Optimizing Supply Chain Configuration Considering Supply Disruption

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Abstract: The purpose of this paper is to investigate a supplier-retailer supply chain that experiences disruptions in supplier during the planning horizon. There are multiple options to supply a raw material, to manufacture or assemble the product, and to transport the product to the customer. While determine what suppliers, parts, processes, and transportation modes to select at each stage in the supply chain, options disruption must be considered. In this paper, we show that changes to the original plan induced by a disruption may impose considerable deviation costs throughout the system. When the production plan and the supply chain coordination scheme are designed in a static manner, as is most often the case, both will have to be adjusted under a disruption scenario. Using dynamic policies, we derive conditions under which the supply chain can be coordinated so that the maximum potential profit is realized.

Key Words: Supply chain disruptions management, Scenario planning, Business continuity management, Supply disruption, Supply chain configuration, Dynamic Programming

1. Introduction

In 1905, ‘The Independent’ newspaper uses the word “Supply Chain” in the news article about wartime situation, which is the first use of the word “Supply Chain”. A supply chain is the application of processes and tools to ensure the optimal operation of a manufacturing and distribution supply chain. Supply chain activities transform natural resources, raw materials, and components into a finished product that is delivered to the end customer. It takes a while for people to realize a supply chain can be managed and optimized. To make the supply chain more optimal and flexible to utilize, a concept is introduced. In 1982, the term “supply chain management” first entered public domain. Supply chain management (SCM) is the management of the flow of goods. It includes the movement and storage of raw materials, work-in-process inventory, and finished goods from point of origin to point of consumption. Interconnected or interlinked networks, channels and node businesses are involved in the provision of products and services required by end customers in a supply chain. To be more specific, it includes the optimal placement (including safety stock) of inventory within the supply chain and minimizing operating costs. When we talk about and try to function the SCM, the mathematical modeling techniques are often involved. Most of these models are strategic in the sense that they optimize both safety stock levels and safety stock holding locations across the supply chain. There has been significant advancement in the safety stock optimization strategies in the last few decades. There are two main reasons for this. First, the past decades has seen a diffusion of supply chain knowledge throughout the organization. This diffusion of knowledge enables companies and managers to analyze and model supply chain. Second, more advanced tools including computer software are made that business users can use to actually perform the analysis.

1.1 Supply Chain Network

What is a supply chain network? And why are they so important for logistics and business managers? Supply chain networks allow us to look at the big picture; giving us a better understanding of the flow of materials and information. Often organizations focus only on their organization; what they produce or provide and not what the end customer receives. Looking at a supply chain network enables firms to look at the overall movement of materials/information from start to end, allowing organizations to see the value in creating partnerships; and the value in working together to ensure the best possible value is provided to the end-customer.

Supply chain networks describes the flow and movement of materials & information, by linking organizations together to serve the end-customer.

Network describes a more complex structure, where organizations can be cross-linked and there are two-way exchanges between them; chain describes a simpler, sequential set of links.

A supply chain network shows the links between organizations and how information and materials flow between these links. The more detailed the supply chain network the more complex and web like the network becomes. And to get a complete picture of an organizations supply chain network; information & material flow should be mapped. Inefficiency can then be located and removed.

- Material flow: Is the movement of goods from raw primary goods (such as Wool, Trees and Coal etc.) to complete goods (TVs, Radios and Computers) that are to be delivered to the final customer
- Information flow: Is the demand from the end-customer to preceding organizations in the network.

If a focal firm provides their suppliers with their sales data/forecasting demand information; their supplier will be able to
reduces costs (such as over production waste) and improve prices. In order to better serve end customers it is important to develop strong partnerships within your supply network which has a flow on effect to your end customers whether you are a manufacturer, distributor or retailer. Better communication will increase efficiency and productivity. Trust is the core ingredient to developing better communication and relationships. We will talk about this topic based on our assumption afterwards.

1.2 Demand Planning and Sales Forecasting

When we talk about SCM, it always comes as the problem such as who is responsible for forecasting the needs of the supply chain? Where does demand/usage begin? These are just two questions supply chain professionals might ask when focusing on the end user or consumer.

Without shared and readily available information on end user sales and demands, all other trading partners and those within a company not directly related to end user demand are working off “derived demand” from supply chain individual enterprise sales.

Within each echelon, several forecasts are alive but often without the consensus of all parties in a company, much less the entire supply chain. A company develops business forecasts and goals, as well as product/market forecasts, to achieve broad long-term financial development benchmarks. These forecasts provide a basis for resource planning, which ultimately leads to shorter-term, monthly forecasts aimed at deriving the “numbers” that drive earnings for the year.

Sales and operations planning next addresses resource loading to meet two to six month plans for capacity use and supply planning. Finally, short-term production forecasts are needed to set production, operations, and sales schedules.

For most businesses, a key question is whether they have consensus for forecasts to drive the company. Forecasts are often based on different assumptions and metrics dollars, units, and shipments, for example.

Extend this thinking to supply chain forecasting among trading partners, and a similar question arises. Is there consensus-based communication among trading partners? Often, forecasts and schedules are not shared, leading to the bullwhip effect that Dr. Jay Forrester and his MIT colleagues first discussed in the late 1950’s.

1.3 Sourcing Strategy

With the development of supply chain management and models, there are much more aspects of the chain that the companies and managers and business users need to concern. Among them are the single or dual sourcing and supply disruptions.

When setting up an inventory policy, first of all it has to be decided whether to source all of the replenishment from one supplier, or to divide the orders among dual sources. To dual source means to use two preferred suppliers to provide the same product or service. To single source means to use just one preferred supplier, despite there being multiple capable suppliers available. Both single sourcing and dual sourcing have their own advantages and disadvantages. The selection of suppliers heavily depends on the purchase price and the lead time characteristics of the suppliers. Often the choices are made either for an expensive and flexible (for example choices with short lead time) suppliers or cheap but rigid suppliers. Yet, it may be profitable to use two suppliers. Many purchasers decide to single or dual source based on certain assumptions.

1.4 Supply Disruption

Supply disruptions may be caused by diverse reasons including nature disasters, equipment failures or damaged facilities, during which a supplier cannot fulfill customer orders and then influence flows of the whole supply chain (Chen, H. Zhao and X. Zhao, 2012[4]). Supply chain disruption has been proven to have seriously negative impact on corporate profitability and shareholder value. In order to cope with uncertainty in inventory systems, buffers are held to protect service performance against unforeseen events. If distribution takes place at various stages, the problem becomes more complex because of additional opportunity of allocating buffers to the stage of the systems.

