# OPTIMAL DESIGN OF SUPPLY CHAIN NETWORK: A CASE STUDY IN TOOTHBRUSH INDUSTRY

**BY**

**TAI PHAM**

**A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF**
**THE REQUIREMENTS FOR THE DEGREE OF MASTER OF**
**ENGINEERING (LOGISTICS AND SUPPLY CHAIN SYSTEMS**
**ENGINEERING)**
**SIRINDHORN INTERNATIONAL INSTITUTE OF TECHNOLOGY**
**THAMMASAT UNIVERSITY**
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A Thesis Presented

By
TAI PHAM

Submitted to
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# Abstract

OPTIMAL DESIGN OF SUPPLY CHAIN NETWORK: A CASE STUDY IN TOOTHBRUSH INDUSTRY

by

TAI PHAM

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Supply chain management has long been a compass for every successful business. Its long-term decision plays an important role in shaping the supply chain structure, or design of supply chain network, which significantly affects supply chain performance for prolong period. Since each industry has a unique set of characteristics which evidently drive the design of supply chain network, a number of various models have been formulated to meet the needs of such business contexts. Even though many models have been proposed for manufacturing industry context, most of them are based on the facility location model. The model tends to lead the supply chain network design model to be complicated. Therefore, the purpose of this research is to propose an alternative approach to formulate manufacturing network design problem. Features, such as multi-echelon, multi-commodity, product's structure, and manufacturing process, are taken into consideration as characteristics of the studied environment. Moreover, uncertainty factors are also integrated to the model by employing possibilistic theory. Eventually in addition to the methodology, a case study in a consumer product firm is used to demonstrate applicability of the suggested method. Two models, deterministic and fuzzy, has been explored in the study and both of them has demonstrated the validity of the proposed formulation method. Moreover, it is shown that the fuzzy model outperforms its deterministic counterpart in term of cost effectiveness.

**Keywords**: strategic supply chain planning, supply chain network design, network flow, production network, fuzzy programming, optimization, mixed-integer linear programming (MILP), uncertainty

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# Chapter 1

# Introduction

Under tough pressure of competition on global playground and high expectation from customer nowadays, businesses are pushed to pay more investment and focus on managing their supply chains effectively. A supply chain is a network of facilities and streams of commodities that flow among them. Those facilities are composed of suppliers, manufacturing plants, warehouses, distribution centers, and retail premises, while commodities comprise raw materials, work-in-process, and finished goods. Supply chain management (SCM) defined by Simchi-Levi (2007) as "a set of approaches utilized to efficiently integrate suppliers, manufacturers, warehouses, and stores, so that merchandise is produced and distributed at the right quantities, to the right locations, and the right time, in order to minimize systemwide costs while satisfying service level requirements". By this definition, it is indicated that SCM involves activities at many levels ranging from strategic through tactical to operational within a business. Chopra and Meindl (2007) described that strategic level aims at determining the optimal structure or design of supply chain network. The addressed decisions are about number, location, and size of warehouses and/or plants as well as the connections among them. Both Watson, Lewis, Cacioppi, and Jayaraman (2012) and Simchi-Levi (2007) demonstrated that such decisions at this level have a high impact on supply chain performance since they are expensive and difficult to be changed. It is discussed that roughly 80% of supply chain expenses are trapped in its facilities which is equivalent to that of the cost kept in a product design. As a result, strategic network planning – or supply chain network design (SCND) – has drawn much attention from management and has required extensive research.

In different industrial contexts, Vila, Martel, and Beauregard (2006) argued that nature of SCND problem has changed significantly. In retail or distribution context, the main concerns are the movement of products and locations of facilities because flows from origin to destination are identical. On the other hand, the stream is no longer uniform in the context of manufacturing because most of the products are not simply collected and transported. Instead, there are series of transformation activities which are performed among production facilities to convert materials into a particular product. Each product has its own recipe of materials and set of desired production stages. The recipe of materials involves in supply side sourcing decisions, while the set of desired production stages associates with capital decisions and configuration of the network. Therefore, it is necessary to address impacts from not only movement of goods and locations but production processes and product architectures in manufacturing-related-network design problem.

Melo, Nickel, and Saldanha da Gama (2009) accomplished a thorough review on development of optimization models which support supply chain management. They revealed many studies that are related to manufacturing context. Most of those research works had been developed and formulated based on classical facility location models which are centered on facility decision. However, this approach makes the models more complicated. This has provided a motivation to elaborate a novel approach which will generate a more simplified model. In addition to the approach, another obstacle which is very common to every strategic decision is that the future is always unpredictable. Therefore, taking uncertainty into account is inevitable.

The purpose of the thesis is to introduce a new method to formulate the supply chain network design problem in manufacturing industry. The problem encompasses two decisions which are related to network structure and configuration. The first decision is to determine number of locations, transportation links, supply sourcing, and demand allocation, while the second one aims at identifying production process network within each selected location. In addition, features, such as multi-echelon, multi-commodity, product’s structure, and manufacturing process, are considered to capture characteristics of manufacturing business. Besides, uncertainty is also accounted for. Although probability theory has become popular in SCND by the mean called stochastic programming, the drawback is that this method depends heavily on past collected data to describe the future situation which might not actually be realized accordingly. As a result, instead of using probability theory, possiblistic theory is proposed to be used as a mean to dictate the future. An advantage of this theory is that it does not require extensive efforts to collect data. Instead, experts’ experience and management references are the inputs. However, since these inputs sometimes may not yield a good result, it is reasonable to perform post hoc analysis to improve the result intuitively by alternative methods. Finally, a case study of a toothbrush producer has been employed to demonstrate the applicability of this method on modelling network design problem in manufacturing industries.

The remaining of the thesis is organized as follows. Related literature is reviewed in Chapter 2. Conceptual design, problem formulation, and experimental design are presented in Chapter 3. The implementation of the experiment and its results are discussed in Chapter 4. Finally, the conclusion from the research has been drawn in Chapter 5.

