increased (thousand rolls)

The total average inventory required is the least for the single-stage supply chain in all three scenarios. This is reasonable since the total average inventory involves only the inventory at two local warehouses for the single-stage supply chain, whereas for the multi-stage supply chains, the total average inventory also involves the central warehouse inventory. Even as base paper commonality increases, this still applies; hence the single-stage supply chain requires the least average inventory in all three scenarios.

For each of the supply chains, as base paper commonality is increased, the total average inventory required is also decreased. This is because when base paper grades are combined, the combined forecast error variation, σ_{fe}, is less than the sum of forecast error variations for each individual paper grades. Hence, according to Equation 4.7, the average inventory required is also less. However, average inventory does not decrease at the same rate for all the supply chains since the shipping lead times, L, are different as depicted in Table 5.14.

Table 5.14 Shipping Lead Times (months)

To \ From	Sweden A	Brazil	Difference
Singapore, SG	0.95	0.85	-0.10
Pune, IN	1.45	1.18	-0.26
Laem Chabang, TH	1.25	0.99	-0.26
Yantian, CN	1.12	1.02	-0.10
Ho Chi Minh City, VN	1.22	1.02	-0.20
Tanjung Pelepas, MY	1.05	1.15	0.10
Chennai, IN	1.25	1.22	-0.03
Jakarta, ID	1.22	1.05	-0.16

Figure 5.5 plots the percentage decreases in total average inventory for each supply chain as base paper commonality is increased from 30% to 60% and from 60% to 100%.

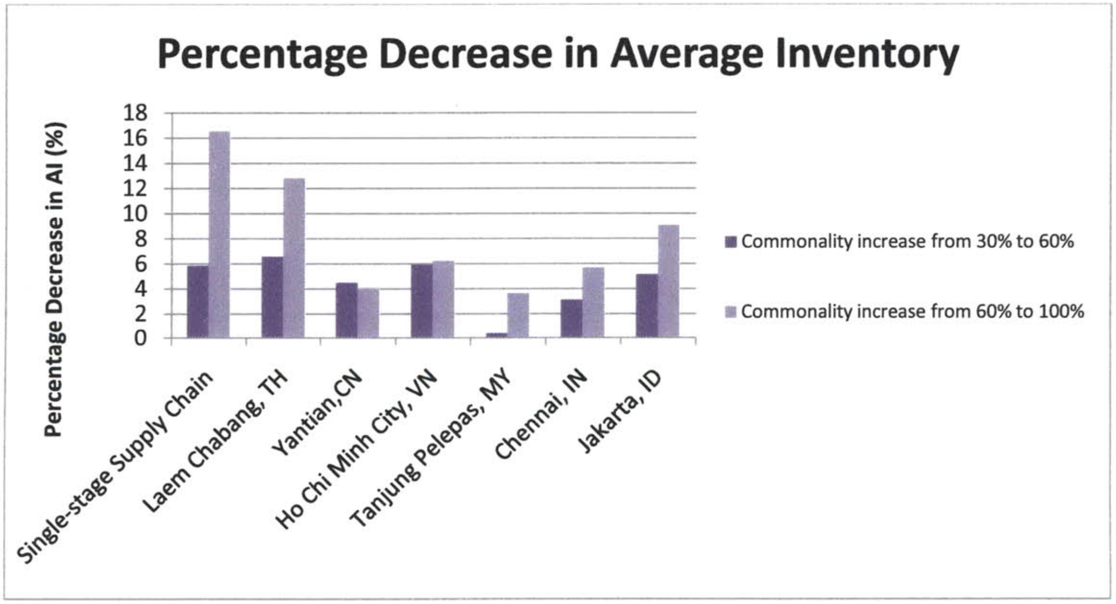


Figure 5.5 Percentage Decrease in Average Inventory as Base Paper Commonality is Increased (%)

As base paper commonality is increased from 30% to 60%, the multi-stage supply chain with central warehouse in Laem Chabang gave the largest percentage decrease in total average inventory. This is reasonable since the reduction in shipping lead times is the greatest for shipping to Laem Chabang and Pune as shown in Table 5.14.