Every supply chain faces disruptions of various sorts. Recent examples of major disruptions are easy to bring to mind: Hurricanes Katrina and Rita in 2005 on the U.S. Gulf Coast crippled the nations oil refining capacity, destroyed large inventories of coffee and lumber, and forced the rerouting of bananas and other fresh produce. A strike at two General Motors parts plants in 1998 led to the shut-downs of 26 assembly plants, which ultimately resulted in a production loss of over 500,000 vehicles and an 809 million quarterly loss for the company. An eight-minute fire at a Philips semiconductor plant in 2001 brought one customer, Ericsson, to a virtual standstill while another, Nokia, weathered the disruption. Moreover, smaller-scale disruptions occur much more frequently. For example, Wal-Marts Emergency Operations Center receives a call virtually every day from a store or other facility with some sort of crisis. There is evidence that superior contingency planning can significantly mitigate the effect of a disruption. For example, Home Depots policy of planning for various types of disruptions based on geography helped it get 23 of its 33 stores within Katrinas impact zone open after one day and 29 after one week, and Wal-Marts stock prepositioning helped make it a model for post-hurricane recovery. Similarly, Nokia weathered the 2001 Phillips fire through superior planning and quick response, ultimately allowing it to capture a substantial portion of Ericsson’s market share.
2. Literature Reviews

Numerous papers address optimizing inventory and safety stock placement across the supply chain. Lin et al. (2000) and Billington et al. (2004) both present examples where multiechelon inventory theory was successfully distributed to a large set of business users within a company. In the work summarized in Billington et al. (2004), multiechelon inventory theory optimization tools have been transferred to more than 100 business users within Hewlett Packard, producing savings in excess of $150 million. But all those theories are derived from various papers from the past.

There are some approaches to safety stock placement. One of them is stochastic-service model approach. Lee and Billington (1993) develop a multi-echelon inventory model to reflect the decentralized supply chain structure they witnessed in Hewlett Packard’s DeskJet printer supply chain. Their goal was to produce a model that manufacturing and materials managers could use to evaluate different strategic decisions involved with the creation of a new-product supply chain. They model a supply chain as a collection of locations where each stage in the supply chain accepts as an exogenous input a service level target or a base stock policy. In the case where service level targets were inputs, the authors develop a single-stage base-stock calculation that, while approximate, is tractable. The single-stage base-stock level is a function of the replenishment lead-time as the stages, which includes the production lead-time. Lee and Billington show how to propagate the single-stage model to multiple stages. Ettl, Feigin, Lin and Yao (2000) also consider a supply chain context that is quite similar in spirit to the work of Lee and Billington (1993). The single-stage base-stock model in Ettl et al. (2000) makes a distinction between the nominal lead-time a stage quotes and the actual lead-time the stage experiences. The actual lead-time will exceed the nominal lead-time when there is a stock-out at a supplier. Glasserman and Tayur (1995) consider a context very similar to that of Lee and Billington (1993) and Ettl et al. (2000) but go on to introduce capacity limits into their multi-echelon model. The problem formulation of Glasserman and Tayur (1995) follows the framework of Clark and Scarf (1960) with the addition of capacity.

The guaranteed service-time approach traces its lineage back to the 1955 manuscript, which was later reprinted in 1988(Kimbball, 1988). In that paper, Kimball describes the mechanisms of single stage that operated a base-stock policy in the face of random but bounded demand. In particular, beyond the deterministic production time assumed at the stage, there is an incoming service time that represents the delivery time quoted from the stage’s supplier and an outgoing service time representing the delivery time the stage quotes to bounded. Simpson (1958) determined optimal safety stocks for a supply chain modelled as a serial network by using Kimball’s work as the building block, coupling adjacent stages together through the use of service time. This topic is based on similar assumption about the demand process and internal control policies for the supply chain.

Our work is related to Simpson (1958), and is also related to that of Inderfurth (1991,1993), who also build off Simpsons framework for optimizing safety stocks in a supply chain.  Inderfurth(1993) considers the optimization of safety stock costs and lead times for a single production process production multiple end items. The optimization captures the impact that the finished goods lead time have on the safety stock in the supply chain and the procedure for valuation of these effects that is presented in his paper can be applied to general multi-stage production systems with convergent or divergent structure and can be used as a helpful tool for assessing the cost/service performance of investments in reducing length and variability of lead-time in complex production systems. However, the model only considers changing the configuration at one stage in the supply chain and only considers safety stock costs. Also, our work is related to Ettl et al. (2000), which examines the determination of the optimal base-stock levels in a supply chain, and tries to do so in a way that is applicable to practice. Ettl et al. (2000) also develops performance evaluation models of a multi-stage inventory system, where the key challenge is how to approximate the replenishment lead-time within the supply chain. They then formulate and solve a non-linear optimization problem that minimizes the supply chain inventory costs subject to user-specified requirement on the customer service level. Because the models from Ettl et al. and its cited papers consider existing supply chains, there is already one option chosen at each stage. Therefore, the cost of goods sold (COGS) is set, as is the holding cost of the pipeline inventory, and these costs do not enter into the analysis. Geoffrion and Powers (1995) describe the evolution in the network design field which focuses on developing the optimal manufacturing and distribution network for a company’s entire product line. Network design focuses more on the two or more echelons in the supply chain for multiple products the supply chain configuration problem focus on a single product family at the supply chain level, allowing it to model all the echelons in the supply chain and to explicitly capture the impact of variability on the supply chain.

Graves and Willems(2000a) and Graves and Willems(2005) address the optimizing safety stock placement across the supply chain. The work of Graves and Willems (2000a) is similar in that we also assume base-stock policies and focus on minimizing the inventory requirements in a supply chain. The resulting models and algorithms are much different, though, due to different assumption about the demand process and different constraints on service levels within the supply chain.

The objective of our paper differs from the existing single-echelon and multi echelon models with multiple suppliers in two respects. First, we are not trying to model an optimal replenishment policy at an operational level of detail. We rather take a more strategic view and focus on the placement of safety stock across the network. Based on the empirical evidence provided in the introduction and for reasons of analytical tractability, we assume that a static allocation of the demand shall be assigned to each supplier in every period at a strategic planning level. The static allocation is treated as exogenous based on long-run time averages and company-specific policies, such as minimum production quantities for facilities.