# Chapter 2

# Literature Review

Supply chain network is defined as a set of facilities such as suppliers, plants, distribution centers, and customers. All of them are linked by transportation routes carrying raw material, semi-finished goods, and finished products. With increasing competition and market uncertainty on global basis, supply chain management (SCM) is getting more and more attention from many companies around the world as a key competitive capability. Based on the length of time horizon, SCM decision levels has been divided into strategic, tactical, and operational levels. Strategic decisions have a long term effect on supply chain performance, since they involve determining number, location and capacities of various types of facilities, or the flow of material in the system. Such decisions require a large sum of capital investment, which is difficult to recover once it is allocated. Also, those facilities tend to stay in operation for extended periods of time from now which makes them vulnerable to be affected by external factors. Any change which occurs during their life-time may turn a selected site from a good choice to an undesirable one. Consequently, strategic supply chain planning has become the most important part of SCM. It is the reason that this topic gains much attention from academic researchers. The intention of this chapter is to review studies in supply chain network design, especially in manufacturing area. At first, the relationship between strategic SCM problem and facility location problem (FLP) has been outlined. Secondly, basic extensions of FLP which were conducted to handle the strategic SCM problem are examined. After that, special extensions for manufacturing sector have been discussed. Finally, conclusion is drawn from the review to provide supports for the proposed research.

Currently, terms such as *network design*, and *supply chain network design* (SCND) are often used, in most cases, as strategic SCM. As SCND is concerned with optimal number, location, and size of warehouses and/or plants, it is apparent to recognize the connection between network design and FLP in which locations are considered to be selected from a limited set of potential candidates in order to satisfy customers. If it is the case that setup cost is not different among all sites, the problem is defined as p-median problem with the objective of minimizing total travel distance or cost of meeting customers' requirements. Otherwise, it may be considered as uncapacited facility location problem (UFLP). On the other hand, when capacity is known in advance, UFLP is renamed as capacitated facility location problem (CFLP). All above models have shared common characteristics that are single period, deterministic parameters, single product, mono type of facility, and location-allocation decisions. The FLP has provided a solid foundation for developing SCND models. However, the FLP models contain only a fundamental decision, location-allocation, and features which do not reflect complicated relationship involving different kinds of decision and advanced characteristics. Therefore, many extensions should be included to cope with complicated circumstances.

In practical networks as defined above, there exist many types of facility which play various roles in the network such as supplier, plant, and warehouse. Each facility has been grouped into sets, called layers or echelons, according to its specific function. Those facilities are connected together in order to transport goods from origins to destinations. Multi-echelon facilities appeared in Arntzen, Brown, Harrison, and Trafton (1995), Karabakal, Günal, and Ritchie (2000), Tsiakis, Shah, and Pantelides (2001), Vidal and Goetschalckx (2001), Jang, Jang, Chang, and Park (2002), Wouda, van Beek, van der Vorst, and Tacke (2002), Yan, Yu, and Cheng (2003), Kouvelis and Rosenblatt (2005), Wilhelm *et al.* (2005), Cordeau, Pasin, and Solomon (2006), Melo, Nickel, and Saldanha da Gama (2006), Ommeren, Bumb, and Sleptchenko (2006), Vila *et al.* (2006), and A. S. Zadeh, Sahraeian, and Homayouni (2014). In addition, there are many studies considering multi-products in their supply chains. Since strategic planning spans for long time horizon, there are motivations to introduce multi-periods or stochastic components to represent either predictable changes over time or uncertainty associated with parameters, respectively. Fleischmann, Ferber, and Henrich (2006), Melo *et al.* (2006), Ulstein, Christiansen, Grønhaug, Magnussen, and Solomon (2006), Vila *et al.* (2006), and A. S. Zadeh *et al.* (2014) focused on uncertainty elements, while multi-time-segments was taken into account by Arntzen *et al.* (1995), Tsiakis *et al.* (2001) and Ommeren *et al.* (2006).

Furthermore, a supply chain does not simply send the same product from one end, suppliers, to the other end, customers. The raw materials have to undergo transforming processes to become finished goods before being delivered to customers. It is necessary to include product's Bill of Materials (BOM) to represent the impacts of product's ingredients and production processes to supply chain on overall product cost, ingredient sourcing constraints, finished-goods manufacturing, overall throughput capacity, and key capital decisions. Arntzen *et al.* (1995), Tsiakis *et al.* (2001), Vidal and Goetschalckx (2001), Jang *et al.* (2002), Wouda *et al.* (2002), Yan *et al.* (2003), Kouvelis and Rosenblatt (2005), Wilhelm *et al.* (2005), Cordeau *et al.* (2006), Fleischmann *et al.* (2006), Vila *et al.* (2006), and A. S. Zadeh *et al.* (2014) took this issue into consideration.

The most important extension is the inclusion of typical supply chain decisions, which are capacity, production, and procurement. In traditional location problem, capacity is usually assumed either unlimited or fixed amount. However, this assumption is not held in contemporary supply chain settings because capacity is influenced by several constraints such as budget, technology and so on. Therefore, many studies have included this decision. Melo *et al.* (2006) and Vila *et al.* (2006) concurrently considered capacity reduction and expansion over planning horizon. Melo *et al.* (2006), Ommeren *et al.* (2006), Ulstein *et al.* (2006), and Vila *et al.* (2006) addressed setting up modules which are pre-defined sizing. Combining capacity with choice of equipment and/or technology has been handled by Arntzen *et al.* (1995), Mazzola and Neebe (1999), Karabakal *et al.* (2000), Verter and Dasci (2002), Ulstein *et al.* (2006), and Vila *et al.* (2006). The participation of multi-commodities feature in FLP has led to the need of determining which product should be produced in which plant with which quantity. It is the incentive to include production decision to deal with that requirement. Incorporating BOM into facility location has created a strong stimulus to combine procurement into the models. Such decision deals with selecting supplier for the best price and purchasing sufficient amount of required goods. Jang *et al.* (2002), Yan *et al.* (2003), Wilhelm *et al.* (2005), Cordeau *et al.* (2006), and A. S. Zadeh *et al.* (2014) developed models with raw material procurement, while Melo *et al.* (2006), and Vila *et al.* (2006) cared for acquiring finished products.