However, as base paper commonality is increased from 60% to 100%, the single-stage supply chain has the greatest decrease in average inventory. When base paper commonality is 100%, the reduction in the total forecast error fluctuation for each converting factory is large, and so any risk pooling effect between the two converting factories may be overridden by the fact that multi-stage supply chains require additional warehouses and additional lead times from the central warehouse to the converting factories.

On the other hand, as base paper commonality is increased from 30% to 60% and from 60% to 100%, the multi-stage supply chain with central warehouse in Tanjung Pelepas has the least percentage decrease in average inventory. This could be because of the shipping lead times difference: shipping from Brazil instead of Sweden A actually requires a longer lead time as shown in Table 5.14.

Overall, it can be seen that multi-stage supply chains do not perform better than the single-stage supply chain in terms of average inventory reduction as base paper commonality is increased.

Warehouse Capacity

Figure 5.6 depicts the required warehouse capacity for the three locations for each of the three scenarios, according to Equation 4.6.

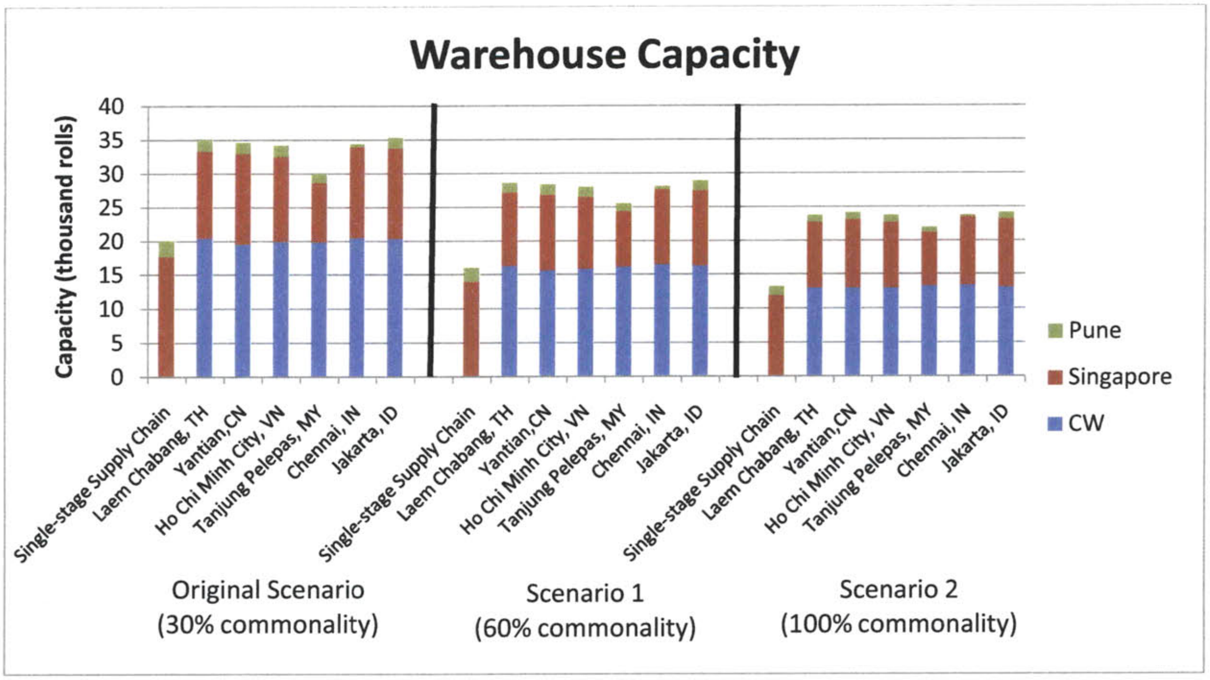


Figure 5.6 Warehouse Capacity as Base Paper Commonality is Increased (thousand rolls)

The effect of increased base paper commonality on the warehouse capacity is similar to that on the average inventory presented in Figure 5.4. This is reasonable since comparing Equations 4.6 and 4.7 shows that warehouse capacity is actually a linear function of average inventory, except that it involves an additional component of demand variation, which is correlated with forecast error variation. Hence, similar inference can be made about warehouse capacity when base paper commonality is increased: the results do not show that multi-stage supply chains perform better than the single-stage supply chain in terms of estimated warehouse capacity as base paper commonality is increased.