Second, we consider larger networks with multiple suppliers and multiple echelons. To this end, we build on the Graves approach for multi echelon inventory optimization, which has been shown to be applicable to supply networks of larger sizes. So far, all the model of Graves and Willems contributions assume that each item is sourced from a single supplier. Therefore, in this paper, we investigate an supplier-retailer
supply chain that in which the suppliers may have the probability of disruptions during the planning horizon. The model under investigation is mostly related to Graves and Willems (2005). Yet, more aspects are concerned based on the origin model. Soley, Graves and Willems (2005) briefly outline an approximate approach of how to incorporate multiple suppliers in the final section of their paper. We extend the Graves and Willems (2005) model to dual sourcing strategy and also the disruption risk is added. The goals of this research are therefore:

- To extend and compare the single and dual sourcing.
- To analyse in both cases the effects of a suppliers disruption.
- To compare the model with some existed solutions related to supply chain

All those goals are applied to a multi-stage supply chain with a configuration optimization problematic.

The structure of this paper is shown as follow. In chapter 3, we introduce the assumptions. The model is formulates in chapter 4 and in chapter 5 we will show the dynamic programming method we use to solve the problem. Numerical cases are provided in chapter 5 and we conclude the paper in chapter 6.

3. Supply Chain Configuration

3.1 Multi-stage Network

We model a supply chain as a network where nodes, stages and arcs are included. Arcs denote that an upstream stage supplies a downstream stage. A stage can represent a major processing function in the supply chain. A stage might represent the procurement of a raw material, or the production of a component, or the manufacture of a sub-assembly, or the assembly and test of a finished good, or the transportation of a finished product from a central distribution center to a regional warehouse. Each stage is a potential location for holding a safety-stock inventory of the item processed at the stage. Nodes denote the options for the stage. An option at a stage is characterized by its lead time and added cost.

We assume that if a stage is connected to several upstream stages, then its production activity is an assembly requiring inputs from each of the upstream stages. A stage that is connected to multiple downstream stages is either a distribution node or a production activity that produces a common component for multiple internal customers.

3.2 Production Lead-Time

For each stage, we assume a known deterministic production lead time. When a stage reorders, the lead time is the time from when all of the inputs are available until production is completed and available to serve demand. The production lead time includes the waiting and processing time at the stage, plus any transportation time to put the item into inventory. For example, if stage \( k \) requires inputs from stage \( i \) and \( j \), then for a production request made at time \( t \), stage \( k \) completes the production at time \( t + T_k \). \( T_k \) represents the lead time of stage \( k \), provided that there are adequate supplies of \( i \) and \( j \) at time \( t \).

We assume that the lead time is not impacted by the size of the order; hence, we assume that there are no capacity constraints that limit production at a stage.

3.3 Inventory Policy

We assume that all stages operate with a periodic review base-stock replenishment policy with a common review period. For each period, each stage observes demand either from an external customer or from its downstream stage, and places orders on its suppliers to replenish the observed demand. No time delay in ordering need to be concerned, hence, in each period the ordering policy passes the external customer demand back up the supply chain so that all stages see the customer demand.

3.4 Demand Process

We assume that external demand occurs only at nodes that have no successors, which we term demand nodes or stages. For each demand node \( j \), we assume that the end-item demand comes from a stationary process for which the average demand per period is \( u_j \). Because an internal stage has only internal customers or successors; its demand at time \( t \) is the sum of the orders placed by its immediate successors. Since each stage orders according to a base-stock policy, the demand at internal stage \( i \) is \( d_i(t) = \sum_{(i,j)\in A} d_j(t) \), where \( d_j(t) \) denotes the realized demand at stage \( j \) in period \( t \) and \( A \) is the arc set for the network representation of the supply chain. For every arc \((i,j)\) belongs to \( A \), stage \( j \) orders an amount \( d_j(t) \) from upstream stage \( i \) in time period \( t \). The average demand rate for stage \( i \) is \( \mu_i = \sum_{(i,j)\in A} \mu_j \).

We assume that demand at each stage \( i \) is bounded by a maximum demand function \( D_i(t) \). We have \( D_i(t) \geq d_i(t - \tau + 1) + d_i(t - \tau + 2) + \ldots + d_i(t) \) We define \( D_i(0) = 0 \) and assume that \( D_i(t) \) is increasing and concave.

We presume that it is possible to establish a meaningful upper bound on demand over varying horizons for each end item, which means in the context of setting safety stocks: the safety stock is set to cover all demand realizations that fall within the upper bounds. If demand exceeds the upper bounds, then the safety stock will not be adequate by design. Given such case, the manager resorts to other tactics to handle the exceed demand. A manager indicates explicitly a preference for how demand variation should be handled what range is covered by safety stock and what range is handled by other actions or responses.

As an example, consider a typical assumption where demand for end item \( j \) is normally distributed each period and \( i.i.d. \), where mean \( \mu \) and standard deviation \( \sigma \). Therefore, a manager might specify the demand bounds at the demand node by \( D_j(t) = \mu_j + k\sigma \sqrt{T} \) where \( k \) represents the percentage of time that the safety stock covers the demand variation. The choice of \( k \) indicates how frequently the manager is willing to resort to other tactics to cover demand variability. For the rest of the paper, we will define \( D \) as shown above.

3.5 Guaranteed Service Time

We assume that each demand node \( j \) promises a guaranteed service time \( S_j^{\text{guar}} \). Which means, the customer demand at time \( t \), the demand at stage \( j \) in period \( t \), \( d_j(t) \), must be filled by time \( t + S_j^{\text{guar}} \). We do not explicitly model a trade-off between possible shortage costs and the costs for holding inventory. However, when we have asked the managers for their desired service level, we have found that managers seem more comfortable with the notion of 100% service for some range of demand; they accept the fact that if demand exceeds this range, they will have
shortages unless they can somehow expand the response capability of their supply chain. (Graves and Willems, 2000) Therefore, we assume that stage \( j \) provides 100% service for the specified service time: stage \( j \) delivers exactly \( d_j(t) \) to the customer at time \( t + s_{ij}^{out} \).

We assume that an internal stage \( i \) quotes the same outbound service time, \( S_{ij}^{out} \) to all its downstream customers. We also define \( S_{ij}^{in} \) as the inbound service time for stage \( i \), which is the time to receive all the required inputs from the suppliers when stage \( i \) reorderers. Also, we assume that for stages with one or more upstream adjacent stages, the inbound service time for stage \( i \) equals to the maximum of the service times of its suppliers.