In the past decade, FLP has been extended exhaustively to adapt to new situations faced by SCND. However, even though FLP models have been modified heavily to integrate new features and decision variables, the modelling perspective, which can be called location-oriented approach, are kept unchanged. It is the approach that a supply chain system is represented by a web of nodes connected by arcs. Each node stands for a facility whose location may be either known or determined. Each arc linking two nodes acts as a flow of material between two facilities. One property of FLP models is that the inflow and outflow at any node must be balanced. This property is still held as long as the inflows and outflows at a node are homogenous. However, with the introduction of BOM into FLP models, this balance has been lost, since inflows and outflows at a location are not homogenous anymore. The incoming streams correspond to required ingredients for manufacturing a product or a sub component which may be used in other stages, while outgoing ones may represent either semi-products or finished goods. Another aspect of product structure is that it is related to production processes which are used to convert raw materials to finished products. These processes are strongly associated with choices of technology which make up of capacity of a facility. Some researchers, such as Wouda *et al.* (2002), Yan *et al.* (2003), and Cordeau *et al.* (2006) adapted the assumption that manufacturing operations are inseparable. Therefore, whenever a potential site was selected, it is implied that the whole production process are set up as well. Some other authors, Jang *et al.* (2002), Kouvelis and Rosenblatt (2005), Fleischmann *et al.* (2006), and A. S. Zadeh *et al.* (2014), gave a context in which a manufacturing processes could be divided into smaller processes. Each of those has been assigned to a set of locations. Several papers stated that production processes should be independent from location. In other words, choice of location and choice of production process can be carried out concurrently. Arntzen *et al.* (1995), Wilhelm *et al.* (2005), and Vila *et al.* (2006) explained this idea in their studies.

Table 2.1 Summary of Supply Chain Network Problem

| | Features | | | | | Decisions | | |
|---|---|---|---|---|---|---|---|---|
| | Multi-echelon | multi-product | multi-period | uncertainty components | BOM | Capacity | procurement | Manufacturing Process |
| Arntzen *et al.* (1995) | x | x | x | | x | | | |
| Cordeau *et al.* (2006) | x | x | | | x | | x | x |
| Fleischmann *et al.* (2006) | | x | | x | x | | | x |
| Jang *et al.* (2002) | | x | | | x | | x | x |
| Karabakal *et al.* (2000) | x | x | | | | x | | |
| Kouvelis and Rosenblatt (2005) | x | | | | x | | | x |
| Mazzola and Neebe (1999) | | x | | | | x | | |
| Melo *et al.* (2006) | x | x | | x | | x | x | |
| Ommeren *et al.* (2006) | x | | x | | | x | | |
| Tsiakis *et al.* (2001) | x | x | x | | x | | | |
| Ulstein *et al.* (2006) | | x | | x | | x | | |
| Verter and Dasci (2002) | | x | | | | x | | |
| Vidal and Goetschalckx (2001) | x | x | | | x | | | |
| Vila *et al.* (2006) | x | x | | x | x | x | x | |
| Wilhelm *et al.* (2005) | x | x | | | x | | x | |
| Wouda *et al.* (2002) | x | x | | | x | | | x |
| Yan *et al.* (2003) | x | x | | | x | | x | x |
| A. S. Zadeh *et al.* (2014) | x | x | | x | x | | x | x |

In conclusion, strategic supply chain management has received much attention from research community. There are a number of studies dedicated to extend FLP to address supply chain network issues, especially in manufacturing network problems as summarized in Table 2.1. Several features such as multi-products, multi-periods, stochastic components, bill-of-materials, and production and procurement decisions are successfully integrated. However, all of problems are approached by modelling perspective originated from FLP. This approach largely focuses on network structure with location as fundamental entity. It tends to generate more parameters and decision variable types when a supply chain in production environment is modelled to represent relationship of manufacturing processes with network topology. Therefore, it is necessary to come up with a new approach which is suitable for delivering a more straightforward model for such a network. Besides, it is decisive to consider not only deterministic circumstances but uncertainty conditions as well. Although stochastic component have been introduced to SCND, probability theory has dominated most of the studies. However, such method is based on collection of past data which are obviously difficult to obtain in case of design problem. Moreover, Lai and Hwang (1992) argued that "probability might not give us the right meaning to solve some practical decision-making problems" and that computational efficiency may be affected negatively when probability theory is applied to optimization problem. As a result, possibilistic theory, developed by L. A. Zadeh (1999), is proposed to be used as a mean to dictate future situation instead. Based on the stream of literature, the goal of this thesis is to propose a new method of modelling the supply chain network design problem in which all features and decisions except multi-period in table 2.1 are thoroughly considered.

# Chapter 3

# Methodology

## 3.1 Problem formulation

The purpose of this research is to propose a new approach for modelling production supply chain problem which involves multi-echelons, multi-commodities, product's architectures, manufacturing processes. With process-oriented perspective, new conceptual models for production processes, products and network structure are introduced. They are a foundation for mathematical model to be formulated. Moreover, due to these abstract models, some parameters and types of variables, included in other studies, are easily neglected.

### 3.1.1 Conceptual Design

#### 3.1.1.1 Processes and Products

In developing a general supply chain model for manufacturing sector, it is necessary to come up with a conceptual model of manufacturing process. Martel (2005) pointed out that in such model, products and production stages are considered at an aggregate level in which, only essential elements are captured. Products are grouped into families. Each of which shares some mutual characteristics such as design, raw material, production technique, and so on (Shapiro, 2006; Simchi-Levi, 2007). Similarly, raw material and semi-products are grouped using the same technique. Production stages are regarded as collections of several operations. There are two types of conceptual model which are activity network (Wouda *et al.*, 2002) and bill of materials (BOM) (Arntzen *et al.*, 1995). The former is, as shown in Martel (2005), widely used in process manufacturing industries such as petro-chemicals, food, pulp and paper, pharmaceutical, etc. Each activity may have multiple recipes, which specify outputs and inputs according to potential technologies. In assembly systems such as electronic and automobile businesses, the latter type, however, is more appropriate.