Warehouse Costs

Varying stock commonality changes the quantity of paper rolls being supplied from the various suppliers and hence affects σ_{df} and σ_{fe} as expressed Equation 4.6 and 4.7 with regards to the expected warehouse capacity and the average inventory. These two values hence influence the total warehouse costs of the supply chain according to Equations 4.8 to 4.14. Figure 5.7 depicts the total warehouse costs for the three scenarios for the different supply chains.

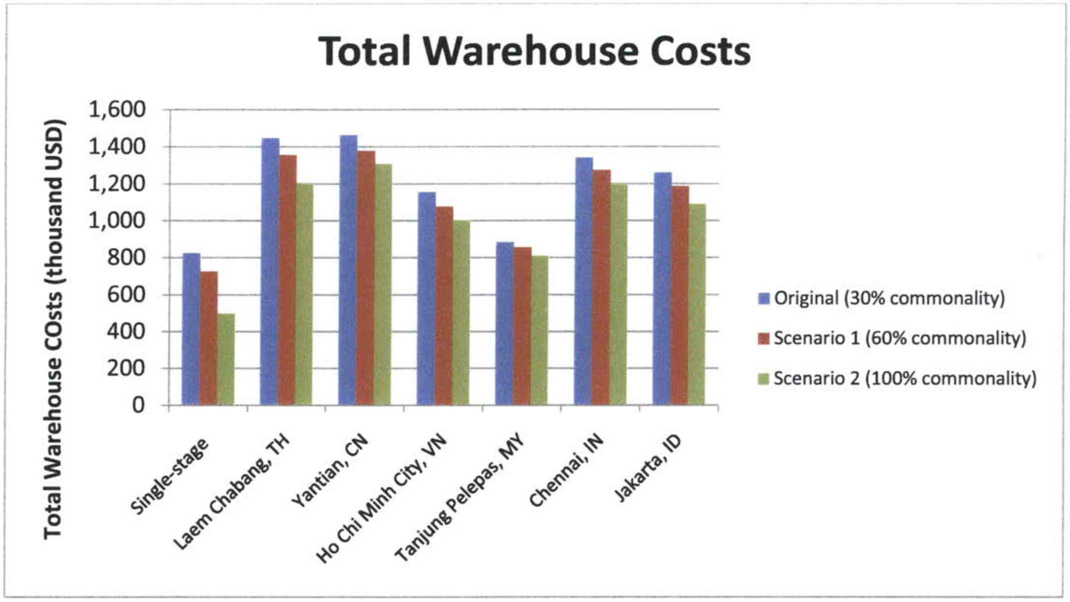


Figure 5.7 Total Warehouse Costs for Increased Base Paper Commonality (thousand USD)

From Figure 5.7, it can be seen that the single-stage supply chain has the lowest warehouse cost for all three scenarios. This is because the least amount of total average inventory and warehouse capacity is required among all the supply chains in all three scenarios, as concluded in the previous sections.

Further observing the columns for each central warehouse location separately, it can be seen that the rate of decrease in warehouse costs is the lowest for the multi-stage supply chain with a central warehouse in Tanjung Pelepas. On the contrary, looking at columns for the single-stage supply chain, warehouse costs decreases more as base paper commonality is increased, as compared to the other supply chains. This result is reasonable since as base paper commonality is increased, the decreases in average inventory and warehouse capacity are the smallest for the multi-stage supply chain with central warehouse in Tanjung Pelepas and the largest for the single-stage supply chain.

This implies that the single-stage supply chain is more resilient to a possible increase in stock commonality with regards to warehouse costs than the multi-stage supply chains since it is able to move to a more desirable state, ie. it gains cost benefits faster, as base paper commonality is increased.

Shipping Costs

In addition, increasing base paper commonality would also mean a change in point of export for the affected paper grades but not the actual quantity shipped since shipping cost is estimated according to Equation 4.3, which does not depend on σ_{df} and σ_{fe}. This implies an effect on the shipping costs involved for the supply chain. Figure 5.8 depicts the total shipping costs estimated for each of the three scenarios for the different supply chains. Total shipping costs for each supply chain include the shipping costs associated with all transportation segments involved.