![Fig. 2 Guaranteed Service Time](image)

3.6 Supply Chain Disruption Risk

We assume that some suppliers may have the probability to disrupt. When the disruption occurs, according to the contract, the demand stages decide to stick to the original suppliers instead of choosing another one. Hence, to avoid out of stock when demand arrives, the extra stock is needed. The extra stock will not be used unless the disruption occurs. We define the \( p_i \) as the probability that the selected node stage \( i \) does not work when order arrives. We assume the disrupted node needs certain period to recover, which, however, is not considered in this paper. That is, when disruption occurs, the suppliers must use the extra stock to make sure that the demand will be fulfilled and manage to recover in the certain period. Meanwhile, the demand stage only concern about if the demand arrives in time. The extra safety stock is as follows:

\[
S_{ij}^* = D_i(t_i)p_i^2
\]

where \( t_i \) is the lead time of the selected node at stage \( i \).

![Fig. 3 Figure of extra safety stock](image)

3.7 Inventory Model

The model considered is a multi-stage and multi-option model. The supply chain that is represented has several stages and several options at each stage. We assume the inventory system starts from time 0 with initial inventory \( I_j(0) \). Given our assumption, we can express the finished inventory at stage \( i \) options \( j \) at the end of period \( t \) as

\[
S_{ij}(t) = d_j(t - s_{ij}^{in} - l_{ij} - t - s_{ij}^{out})
\]

where \( l_{ij} \) is the lead time of the option \( j \) at stage \( i \) and \( S_{ij} \) is the base stock of the inventory at stage \( i \) option \( j \). In time period \( t \), stage \( i \) option \( j \) completes the replenishment of the demand observed in time period \( t - s_{ij}^{in} - l_{ij} \). For time period \( t - s_i - l_{ij} \), at the end of time period \( t \), the cumulative replenishment equals

\[
d(0, t - s_{ij}^{in} - l_{ij})
\]

In period \( t \), stage \( i \) option \( j \) fills the demand observed in time period \( t - s_{ij}^{out} \), from its inventory. By the end of period \( t \) the cumulative shipment equals \( d(0, t - s_{ij}^{out}) \). Hence, the inventory shortfall is the difference between the cumulative replenishment and the cumulative shipments \( d(t - s_{ij}^{in} - l_{ij}, t - s_{ij}^{out}) \). The on-hand inventory at stage \( i \) is the initial inventory or base stock minus the inventory shortfall. As given above, the base stock must be greater than the demand at stage \( i \) during the time interval \( t - s_{ij}^{in} - l_{ij} \).

We have defined a maximum demand function that will be used here. The precedent constraints can be written as

\[
S_{ij} = D_i(t_i) \quad \text{where} \quad l_{ij} = \max \{0, s_{ij}^{in} + l_{ij} - s_{ij}^{out}\}
\]

\[s_{ij}^{in} + l_{ij} - s_{ij}^{out}\] represents the net replenishment time of stage \( i \) option \( j \). In a word, the base stock equals the maximum possible demand over the net replenishment time. The net replenishment time for stage \( i \) is the replenishment time \( s_{ij}^{in} + l_{ij} \) minus its service time \( s_{ij}^{out} \). At any time \( t \), stage \( i \) has filled its customers’ demand through time \( t - s_{ij}^{out} \), but has only been replenishment for demand through time \( t - s_{ij}^{in} - l_{ij} \). The base stock must cover this time interval of exposure, namely the net replenishment time.

By using the function shown above, we determine the expected inventory level at stage \( i \) as

\[
E[I_i] = \sum_{j} (D_i(S_{ij}^{in} + l_{ij} - s_{ij}^{out})- (S_{ij}^{in} + l_{ij} - s_{ij}^{out})\mu_i) \quad \text{where} \quad \mu_i \text{ is the mean demand rate at stage } i \text{.}
\]

3.8 Pipeline Stock

In addition to the safety stock, we will account for the in-process or pipeline stock at the stage. We establish the work-in-process inventory at time \( t \) of stage \( i \) option \( j \).

\[
PS_{ij}(t) = d(t - s_{ij}^{in} - l_{ij}, t - s_{ij}^{out})
\]

Moreover, we have to set the average value of the work-in-process stock. We follow the assumption that the cost increase is linear function of the time spend at the stage. Hence, the average value of a unit of pipeline stock at stage \( i \) option \( j \) equals

\[
C_i = c_{ij}/2, \quad C_i \text{ represents the cumulative cost at stage } i \text{ and } c_{ij} \text{ represents the cost of stage } i \text{ option } j \text{.}
\]

We define the pipeline stock cost as

\[
PS_C = \alpha(C_i - c_{ij}/2l_{ij})
\]

where \( \alpha \) is the holding cost rate.

3.9 Cost of Goods Sold

The cost of goods sold (COGS) represents the total cost of all the units that are delivered to the customers during a company-defined period of time. We define the COGS as

\[
COGS = \beta c_{ij}
\]
where $\beta$ is a scalar converting the model’s underlying time unit into the company’s time interval of interest. Here we keep the models underlying time unit and thus $\beta = 1$ and we will use the same parameter for $\beta$ for the rest of this research.

4. Optimization Model

By using the equations and definitions we introduced above, we are now able to formulate the optimization model to find the optimal option and service time configuration for the entire supply chain.

$$P: \min \alpha[C_i(s^m_t + \ell_{ij} - s^{out}_j) - (s^m_t + \ell_{ij} - s^{out}_j)\mu_t + S S^t_j] + \alpha(C_i - \frac{1}{2}\ell_{ij}\mu_t + \beta\ell_{ij}\mu_t)$$

$$s^m_t \geq s^{out}_j \geq 0 \quad \text{for } i = 1, 2, \ldots, N, j : (j, i) \in A$$

$$s^m_t + t_i - s^{out}_i \geq 0 \quad \text{for } i = 1, 2, \ldots, N$$

There are three terms in the function. The first term represents stage $i$’s safety stock cost, which is a function of the stage’s net replenishment time extra safety stock and demand characterization and extra safety stock. The cumulative cost of the product plus extra safety stock at stage $i$ times the holding cost rate makes the holding cost. The second term represents the pipeline stock cost. The third term represents the COGS(cost of goods sold), which is the total cost of all the units that are delivered to customers during the company-defined interval of time. Constraints assures that the service time is feasible and replenishment time is non-negative.

The objective of the problem $P$ is to minimize the sum of the supply chain’s safety cost, pipeline cost and cost of goods sold. The service times and the selected options are the decision variables.

4.1 Dynamic Programming Formulation

In this section, we will describe how to solve the problem $P$ under the dynamic assumption.