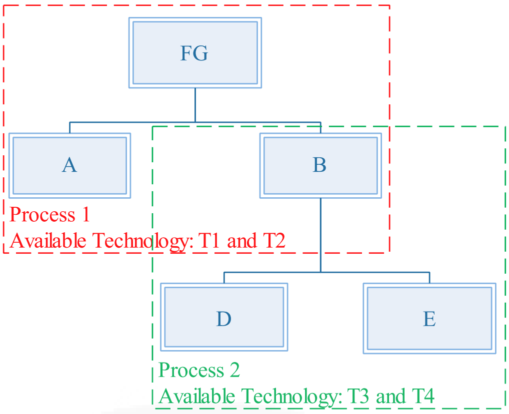

Figure 3.1 BOM tree

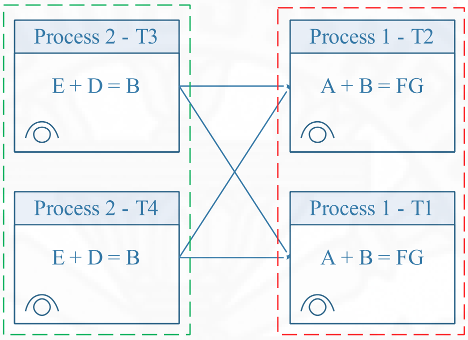

Figure 3.2 Process Network

For the purpose of supporting the proposed approach, a hybrid conceptual model, as shown in Figure 3.1 and 3.2, has been elaborated. It is a combination of process network and BOM representation. BOM is represented as an arborescence: root vertex denotes finished product; leaf vertices denotes raw material, while immediate vertices denotes semi-products. All edges that connect some vertices to a vertex stand for a production process. In addition to BOM, Network process has been deployed as a directed graph enumerating all possible combination of all manufacturing processes in term of technologies.

#### 3.1.1.2 Network Structure

The structure of supply chain is usually modelled by a diagraph which contains two basic elements: Nodes often correspond to facilities which may be either predetermined, such as suppliers and customers, or potential sites for selection, such as factories and distribution centers; Arcs play as transportation routes linking nodes together. In this study, an alternative network structure has been designed. The different point is that each intermediate vertex, subjected to selection, is replaced by network process diagram which is discussed in section 3.1.1. An example of this structure has been demonstrated in Figure 3.3.

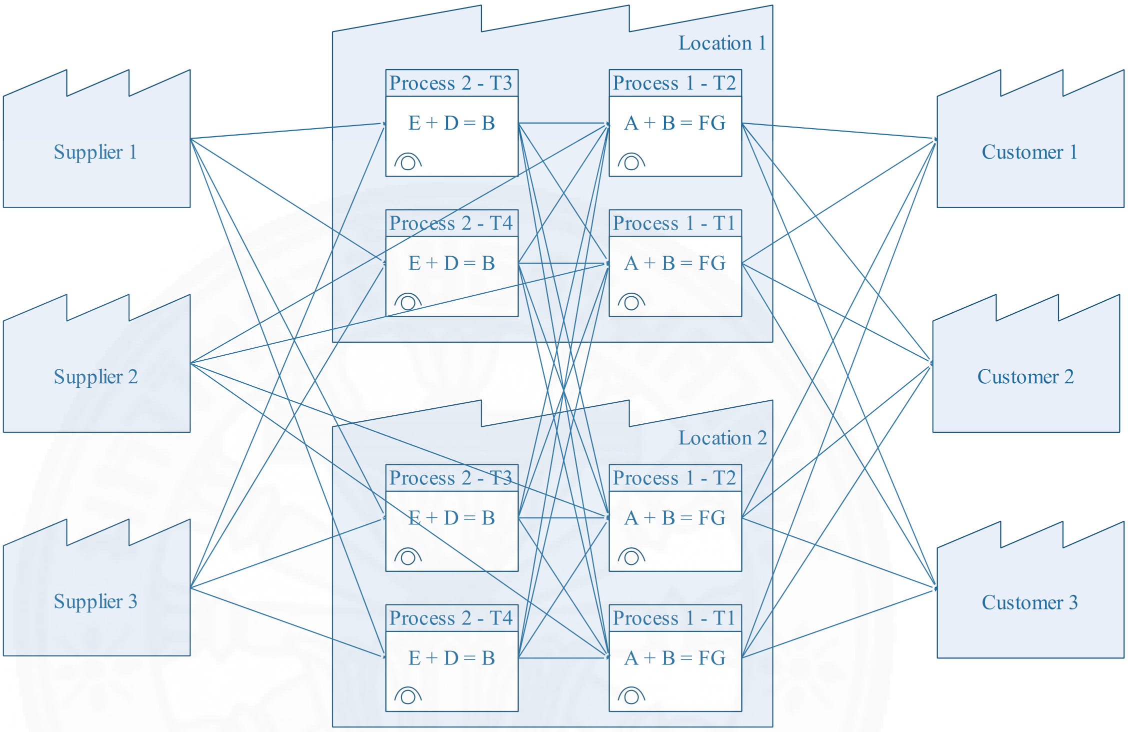

Figure 3.3 Network representation

### 3.1.2 Mathematical model development

Based on previous abstract model of supply chain and possibilistic programming presented by Lai and Hwang (1992), this section describes the developing of SCND problem in term of mathematical formulation. Sets, parameters, and decision variables are defined. Then, objective function, and constraints are formulated.