Figure 5.8 Total Shipping Costs for Increased Base Paper Commonality (thousand USD)

From Figure 5.8, it can be seen that the single-stage supply chain and the multi-stage supply chain with a central warehouse in Tanjung Pelepas require the least shipping costs among all the supply chains in all three scenarios. The single-stage supply chain requires the least shipping costs naturally because the multi-stage supply chains require an additional secondary shipping cost. The multi-stage supply chain with central warehouse in Tanjung Pelepas require the least shipping cost among all the multi-stage supply chains because the unit shipping cost from Brazil to Tanjung Pelepas is the cheapest among all the central warehouse locations.

As the paper grades commonality increases, shipping costs would decease for all supply chains since shipping cost from Brazil is much cheaper than from Sweden A for all destination locations. However, the rate of decrease in shipping costs is not uniform for all the supply chains since the unit shipping costs are different for each central warehouse locations ie. those supply chains that have a larger cost difference between Sweden A and Brazil will see a larger shipping cost reduction as base paper commonality is increased. .

Looking at the decreases in the shipping costs as base paper commonality is increased from Figure 5.8, it can be seen that multi-stage supply chains do not guarantee higher costs benefits as compared to the single-stage supply chain. This is mainly because of the additional secondary shipping costs required for the multi-stage supply chains. Hence, multi-stage stage supply chains are not more resilient to an increase in paper grade commonality in terms of shipping costs.

Total Supply Chain Costs

Combining the warehouse and shipping costs, Figure 5.9 depicts the total costs of the supply chains for each of the three scenarios.

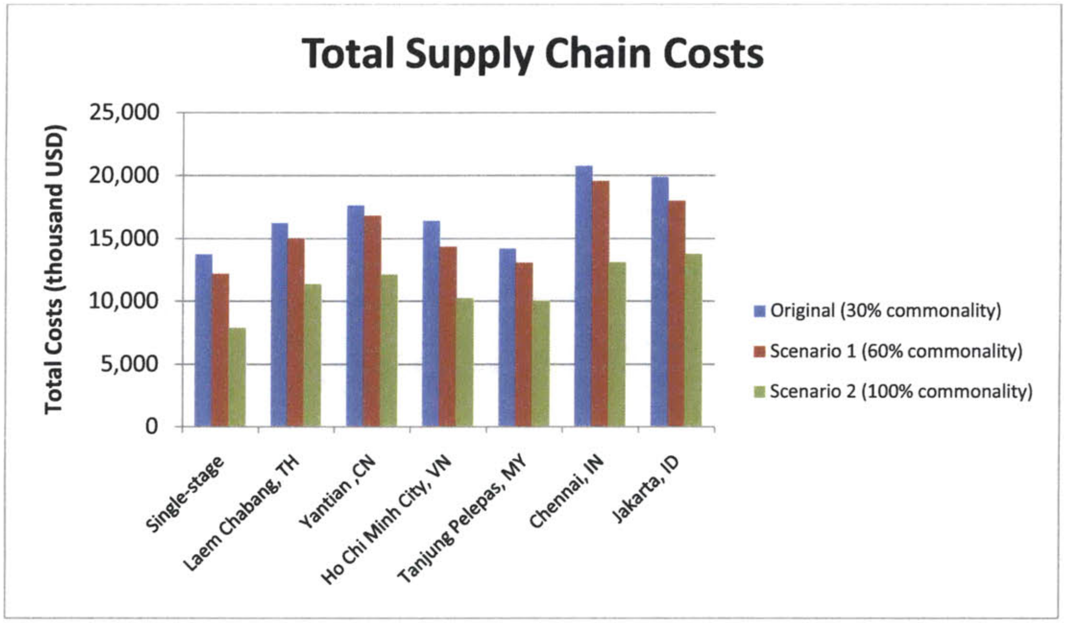


Figure 5.9 Total Costs for Increased Base Paper Commonality (thousand USD)

Due to the results of the warehouse and shipping costs, from Figure 5.9, it is not surprising that the single-stage supply chain costs the least for all three scenarios as compared to all the other options. Furthermore, the single-stage supply chain benefits the most as paper grade commonality is increased. Hence, multi-stage supply chains do not improve supply chain resilience with regards to increase in paper grade commonality.