We solve the configuration formula by decomposing the problem into $N$ stages, where $N$ is the number of nodes in the supply chain spanning tree. The dynamic program evaluates a functional equation for each node from $1$ to $N$. The solution of the configuration problem for the sub-graph $N_i$ will be the solution at each node. We define $E_{ij}$ as the supply chain cost for the sub-network with node set $N_i$ when node $j$ is chosen at stage $i$. The function of $E_{ij}$ is as follows

$$E_{ij}(s^m_t, c^i, c^j) = \alpha c_i[D_i(s^m_t + \ell_{ij} - s^{out}_j) - (s^m_t + \ell_{ij} - s^{out}_j)\mu_t + S S^t_j] + \alpha(C_i - \frac{1}{2}\ell_{ij}\mu_t + \beta\ell_{ij}\mu_t) + \sum_{k, d(A, k, c^l)} g(A, k, c^l) f_k(C_i, s^{out})$$

where $C_i = c^i + c_{ij}$. $c^i$ is the cumulative cost of all of the upstream adjacent stages of stage $i$. The first three terms represent the safety stock cost, the pipeline stock cost and COGS, respectively. The fourth terms represents the nodes that are downstream from node $i$. For each node $j$ that is a customer to node $i$, we include the minimum supply chain cost at stage $j$ as a function of stage $i$’s contribution to the cumulative cost at stage $j$ and the service time $i$ quotes $j$. The fifth terms represents the nodes that are upstream from node $i$. This term consists of the minimum supply chain cost for the configuration upstream from stage $i$ that is capable of producing a cumulative cost $c^i$. The incoming service time to stage $i$ is the maximum service time that is being quoted to stage $i$.

We evaluate $f_2(s^m_t, C_i, c^j)$ for the upstream from the current node as follows.

$$f_2(s^m_t, C_i, c^j) = \min E_{ij}(s^m_t, 0, C_i, c^j, s^{out})$$

We set several constraints on $f_2(s^m_t, C_i, c^j)$. First, we define $M_i \geq s^m_t \geq 0$, where $M_i$ is the maximum possible replenishment time for node $i$. As $M_i = \max\{\ell_{ij} : 1 \leq j < i\} + \max\{\ell_{ij} : (h, i)\}$ where $O_i$ is the number of candidate options at stage $i$. This constraint can make sure that the $s^m_t$ is positive and is not exceed the maximum inbound service time. Second we have the constraint $s^m_t + \ell_{ij} \geq s^{out}_i \geq 0$. This means the $s^{out}$ has to be positive and so has the replenishment time. Thirdly, we set the cumulative cost to be equal to a cost that can be produced. The upstream configuration of node $i$ can only produce an incoming cumulative cost comprised in a certain set of values.

4.2 Dynamic Program Algorithm

The network has built and now we two 2 important characteristics:

- Multiple sources. As we are studying assembly supply chains, there is several sourcing nodes.
- Different levels of the supply chain are pairwise dependent. The solutions at level $A + 1$ depends on the solutions at level $A$.

We respect the pairwise dependency of the levels and the logic of typical dynamic program. Thus the dynamic programming algorithm is used to solve the problem with $N$ stages as follows:

1. For $i = 1$ to $N-1$
   Evaluate $f_i(C_i, s^{out})$ for $s^{out} = 0, 1, \ldots, M_i$.
2. For $i = N$
   Evaluate $f_i(0, s^{out})$ for $s^{out} = 0, 1, \ldots, M_i$.
3. Minimize $f_N(0, s^{out})$ for $s^{out} = 0, 1, \ldots, M_N$ in order to find the value of optimal objective function. The standard backtracking procedure of the dynamic program can be used to find the optimal set of service times and options.

4.3 Sourcing Strategy Implementation

One of the key issues is to determine the number of suppliers. There are three frequently used sourcing policies and they are divided into:

- Single Sourcing
- Dual Sourcing
- Multiple Sourcing

Each policy has advantages and disadvantages. Dual sourcing is also a type of multiple sourcing. In this research, we will focus on single sourcing and dual sourcing.

Single Sourcing

With the single sourcing strategy, the buyer selects only one supplier from the supplier base. In other words, this supplier will be in charge of all the demand that from the buyer. There are reasons that buyer only chooses single supplier.

- increases involvement and better communication
- higher quality standards through continuous improvement
• better pricing through higher volumes
• build stronger and longer-term relationship
• single sources are typically open to negotiations. These vendors need business and they are often willing to accommodate business owners and modify contract terms in order to stay a step ahead of their competition

Even though single sourcing has some benefits, it also has weakness. Putting all the requirement on one supplier also means risky. The risk of production disruption for the buyer can be high in case of supply difficulties. For example, in 2000, Philips, the microchip supplier for Ericsson, suffered a fire so that it was disabled to produce and provide any chip to Ericsson for a few weeks. This factory was the only supplier of Ericsson. As we can expect that this accident had dramatic consequences on Ericsson at least $400 million in potential revenue lost. Another issue is that single sourcing is less flexibility as the supplier has a limited production capacity. Finally the purchase product might not be the cheapest because of the loyalty to the supplier and the potentially existing supplier changing costs.

Dual Sourcing
By using dual sourcing policy, the buyer or the business decisioner chooses two suppliers, one of which may dominate the others in terms of business, share, price, reliability, etc. In the event of disruption, such as the Thailand floods of 2011, the company envisions with the possible loss of one supplier, the second supplier could ramp up production to offset and minimize production disruption. However, normally applying dual sourcing will cost more than single sourcing and another issue with dual sourcing as well as multiple sourcing is to determine the procurement quantities to each supplier. Table 4.1 shows the benefits of the single sourcing and dual sourcing.

Sourcing Splitting Ratio
With dual sourcing policy, we have to set the sourcing ratio between the selected suppliers. There are various strategies available. We can choose either 50%-50% splitting or a strategy that a dominant supplier providing the main part of the necessary supply and a second supplier providing the rest. Therefore, we will follow the 80%-20% splitting. This ratio is set by Mr. Vilfredo Pareto, hence it is also called The Pareto Principle, which states that roughly 80% of the effects come from 20% of the causes. For example in business 80% of the sales come from 20% of the clients. This ratio is widely used in both business and industry area.

Select the Second Option of the Dual Sourcing
After choosing the best option at each node, we have to choose the second option in order to use dual sourcing. A few decision strategies are available here.

One would be choosing the second option at each node with the configuration program. That is, we first run the program normally. We obtain as solution the best options at each stage to minimize the total supply chain cost. As we want to find the second best options at each node, we erase the best options from the set of all available options. We return the configuration program. Therefore, as we removed the best options, we obtain the second best options for minimizing the total supply chain cost. In this case, we do not have to change the logical part of the program based on our definition in previous sections.