#### 3.1.2.1 Sets

Consider a directed graph $G(V,A)$ with $V$ is set of vertices and $A$ is set of arcs. There are 3 subsets in $V$ : set of suppliers – $S$; set of customers – $C$ ; set of intermediate nodes – $V\setminus(S\cup C)$, each of them represents a production process with a technology in a candidate site. Associated with each $i \in S$ , there is a set $S'(i)$ which contains components supplied by supplier $i$. Furthermore, with the definition of in-between vertices, there are two additional sets, $O(i)$ and $Ouput(i),\ \forall i \in V \setminus (S \cup C)$, corresponding to levels of capacity and output products. Also, there is a set of components which are allowed to carry, $K'[(i,j)],\ \forall i,j \in V,\ \forall (i,j) \in A$. Let $L$ is a set of subsets of intermediate nodes. Each subset indicates a potential location under consideration. Let $K$ and $F$ are respectively set of raw materials and of intermediate products and set of finished products. Finally, since the uncertainty is also integrated in the model formulation in term of fuzziness, there is a set which represents the states of possibilistic distribution. As that distribution is assumed to be triangular with three occasions which are Optimistic, Most likely, and Pessimistic, set $E$ is considered comprising such occasions.

#### 3.1.2.2 Parameters

Parameters are divided into three categories which are Demand side, Supply side, and Internal business. Each category reflects a dimension from which supply chain operation is affected. Demand side provides annual required amount of products at customer points; Supply side provides a portfolio of raw material suppliers with their price quotations. Internal business describes information originated from entity who runs supply chain. It is included transportation, facility, and process data. Transportation cost demonstrates expense to move a unit of commodity between two points in the network. Facility cost represents annual investment required to acquire, to build and maintain infrastructure for any potential site. Process data contains information about operational aspects consisting of installation cost, process capacity, production cost, products' recipe, and operational policies. The first three terms are designed in order to exhibit economies of scale characteristic of the manufacturing process in each potential location. Production cost for a product will be lower if a higher capacity are installed. However, it requires larger amount of money to run that process annually. All notations of described parameters are shown below:

$\widetilde{D}_{ik}$ is fuzzy demand of product $k$ of customer node $i$ $\forall i \in C, \forall k \in F$

$Sup_{ik}$ is the supply capacity of component $k$ of supplier node $i$ $\forall i \in S,\ \forall k \in S'(i)$

$B_{ik}$ is the cost of component $k$ at supply node $i$ $\forall i \in S,\ \forall k \in K$

$T_{ij}$ is the transportation cost between node $i$ and node $j$ $\forall i, j \in V,\ \forall (i, j) \in A$

$\widetilde{OP}_{l}$ is the fuzzy annualized cost of opening location $l$ $\forall l \in L$

$\widetilde{SE}_{io}$ is the fuzzy annualized setup cost of using each process inside a node $i$ with capacity $o$ $\forall i \in V \backslash (S \cup C), \forall o \in O(i)$

$Cap_{io}$ is the processing capacity $o$ of node $i$ $\forall i \in V \backslash (S \cup C), \forall o \in O(i)$

$\widetilde{P}_{iko}$ is the fuzzy cost of producing a component $k$ at a node $i$ using a level of capacity $o$ $\forall i \in V \backslash (S \cup C),\ \forall k \in K \cup F, \forall o \in O(i)$

$R(k,l)$ is amount of component $k$ which is used to manufacture part $l$ $\forall k, l \in K \cup F$

$\widetilde{TC}$ is total cost including opening, setup, transportation, purchase, and production costs.

### 3.1.2.3 Decision variables

Decision variables are formed by defined supply chain conceptual model. There are three types of variable consisting of facility, process, and flow. The facility specifies which potential site is selected to establish premise. The process indicates configuration of each plant and the flow specifies amount of commodity streaming among network nodes from supplier side through manufacturing network to customer side. In addition to flow determination, the flow also furnishes information shaping sourcing and production programs such as selection of suppliers, product portfolio, production level, etc.

$$Y_l = \begin{cases} 1 & \text{open facility at location } l, \forall l \in L \\ 0 & \text{otherwise} \end{cases}$$

$$Z_{io} = \begin{cases} 1 & \text{node } i \text{ is included in the network with capacity option } o \\ 0 & \text{otherwise} \end{cases}$$

$$\forall i \in V \setminus (S \cup C), \forall o \in O(i)$$

$X_{ijko}$ denotes flow of product/component $k$ from node $i$ to node $j$ with capacity $o$, $\forall i, j \in V$, $(i, j) \in A, k \in K'\left[(i, j)\right], o \in O(i)$

### 3.1.2.4 Objective function

There are many objectives which had been introduced to SCND problems. Their advantages and disadvantages was also discussed in many studies. Since the purpose of this research is to demonstrate a different modelling perspective, the cost function, including opening, setup, transportation, purchasing, and production costs, is chosen as the objective in this model aiming to find the least cost network design. It is, however, noteworthy that the objective function could be changed to cope with various references of decision maker without any difficulties.

$$\begin{aligned} \widetilde{TC} = {} & \sum_{\forall l \in L} Y_l \times \widetilde{OP_l} + \sum_{\forall i \in V \setminus (S \cup C)} \sum_{o \in O(i)} Z_{io} \times \widetilde{SE_{io}} \\ & + \sum_{\forall i \in V} \sum_{\forall j \in V} \sum_{\forall k \in K'[(i,j)]} \sum_{\forall o \in O(i)} X_{ijko} \times T_{ij} + \sum_{\forall i \in S} \sum_{\forall j \in V} \sum_{\forall k \in K'[(i,j)]} \sum_{\forall o \in O(i)} X_{ijko} \times B_{ik} \qquad (1) \\ & + \sum_{\forall i \in V \setminus (S \cup C)} \sum_{\forall j \in V} \sum_{\forall k \in K'[(i,j)]} \sum_{\forall o \in O(i)} X_{ijko} \times \widetilde{P_{iko}} \end{aligned}$$