5.2.2 Demand Forecast Accuracy Fluctuation

Demand forecast accuracy directly affects the amount of safety stock to be stored at each warehouse according to Equation 4.5. As CAJ's factory complexity increases, clients are more demanding and number and types of products offered are always on an increasing trend. As such, demand forecast accuracy may be affected negatively. Hence, this resilience analysis aims to discuss the effect of variation in demand forecast accuracy on the supply chain.

Demand forecast accuracy can be indicated by σ_{fe}, the standard deviation of the demand forecast error. From the monthly demand data for the years 2008 and 2009, it was found that variation in σ_{fe} ranges from -10% (ie. forecast errors decrease) to +100% (ie. forecast errors increase) for all paper grades. Hence, this range would be investigated to investigate on its impact on the supply chain. Since a positive variation implies a worse forecast and vice versa, this selected range is also reasonable as it provides a conservative estimate in view of forecast accuracy.

Since σ_{fe} is involved in the calculation of safety stock, variation in σ_{fe} affects warehouse costs. However, demand forecast accuracy is taken to have no effect on shipping costs since shipping costs were estimated using actual demand volume according to Equations 4.1 to 4.3.

Figure 5.10 depicts the total warehouse costs involved when demand forecast accuracy is varied, represented by σ_{fe} varying across a -10% to +100% change.

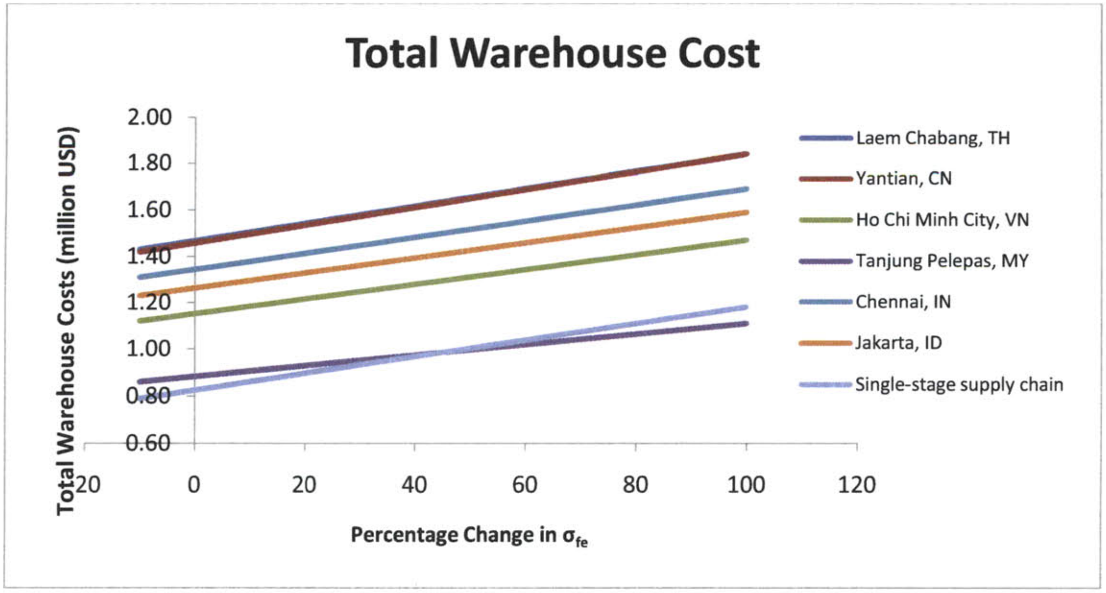


Figure 5.10 Total Warehouse Costs for σ_{fe} Variation (million USD)

From Figure 5.10, it is obvious that when σ_{fe} increases, warehouse costs increase for all supply chains. This is because an increase in σ_{fe} leads to an increase in safety stock required and hence increases warehouse costs, as shown in Equation 4.6. However, the rate of total warehouse cost increase is different for each supply chain since safety stock level is also dependent on other factors such as the shipping lead times and the original σ_{fe}'s. The rates of total warehouse costs increase are indicated by the slopes of each corresponding graph. Table 5.15 lists the slopes for each of the trend lines.