We only need to run the program twice to get the results. However, this method can not guarantee that the solution of the total supply chain is the overall most optimized options. Cost of first best options plus the cost of second best options does not mean it is most optimal for logical reasons.

The second decision policy is that we reform the options we have to make it fit the configuration model. To be more specific, we make new ‘options’ for each stage. For example, if a stage has 3 options available, we assign 80% of the cost for option 1 and 20% of the cost for option 2 so that we make a new ‘option 1’. Within this option, the new added cost would be 80% of the cost of old option 1 plus 20% of the cost of old option 2. What is more, the lead time of the new option 1 will be the longer lead time between the old option 1 and old option 2. By using the same method, we create new option 2 with 20% of the cost of old option 1 and 80% of the cost of old option 2, the lead time will be the longer one between the two options. Hence, after reforming the options, we have this stage with 2×3=6 new options instead of 3 options. The number of new options is growing exponentially. For two original options we have only 2 new options, for 3 original options we will have 6 new options, for 5 original options we will have 20 new options. Therefore one weakness of this method to model dual sourcing is that we will be considerably increasing the number of calculation with the number of original options. However, in the reality, when a buyer or a business decisioner has to choose new suppliers, they make a shortlist of potential suppliers and they will not consider a very large pool of suppliers. Therefore, as long as we do not have large number of options at supplier stages, this method is still one of the easiest and most reasonable way to use to fit the program and to calculate so as to get the optimal solutions for dual sourcing. We can utilize the configuration model with the new structure of the stages without changing the logical parts of the model. This method can guarantee that the total cost for the whole supply will be the most optimized globally. We only have to run the program once and do not need to erase or change anything from the set of available options.

Expected Cost of Single Sourcing & Dual sourcing
We run a simple example to test the two different sourcing strategies. The model we build is shown as figure 4.4. It is a supply chain modeled into a network as we introduced in previous parts. Table 4.2 and 4.3 show the added cost set and lead time set for each stage and each options, respectively.

| Stage | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|-------|---|---|---|---|---|---|---|---|---|
| Option 1 | 12 | 5 | 12 | 10 | 3 | 7 | 8 | 10 | 7 |
| Option 2 | 2 | 8 | 8 | 8 | 12 | 13 | 9 | 6 | 6 |
| Option 3 | 3 | 4 | 12 | 5 | 20 | 4 | 12 | 4 |

As for the expected total supply chain costs, the program calculated $234,296 for single sourcing and $391,477 for dual sourcing. The result show the dual has higher expected cost than single sourcing. This can be explained easily. In the case

| Stage | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|-------|---|---|---|---|---|---|---|---|---|
| Option 1 | 5 | 15 | 10 | 12 | 18 | 8 | 10 | 10 | 8 |
| Option 2 | 2 | 8 | 12 | 12 | 9 | 12 | 6 | 12 | 14 |
| Option 3 | 3 | 13 | 9 | 15 | 10 | 12 | 8 | 12 | 4 |
Table 1  List of the main benefits of single and dual sourcing

| Single Sourcing                        | Dual Sourcing                                      |
|----------------------------------------|----------------------------------------------------|
| Get better price through higher volumes | Supply security against disruption of one of the suppliers |
| Build longer and longer-term relationship | More supply flexibility to meet fluctuating demand |
| Preferential treatment when problem arise | Maintain competition between the suppliers |
| Increased involvement and better communication |                                             |

Fig. 4  Number of the remake new nodes

of single sourcing, 100% of the demand will be provided by the one best option at each stage. In the case of dual sourcing, one supplier supplies 80% of the whole demand and the not the best supplier supplies 20% of the demand. Therefore, part of the demand is supplied by a supplier with more expensive added cost or longer lead time or both. Hence, the overall cost increases. Thus having a higher cost or a longer lead time in the case of dual sourcing compared to the one in the case of single sourcing is coherent.

5. Simulation Program

This section we will presents the results from a computer manufacturer case.

The company employs a target costing approach (Ansari and Bell 1997) when designing new product supply chains. In brief, the market price for the product is set from outside the product design group. Two common reasons for this are (1) that the
product faces many competitors and the firm will be a price taker and (2) that another department within the company, for example, marketing, specifies the product’s selling price. Next, a gross margin for the product is specified, typically by senior management or corporate finance. The combination of the pre-specified selling price and the gross margin target dictates the product’s maximum unit cost. The product’s unit manufacturing cost (UMC) is the sum of the direct costs for the production of a single unit of product. Typical costs include raw materials, the processing cost at each stage, and transportation. The maximum unit cost acts as an overall budget for the product’s UMC.

From an organizational perspective, the supply chain development core team is composed of an early supply chain enabler and one or two representatives associated with each of the product’s major sub-assemblies. The early supply chain enabler is responsible for shepherding the product through the product development process. This individual is brought in during the early design phase and will stay with the project until it achieves volume production.

The core team will allocate the UMC budget across the major sub-assemblies. This is not an arbitrary process. The team will rely on a number of factors, including competitive analysis, past product history, future cost estimates, and value engineering. Once the sub-assembly budgets are set, the design teams for each sub-assembly are charged with producing a sub-assembly that can provide the functionality required subject to its budget constraint. Even if these groups incorporate multidisciplinary teams and concurrent engineering, they will still operate within their own budget constraints.

In much the same way that the UMC is allocated to the sub-assemblies, each sub-assembly group allocates its budget and decides what processes and components to use. There are numerous factors to consider when sourcing a component, some of which include functionality, price, vendor delivery history, vendor quality, and vendor flexibility. Because many of these factors are difficult to quantify, the team establishes a minimum threshold for each of the intangible factors. Suppliers that meet or exceed the thresholds are considered as candidates or options.

The company’s current practice is essentially to choose the lowest unit cost option from the set of options that satisfy the intangible factors. In the framework of the supply chain configuration problem, this corresponds to choosing the options with the lowest cost added at each stage, regardless of its lead time. While this is admittedly a heuristic, there are several reasons the company does this. First, as mentioned earlier, all other factors besides cost are difficult, if not impossible, to quantify. For example, the company only wants to do business with suppliers that have been certified. The certification process involves a rigorous review of the supplier’s quality practices, but given two certified suppliers, there is no mechanism to view one supplier’s quality as superior to the other. Second, the UMC of the product will dictate whether the business case to launch the product is successful. If the UMC were not low enough to meet the gross margin target, then the project will be terminated. Therefore, there is tremendous pressure to focus on the UMC at the expense of other considerations. Finally, the team that designs the supply chain is not the same team that has to manage the supply chain. Although choosing parts with long lead times might significantly increase the supply chain’s inventory requirements, this dynamic has not been explicitly considered during the new product’s business case analysis.