### 3.1.2.5 Constraints

It is mandatory for supply chain design to satisfy requirements imposed by both inside and outside factors. The former are derived from internal operation conditions and management disciplines, while the latter are obtained from environment in which the supply chain is working. There are eight sets of constraints described as follows:

Supply constraint: Amount of raw material supplied by a supplier cannot surpass its capacity

$$\sum_{j\in V\setminus C}\sum_{\forall o\in O(i)} X_{ijko} \le Sup_{ik}, \quad \forall i \in S, \forall (i,j) \in A, \forall k \in K'\left[(i,j)\right] \tag{2}$$

Demand constraint: Customer demand must be satisfied. More than one plant are allowed to provide a product at a customer location.

$$\sum_{\forall i\in V\setminus(S\cup C)}\sum_{\forall o\in O(i)} X_{ijko} \ge \widetilde{D_{jk}}, \quad \forall j \in C, \forall k \in F \tag{3}$$

Balance constraint: Inflow of commodities and outflow products are equalized through their relationship in BOM.

$$\begin{gathered}\sum_{\forall i\in V}\sum_{\forall o\in O(i)} R(k,l)^{-1} \times X_{ihko} = \sum_{\forall j\in V}\sum_{\forall o\in O(i)} X_{hjlo}, \\ \forall h \in V\setminus(S\cup C), \forall k \in K'\left[(i,h)\right], \forall l \in K'\left[(h,j)\right]\end{gathered} \tag{4}$$

Node constraint: Capacity limitation restricts the production of any processes within available capacity

$$\sum_{\forall j\in V\setminus(S\cup C)}\sum_{\forall k\in K'\left[(i,j)\right]} X_{ijko} \le Z_{io} \times Cap_{io}, \quad \forall i \in V, \forall o \in O(i) \tag{5}$$

Location constraint: Configuration of a candidate site can be proceeded as soon as it is selected.

$$Z_{io} \le M \times Y_l, \quad \forall i \text{ associated with } l,\ \forall l \in L, \forall o \in O(i) \tag{6}$$

Capacity selection: Only one option of capacity is allowed for any process in the network.

$$\sum_{\forall o\in O(i)} Z_{io} \le 1, \quad \forall i \in V\setminus(S\cup C) \tag{7}$$

Non-negativity, binary, and integer conditions:

$$Y_l \in \{0,1\}, \quad \forall l \in L \tag{8}$$

$$Z_{io} \in \{0,1\}, \forall i \in V\setminus(S\cup C), \quad \forall o \in O(i) \tag{9}$$

$$\begin{gathered}X_{ij}^{ko} \text{ are non-negative integer,} \\ \forall i, j \in V, \forall k \in K'\left[(i,j)\right], \forall o \in O(i)\end{gathered} \tag{10}$$

According to above sections, the complete possibilistic programming model for the manufacturing SCND can be expressed as:

$$\begin{array}{l} \text{Mininize } (1) \\ \text{s. t.} \\ (2)-(10) \end{array} \qquad \text{(I)}$$

### 3.1.3 Model Tranformation

Model I is the standard form of a possibilistic linear programming model which includes fuzzy parameters. To solve this model, it is essential to transform the model into a solvable form, or a crisp mathematical model in brief. As can be recognized from (I), there are two types of imprecise parameters. The first one is the fuzzy parameters in the objective function. The second one is the technological coefficient in (3). Transformation of these types will be discussed, respectively.

Since the fuzzy parameters are assumed to follow a possibility triangular distribution, equation (1) will be decomposed into three functions which represent the cost of the supply chain design in each state of possibility triangular distribution: optimistic, most likely, and pessimistic situations in particular.

$$\begin{array}{l} TC(e) = \sum_{\forall l\in L} Y_l \times OP_{le} + \sum_{\forall i\in V\setminus(S\cup C)} \sum_{o\in O(i)} Z_{io} \times SE_{ioe} + \\ \sum_{\forall i\in V} \sum_{\forall j\in V} \sum_{\forall k\in K'[(i,j)]} \sum_{\forall o\in O(i)} X_{ijko} \times T_{ij} + \sum_{\forall i\in S} \sum_{\forall j\in V} \sum_{\forall k\in K'[(i,j)]} \sum_{\forall o\in O(i)} X_{ijko} \times B_{ik} \\ + \sum_{\forall i\in V\setminus(S\cup C)} \sum_{\forall j\in V} \sum_{\forall k\in K'[(i,j)]} \sum_{\forall o\in O(i)} X_{ijko} \times P_{ikoe} \\ \forall e \in E \end{array} \qquad (11)$$

Before transforming the imprecise component in (3), it is necessary to provide additional definitions as follows:

$USC_k$ is the cost of being unable to satisfy the demand of product $k$ $\forall k \in F$

$Shortage_{ike}$ denotes unsatisfied demand of product $k$ at a customer node $i$ in situation $e, \forall i \in C, k \in F, e \in E$

$$Shortage_{jke} \geq 0, \quad \forall j \in C, \forall k \in F, \forall e \in E \qquad (12)$$

Based on the additional definitions, a modification has been made for (3) by subtracting the $Shortage_{ike}$ term from the right hand side. Besides, the objective function (11) will include another cost term denoting the total shortage cost of all products in each possibilistic situation.

$$\sum_{\forall i\in V\backslash(S\cup C)}\sum_{\forall o\in O(i)} X_{ijko} \geq D_{jke} - Shortage_{jke} \quad \forall j\in C, \forall k\in F, \forall e\in E \tag{13}$$

$$\begin{aligned}
&TC(e)=\sum_{\forall l\in L} Y_l \times OP_{le} + \sum_{\forall i\in V\backslash(S\cup C)}\sum_{o\in O(i)} Z_{io}\times SE_{ioe} + \\
&\sum_{\forall i\in V}\sum_{\forall j\in V}\sum_{\forall k\in K'[(i,j)]}\sum_{\forall o\in O(i)} X_{ijko}\times T_{ij} + \sum_{\forall i\in S}\sum_{\forall j\in V}\sum_{\forall k\in K'[(i,j)]}\sum_{\forall o\in O(i)} X_{ijko}\times B_{ik} \\
&+\sum_{\forall i\in V\backslash(S\cup C)}\sum_{\forall j\in V}\sum_{\forall k\in K'[(i,j)]}\sum_{\forall o\in O(i)} X_{ijko}\times P_{ikoe} \\
&+\sum_{\forall j\in C}\sum_{\forall k\in F} Shortage_{jke}\times USC_k \\
&\forall e\in E
\end{aligned} \tag{14}$$