Table 5.15 Slopes of Graphs for Total Warehouse Costs (million USD/%)

	Slope
Laem Chabang, TH	0.0037
Yantian, CN	0.0037
Ho Chi Minh City, VN	0.0032
Tanjung Pelepas, MY	0.0023
Chennai, IN	0.0035
Jakarta, ID	0.0033
Single-stage supply chain	0.0035

The slopes for each of the trend lines are dependent on the combination of σ_{fe} and shipping lead times since all other factors in Equation 4.6 are constant. From Table 5.14, it can be seen that the multi-stage supply chains with central warehouses in Laem Chabang and Yantian have the highest rate of increase in warehouse costs as demand forecast accuracy decreases since their slopes have the largest value. This is due to these two locations having the largest overall combination of σ_{fe} and shipping lead times than other central warehouse locations since the shipping lead times to these two locations are the longest on average. These two supply chains are hence the least resilient to decreases in demand forecast accuracy. On the other hand, the multi-stage supply chain with a central warehouse in Tanjung Pelepas gives the smallest slope of 0.0023, indicating that its warehouse cost increases at the slowest rate among all the supply chains as demand forecast accuracy is decreased. This is because on average, the shipping lead times to Tanjung Pelepas are relatively shorter than the other central warehouse locations. In fact, this slope value is also significantly smaller than all the other supply chains. Hence, the multi-stage supply chain with a central warehouse in Tanjung Pelepas is the most resilient to decreases in demand forecast among all the supply chains.

Comparing the single-stage supply chain with others, its slope is larger than that of the multi-stage supply chains with central warehouses in Ho Chi Minh City, Tanjung Pelepas and Jakarta. This is reasonable due to the smaller σ_{fe}'s for each paper grade that is shared between Pune and Singapore for the shipping to the central warehouse. This implies that the single-stage supply chain is less resilient to decreases in demand forecast accuracy than these three supply chains.

The single-stage supply chain costs less than all the multi-stage supply chains as long as σ_{fe} is varied below +42%. At +42% change in σ_{fe}, the total warehouse costs for the supply chain with a central warehouse in Tanjung Pelepas falls below that of the single-stage supply chain. This implies that when forecast accuracy decreases such that σ_{fe} increases by more than 50%, the warehouse costs for the multi-stage supply chain with a central warehouse in Tanjung Pelepas becomes the lowest costing supply chain.

Since the graphs are linear, it should also be noted that should demand forecast accuracy increases, indicated by a decrease in σ_{fe}, total warehouse costs decreases for all supply chains. When that happens, a higher rate of decrease in warehouse costs as σ_{fe} decreases is desirable instead. Therefore, if demand forecast accuracy is expected to increase, the supply chains with the largest slopes are the most desirable instead.

However, in the near future, it is expected that CAJ and Pune converting factories will be faced with increased factory complexities and diversity in clientele base. Hence, demand forecast accuracy may decrease as well. Bearing that in mind, it is relevant to analyze the supply chains based on their prospects as demand forecast accuracy decreases.

Chapter 6 Conclusion and Recommendations

This project demonstrates that in most cases, using a multi-stage supply chain increases supply chain resilience as compared to the existing single-stage supply chain used for base paper supply at CAJ. When a disruption occurs, the response time and costs required to recover are decreased.

To evaluate supply chain resilience, a list of supply chain risks was generated based on the historical data of CAJ since 2003 and the expert opinions of CAJ management team. (8) This list includes the disruptions that occur most frequently and are the most costly to CAJ. However, unquantifiable disruptions were not discussed as their effects cannot be estimated accurately and reflected in the statistical model.