5.1 Notebook Computer Case Study

A notebook computer consists of three major sub-assemblies: the circuit boards, the LCD and the housing. The LCD will be purchased from an external vendor. The housing is a custom designed product that is also sourced from an external vendor. The components are purchased from external markets and assembled by contract manufacturers. The assembly process involves many steps, such as assembly of the components and quality testing and creates a generic notebook computer. The final assembly mainly serves two markets: US demand and Export demand.

Figure 5.1 shows the parameters set. Table 5.1 and Table 5.2 show the lead time set and added cost set for this case, respectively. Figure 5.2 shows the graphic depiction of the supply chain. The \( \mu \) of US demand is 75 while the \( \mu \) of Export demand is 50. The \( \sigma \) of US demand is 50 and the Export demand is 30. The company follows the annual holding cost rate at 45%. For each stage, there are several options available, with different lead time and added cost. The materials management group has to decide which one or two options will be selected as their choices for the options based on diverse purposes.

The two demand stages represents the delivery of product to the company’s retailer. They must provide immediate service to external customers, that is, their maximum service time for each of the demand stages equals zero. The company used the previous product’s sales and market forecasts when deciding the demand requirements for the supply chain. The demand bound will be estimated same as we introduce in previous part of this thesis.

| Stage | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|-------|---|---|---|---|---|---|---|---|---|----|
| Option 1 | 5 | 15 | 10 | 12 | 18 | 8 | 10 | 10 | 8 | 8 |
| Option 2 | 2 | 8 | 12 | 12 | 9 | 12 | 6 | 12 | 14 | 6 |
| Option 3 | 13 | 9 | 15 | 10 | 12 | 8 | 12 | 10 |   |   |

6. Supply chain configuration with and without disruptions

In this section, several cases will be shown based on the same example that is introduced in the previous section. We would
like to consider the supply chain configuration when the disruptions happen. We assume that the disruptions may happen at any stage, we will calculate the numerical case by setting a disruption probability.

Some solutions are available for the disruption case. First is that for all the stages that have probability to disruption, none of them keeps the extra safety stock. When the disruption happens, all the disrupted suppliers will be abandoned instantly and the buyer or the business decider will choose another supplier that works well at the same stage. Second is that for all the stages that have probability to disruption, each of them holds extra safety stock, once the disruption happens, the buyer will not change the suppliers and all the disrupted suppliers will meet the demand from the customers by using the extra safety stock, and we assume that all the disrupted suppliers will recovery in on unit time.

We first do the simulation for the case in which all the disrupted suppliers will be abandoned right after the disruptions happens. We set 5% disruption probability for stage 5. Which means, in the supply chain, there is 95% probability that the whole chain will work without troubles and 5% probability that the the best optimal option, which is responsible for 80% of the whole demand from its customer at stage LCD have to be changed.

We define the expected supply chain cost for this assumption shown as

\[ E_C = (1 - \rho_j)E_i + \rho_j E_i \]

where \( \rho_j \) means the disruption probability at stage \( i \) option \( j \), \( E_i,j \) means the whole supply chain cost without disruption at stage \( i \) option \( j \) and \( E_i \) represents the the supply chain cost with disruption.

Table 5.3 shows the new optimal solutions that after the disrupted supplier is changed, the optimal options of the supply chain using dual sourcing strategy. The total cost for this assumption is $437,418. This increases the cost of no disruption supply chain by 0.8%.

Notice that in the above case we assume that any suppliers that are under disruption will be abandoned. However, in the real world, the demand stage may not be able to change the suppliers in a short period. The suppliers must have extra safety stock to meet the demand in case the disruption happens. Therefore, under this condition, we have another result with the suppliers in a short period. The suppliers must have extra safety stock, once the disruption happens, the buyer will meet the demand from the customers by using the extra safety stock, and we assume that all the disrupted suppliers will recovery in on unit time.

We list the options selected by the algorithm we introduced. Consider all the potential expense if the buy or the business decider want to change the old suppliers, the total cost could be more than the assumption that not change the suppliers.

### 6.1 Different Solutions Approach

We will discuss about the different solution approaches in this section and we will compare the differences. We will draw some conclusions based on our observations from the case study. We set outbound service time of the first stage, which includes all the parts node, is 10. The guarantee service time for the second stage, which includes circuit board assembly and LCD, is 12. The third stage also quotes the guarantee service time as 12. The fourth stage which is node 8 quotes the guarantee service time as 10. All demand stages hold safety stock because they have to quote a zero service time.

#### Minimum UMC Heuristic

The minimum UMC heuristic chooses the lowest added cost options at each stage. If it follows the dual sourcing, it means the business decider will relocate 80% of the whole demand to the option with lowest cost and 20% of the demand to the option with the second lowest cost. The optimal safety stock policy is to relocate safety stocks across the supply chain, shown in Figure 5.3. Red cover means the safety stock is needed, while green cover means not necessary to have safety stock at this stage. As we can see, all demand stages hold safety stock because they must quote a service time of 0. The total cost for this solution is $437,576.

#### Minimum Lead-Time Heuristic

The minimum lead- time heuristic selects the single option at each stage with the shortest lead time if it follows single sourcing and selects the two shortest lead time if it follows dual sourcing.

Safety stock and pipeline stock costs are dramatically reduced due to the reduced lead times across the network. However, this comes a 11.13% increase to the products UMC with the total price $486,281. Shown as figure 5.4.

### Supply Chain Configuration

We list the options selected by the algorithm we introduced

| Stage | Option | Added Cost | Lead Time | Proportion |
|-------|--------|------------|-----------|------------|
| 1     | 3      | 4          | 13        | 80%        |
| 2     | 1      | 5          | 15        | 80%        |
| 3     | 5      | 15         | 80%       |
| 4     | 1      | 10         | 12        |
| 5     | 2      | 13         | 12        |
| 6     | 3      | 4          | 12        |
| 7     | 2      | 6          | 12        |
| 8     | 1      | 10         | 10        |
| 9     | 1      | 12         | 8         |
| 10    | 2      | 10         | 8         |
| 11    | 3      | 9          | 10        | 20%        |
in the previous part of this research in Table 5.4. The optimal safety stock policy is represented in figure 5.5.