As a result of transforming process, model I has become an equivalent multi-objective linear programming (MOLP) model as follows:

$$\begin{aligned}
&\text{Mininize } (14) \\
&\text{s. t.} \\
&(2),(4)-(10),(12),(13)
\end{aligned} \tag{II}$$

## 3.2 Case Study

### 3.2.1 Studied context

Toothbrush has long been used as a medical device to keep teeth clean from plague. The first toothbrush appeared thousands of years ago. Since then, its design and constituent material has been changed dramatically. Contemporary toothbrush consists of two main parts that are handle and bristle cluster. The first part is made of resin, while the second one is usually made of nylon. It is known that toothbrushes were first mass-produced in the late of 1700s. Manufacturing processes consist of three basic phases that are injection molding, bristle filling, and packing. Handle is made by injection molding process which melts plastic pellets into liquid, injects into a metal mold, and cools it down to form the handle with small holes at the tip. The bristles, which are usually made of nylon, are bought by bundle and cut into a specified length. They are positioned on the head of a handle by stapling using metal staples that are cut from a roll of metal wire. After that, the bristles will be trimmed to produce a specified profile. Finished toothbrushes are put into blister pack, made of PVC or PET, and sealed with a backer card, a color printed paper sheet, by using a high frequency welding machine. Blister packs are arranged into carton box which will be shipped to distributors. This case study involves a toothbrush manufacturer who would like to establish worldwide supply chain to provide their products to customers. Its network includes customers, suppliers and candidate sites which are considered to build manufacturing plant. The goal is to determine the least cost design.

### 3.2.2 Description of input data

In this section, collected data are organized into parameters according to the conceptual model. Moreover, all data are altered or scaled in order to maintain confidentiality of the business.

#### 3.2.2.1 Locations

There are four potential locations for setting up production plants. They are Viet Nam, China, India, Brazil locations. The fixed cost of opening a location, including investment of land and fixed administration cost of setting up the plant during its life cycle, are annualized. Since this cost is considered as imprecise in the future, the estimation should be carried out for all states of future situation corresponding to the possibility triangular distribution. The values are shown in Table 3.1.

Table 3.1 Locations’ yearly fuzzy cost – $\widetilde{OP_l}$

| | **Annual fixed cost of opening a location ($)** | | |
|---|---|---|---|
| **Location** | Optimistic | Most Likely | Pessimistic |
| Viet Nam | 1,080,000 | 1,200,000 | 1,440,000 |
| China | 1,134,000 | 1,260,000 | 1,512,000 |
| India | 1,260,000 | 1,400,000 | 1,680,000 |
| Brazil | 1,170,000 | 1,300,000 | 1,560,000 |

### 3.2.2.2 Products and processes

Based on Watson *et al.* (2012), Shapiro (2006), and Simchi-Levi (2007) criteria, products are grouped into three families that are SKU I, C and K. Similarly, material and semi-products are group into the same categories. Raw materials are composed of seven categories that are resin, colorant, metal wire, filament, PVC, backer card, and shipper or carton box. Among them, resin has three sub categories that are PP, TPE, and BR; metal wire includes brass and aluminum wire. Similarly, semi-products are classified as handles and finished toothbrushes. An instance of a BOM and its recipes is shown in Figure 3.4 and Table 3.2.

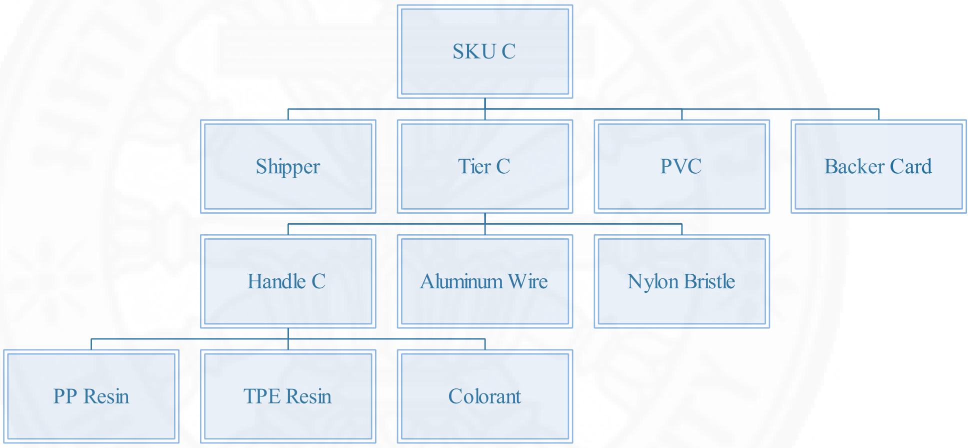

Figure 3.4 BOM structure of SKU C

Table 3.2 Detailed recipe of SKU C – $R(k,l)$

| **Master Item** | **Sub Item** | **Recipe** | **UOM** |
|---|---|---|---|
| SKU C | Tier C | 100 | Piece(s) |
| SKU C | Shipper | 1 | Piece(s) |
| SKU C | PVC | 556 | Gram(s) |
| SKU C | Backer Card | 100 | Piece(s) |
| Tier C | Filament | 1 | Gram(s) |
| Tier C | Aluminum Wire | 1 | Gram(s) |
| Tier C | Handle C | 1 | Piece(s) |
| Handle C | PP | 8 | Gram(s) |
| Handle C | TPE | 3 | Gram(s) |
| Handle C | Colorant | 1 | Gram(s) |

According to BOMs, production processes are classified into two kinds which are common for all families and dedicated for a group of families in each stage of manufacturing. In injection molding stage, 2-phase process are dedicated for SKU C and I, while 3-phase one are reserved for SKU K. In bristle filling stage, anchor-wire process, known as the one that use metal staples to fix bristles in the head of a handle, are used for SKU C and I. Another advanced process, which does not require any metal pieces but heat to retain bristles, is called anchor-free. It is used solely for SKU K. For packing process, it is a common one for all families. Moreover, for each kind of process, there are two types of technology that are eligible for them. Semi-auto partially requires labors in some steps. Automatic, on the contrary, requires no human during production. Process network which represents processes and relevant technologies is shown in Figure 3.5. In addition, associated capacities are displayed in Table 3.3.