From the supply chain resilience analyses, it was found that multi-stage supply chains are more resilient to factors such as changes in exchange rates and demand forecast accuracy, demand surge, fuel price fluctuation, labor cost increase and shipping disruptions as compared to the single-stage supply chain. In these cases, lower additional supply chain cost is incurred in the event of disruptions as compared to the single-stage supply chain. However, when paper grade commonality is increased, multi-stage supply chains do not improve supply chain resilience. These seven scenarios were found representative of the most supply chain risks that CAJ faces.

Among all the multi-stage supply chains, the one with a central warehouse in Tanjung Pelepas is the most cost-effective and resilient in general. Using this multi-stage supply chain, it was found that the Singapore external warehouse would be unnecessary. The total costs savings per year amount to 60,000 USD if Company A adopts this multi-stage supply chain proposed.

In conclusion, Company A is recommended to adopt the multi-stage supply chain model for base paper supply, with a central warehouse in Tanjung Pelepas.

Chapter 7 Future Opportunities

The converting factories in Great China Cluster could be included in this multi-stage base paper supply chain, as they are within close proximity of the South and Southeast Asia Cluster. Moreover they share the same machineries as CAJ and there is a high commonality in base paper stocks used.

The proposed central warehouse could expand to include finished goods and other materials with long supplier lead time. This further reduces the inventory level at converting factory warehouses; and Company A further leverages on the cheaper inventory holding cost in the central warehouse location.

The detailed implementation plans need to be worked out. The possibility to collaborate with suppliers to take over the central warehouse ownership could be considered. By doing so, the suppliers are brought closer to the converting factories, local sourcing is achieved. Moreover, this further reduces the supply chain cost of Company A.

Appendix A – Explanation of Risk Pooling and Postponement

Risk Pooling

Risk pooling in supply chain terms typically refers to the notion of reducing risk for each individual entity by aggregating risk for all the entities as a whole.

Centralized systems are known to perform better than decentralized system due to risk pooling effects. (15) Consider the scenario whereby N regional markets each utilize its own warehouse, resulting in N warehouses. Each warehouse would have to hold inventory and safety stock to cater for the associated market's demand variation. An illustration of the situation is provided in Figure A.1 where W_i stands for warehouses that caters to market i and L is the supplier lead time involved.

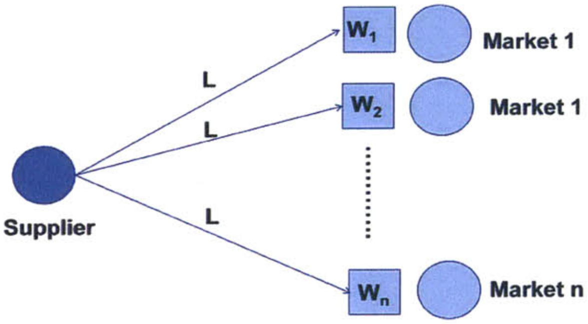


Figure A.1 Decentralized Supply Chain

Assuming a single-period and demand variation for each market is σ, the safety stock level at each warehouse is given by:

$$SS = Z\sigma$$

where Z is the normal probability that corresponds to a certain customer service level.

Hence, the total amount of safety stock required for the entire system is:

$$SS_{system} = Z\sigma N$$

If a single aggregate warehouse is used to cater for all N markets instead, demand variation is aggregated and hence the safety stock and inventory to be held at the aggregate warehouse is much less than the total sum of inventory required in the N warehouses in the previous scenario. Figure A.2 illustrates the centralized system with a single aggregate warehouse where W_{agg} refers to the aggregate warehouse and L_1 and L_2 refer to the relevant transport lead times.

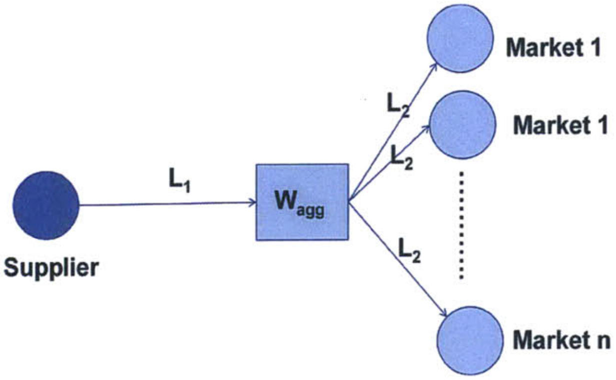


Figure A.2 Centralized Supply Chain

The demand standard deviation across all N markets is given by:

$$\sigma_{agg} = \sigma\sqrt{N}$$

Hence, the safety stock required at the aggregate warehouse is given by:

$$SS_{agg} = Z\sigma\sqrt{N}$$

Since $\sqrt{N} < N$, the total safety stock required is reduced significantly for the same customer service level.