The optimal solution is one where the upstream assemblies are balanced. Which means, the second stage, where the LCD and Circuit Board are involved, will quote a relatively mean service of the three nodes of this at this stage. This configuration has obvious lower cost than any of the previous solutions.

The optimal solution does not include some choices that one might have considered obvious. For example, the business decider may pay more to ask the suppliers to reduce the lead time. Therefore, we have total cost $429,488, which is the most optimal solutions among all the three approaches.

### Insights Drawn From the Case Study

From this case study, we make several observations regrading supply chain configuration.

**Observation 1.** In the supply chain configuration optimization, downstream stages are more likely to use high-cost options and upstream stages are more likely to use low-cost options.

Choosing a high-cost option at a downstream stage increases COGS but has only a local impact on pipeline stock cost. In contrast, choosing a high-cost option at an upstream stage increases not only COGS but also the safety and pipeline cost of all of its downstream stages.

**Observation 2.** The benefits of supply chain configuration increase with longer lead times at down-stream stages.

Downstream stages have higher holding costs than upstream stages. A lead-time reduction may cause great holding cost sav-

ings in pipeline and safety stock at a downstream stage relative to an upstream stage.

**Observation 3.** More echelons increase the benefits of supply chain configuration.

More echelons provide a greater opportunity to offset an increase in COGS with a decrease in inventory costs because there will be more configuration options available from which to choose.

Moreover, we compare the the cost of different approaches under different holding cost rate set. In the figure we see how the supply chain configuration moves close to other approaches, as a function of the holding cost rate, shown as Figure 5.6.

| Stage | Option | Added Cost | Lead Time | Proportion |
|-------|--------|------------|-----------|------------|
| 1     | 3      | 4          | 13        | 80%        |
| 2     | 1      | 5          | 15        | 80%        |
| 3     | 3      | 5          | 15        | 80%        |
| 4     | 1      | 10         | 12        | 80%        |
| 5     | 1      | 13         | 12        | 80%        |
| 6     | 3      | 4          | 12        | 80%        |
| 7     | 2      | 6          | 12        | 80%        |
| 8     | 2      | 6          | 14        | 80%        |
| 9     | 1      | 7          | 8         | 80%        |
| 10    | 3      | 9          | 10        | 80%        |

**Local optimum VS global optimum**

We have showed the different solution approaches such as minimum UMC heuristic and minimum lead time heuristic. But actually there is another heuristic that is possible.

In the reality, each stage of a supply chain can decide to choose the option that will minimize its inventory cost and COGS. That is, the option that is chosen at each stage is the option that minimizes the local supply chain cost, thus this approach gives a local optimal configuration. Sometimes, the buyers at each node may not be able or willing to know what the choices of buyers from other nodes are, therefore, for them, the easiest way to order is just to choose the optimal options for themselves, hence we think this local optimum solution is still a interesting topic.
to discuss about.

On the opposite, the supply chain configuration algorithm gives the options that minimize the total supply chain cost so the solution is a global optimal configuration. Logically speaking, the approach that should give the lowest total supply chain cost should be the global optimal solution.

We define the options as the option that minimizes the cost at the node. Which means, it is the option that incur the lowest inventory stock cost and COGS. In the previous section we define $f_i(s, x, C, x^{out})$ to represent the cost incurred at each node. Therefore here we will find the options that minimize the $f_i$.

To proceed with all those calculation, we have created another algorithm that dedicated to finding the local optimums. Unlike the supply chain configuration we introduced in previous sections, this algorithm only choose the optimal options for each node. To be more specific, we will not consider either the cost from the upstream nodes of each node or the downstream nodes of each node, which is $g_k$ and $f_k$ in the supply chain network formulation shown in chapter 4, respectively.

We use the same input that is in the notebook case study. Table 5.5 shows the solutions for this particular case. As we can say, all the solutions of stages with no adjacent upstream stages stay as same as the supply chain configuration optimization. However, the node final assembly and the node export demand change the plan. Moreover, this approach will contribute a total cost of supply chain as $544,056$, which raises the total cost by $114,568$. Our intuition is confirmed.

The reason why some downstream stages change the option while some upstream nodes remain unchanged is that for the nodes with no no adjacent upstream nodes, the solution they choose from the supply chain configuration optimization approach is already the optimal and since no other parameter needs to be concern every time those node being calculated. However, for the nodes with adjacent nodes especially those downstream nodes such as assembly and demand, there are more parameters that stream from the upstream involved every time they being calculated, therefore the solutions for them might not be unchangeable and sure enough some of them change the optimal options to meet the local optimum.

7. Conclusion and Further Research

In this thesis, we introduce and extend a model for configuring new supply chains. The model is modified as a supply chain network whose nodes represent functional requirement in the supply chain. For each node, there are multiple options that can satisfy the functional requirement. The optimal supply chain configuration minimizes the cost of the supply chain, in which the safety stock cost, pipeline cost and COGS are involved.

We develop the model so that it fits the dual sourcing strategy. Unlike the single sourcing strategy, dual sourcing makes sure that the business decision makers will choose two suppliers instead of one at each stage. We use the 80-20 rules to relocate the demand to each stage, which is that for the two chose suppliers at each stage, one of them contributes 80% of the whole demand and the other one denotes 20%. Based on such assumption, we redefine the lead time and cost for each new combination at demand stages. What is more, we consider the disruption probability and add it to the model. By setting the dynamic algorithm to fit the model, we manage to calculate the cost of supply chain using the software program. We use Python to calculate the models and to get the results instead of calculating by hand. We compare several different supply chain policies and we have some observations and assumptions based on the results. We also state the differences between supply chain with disruption and without disruption.

This research raises several relevant questions for the further consideration. First, we assume that when disruption happens, the extra safety stock will be used to meet the demand instantly. However, there is another possibility that no extra safety stock will be needed, instead, the suppliers who suffer the disruption need a certain period of time to recovery from the disruption, during this period, the demand will do nothing but wait until everything back to normal. Hence, it would be interest to do the research of supply chain cost consider the time delay. Secondly, so far all we have done on this research all are based on the deterministic assumption, however, in the real world, stochastic cases also exist. It would be necessarily useful to build stochastic structures and evaluate the performance of supply chain. Last but not least, we only consider one stage with disruption in our simulation cases. Actually, in the real world cases, some suppliers could be sensitive, therefore they may hold the extra safety stock all the time even though the disruption never happens to them before, and some suppliers may be quite careless that even though it is possible for them to disrupt, they still do not keep any extra safety stock. What the total cost would be and what the differences between would be? Those are all interesting topics to discuss about for the next steps.

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