Postponement

Postponement concept in supply chain terms refers to the strategic delay of decision making point to minimize risk. For instance, total customization of products ensures that products completely cater to the demand and hence there is minimized risk of overstocking. Postponement also provides risk pooling effects as it involves aggregation of demand variation associated with the original decision points. As in the example used in the previous section, the use of an aggregate warehouse to cater for all N supermarkets would allow the supermarkets to decide the type and quantity of items to order later than in the case of N warehouses.

Appendix B – Illustration of Multi-stage Supply Chain Inventory

Consider the case whereby inventory is used solely to cater for demand during lead times. In the single-stage decentralized supply chain scenario (Figure A.1), the total safety stock required is given by:

$$SS_{system} = Z\sigma N\sqrt{L}$$

In the case of the two-stage supply chain, assuming that $L = L1 + L2$, the safety stock required at each warehouse is given by:

$$SS_i = Z\sigma\sqrt{\frac{L1}{N} + L2}$$

Hence, the total safety stock required for the entire system (with N warehouses and one central warehouse as illustrated by Figure A.2) is given by:

$$SS_{system}{}' = Z\sigma(N+1)\sqrt{\frac{L1}{N} + L2}$$

Therefore, as N increases, a multi-stage system would require fewer inventories as compared to a single-stage system.

References

1. Company A Products and Services. *Company A International.* [Online] [Cited: June 20, 2009.]

2. *Presentation of CAJ Operation, 2008.* s.l. : Unpublished Material, 2008.

3. **Sheffi, Yossi.** *Resilience Reduces Risk.* 1, s.l. : The Official Magazine of the Logistics Institute, 2006, The Official Magazine of The Logistics Institute, Vol. 12, pp. 12-14.

4. **Martin Christopher, Helen Peck.** *Buidling the Resilient Supply Chain.* 2, s.l. : The International Journal of Logistics Management, 2004, The International Journal of Logistics Management, Vol. 15, pp. 1-14.

5. **Handfield, Rob.** *A Managerial Framework for Reducing the Impact of Disruptions to the Supply Chain.* 2007.

6. **Sheffi, Yossi.** *The Resilient Enterprise: Overcoming Vulnerability for Competitive Advantage.* s.l. : The MIT Press, 2005.

7. **Sheffi, Yossi.** *Building a Resilience Supply Chain.* 8, s.l. : Harvard Business School Publishing, 2005, Vol. 1.

8. **Company A Environment, Health and Safety Pillar.** *DPO Contingency Plan Reports.* s.l. : Unpublished Material, 2003 to 2008.

9. **Graves, Stephen.** *A Multi-Echelon Inventory Model with Fixed Reorder Interval.* 1989.

10. *The Labor Cost Report of 40 Developing Countries.* s.l. : Jassin-O'Rourke Group, 2009.

11. ASEAN Electricity Tariff Database. *ASEAN Centre for Energy.* [Online] [Cited: June 20, 2009.] www.aseanenergy.org.

12. **Vermorel, Joannès.** Get Safety Stock With Sales Forecasting. [Online] [Cited: June 4, 2009.] http://www.lokad.com/calculate-safety-stocks-with-sales-forecasting.ashx.

13. **Graves, Stephen.** 15.762 Supply Chain Planning. s.l. : Unpublished Material, Spring 2008.

14. World Economic Outlook Databases . *International Monetary Fund.* [Online] 2009. [Cited: July 20, 2009.] http://www.imf.org/external/ns/cs.aspx?id=28.

15. **D.S.Levi, P.Kaminsky, E.Simchi Levi.** *Designing and Managing the Supply Chain 2nd Edition.* s.l. : Mcgraw Hill International, 2002.