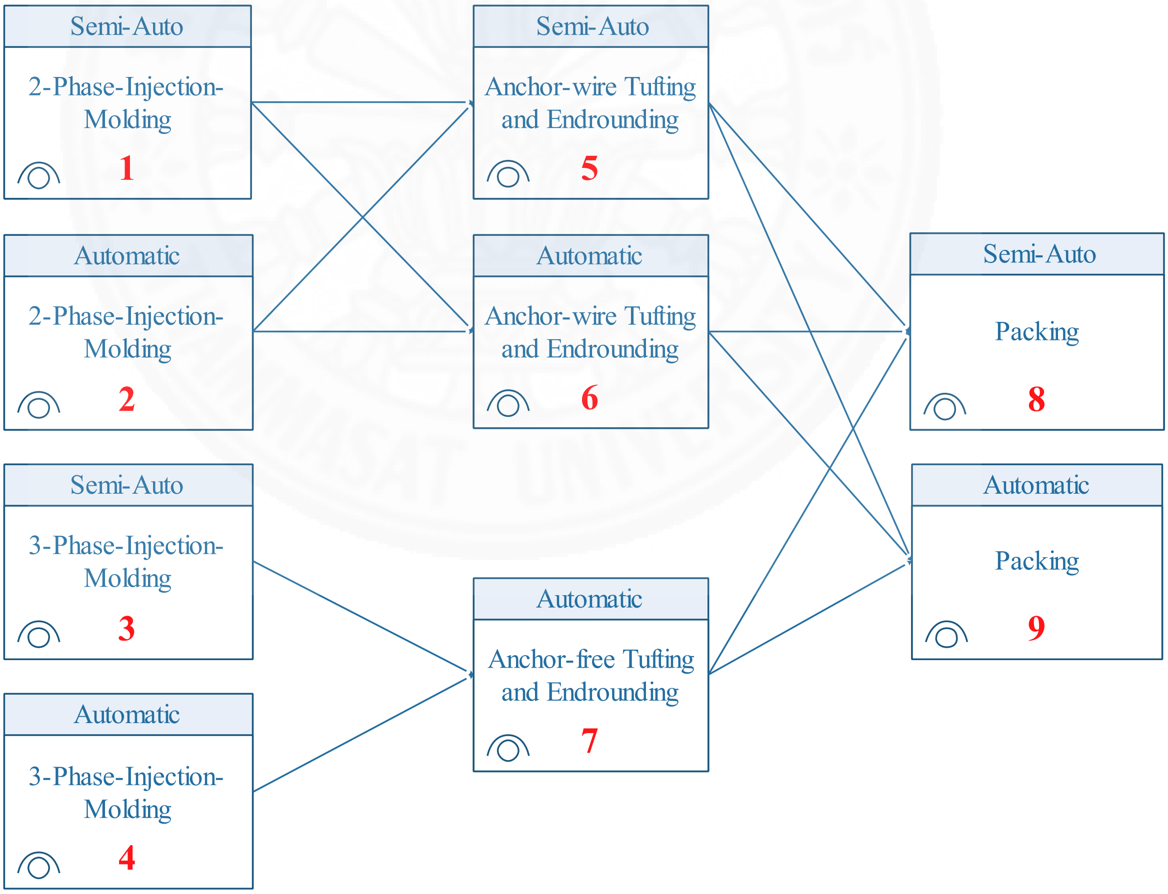

Figure 3.5 Toothbrush manufacturing process network

Table 3.3 Processes' Capacity (in mil. of UOM) – $Cap_{io}$

| **Location** | **Process No.** | **Capacity Levels** | | | **UOM** |
|---|---|---|---|---|---|
| | | **1** | **2** | **3** | |
| Viet Nam | 1 | 95 | 59 | 43.5 | handle |
| | 2 | 50 | 28 | 16 | |
| | 3 | 51 | 40 | 33.5 | |
| | 4 | 52 | 41 | 35.2 | |
| | 5 | 42 | 34 | 24 | toothbrush |
| | 6 | 40 | 31 | 20 | |
| | 7 | 39 | 32 | 26.8 | |
| | 8 | 1.21 | 0.91 | 0.7 | SKU |
| | 9 | 0.86 | 0.67 | 0.59 | |

Besides the capacities, each production process also requires an annualized setup cost, composed of investment of building and production equipment. Moreover, it incurs a production cost, consisting of labor and overhead cost, once operation is commenced. As the costs are apparently uncertain in the future, it is reasonable for management to consider these costs as fuzzy parameters. Therefore, the determination of these expenses has been based on possibility situations. The annualized installation expense and production unit cost of each process are expressed in Tables 3.4 and 3.5:

Table 3.4 Process 1's annualized fuzzy fixed cost ($) – $\widetilde{SE_{io}}$

| **Situation** | **Locations** | **Capacity Levels** | | |
|---|---|---|---|---|
| | | **1** | **2** | **3** |
| Optimistic | Viet Nam | 908,086 | 518,906 | 288,281 |
| | China | 923,147 | 527,513 | 293,063 |
| | India | 909,149 | 519,514 | 288,619 |
| | Brazil | 1,235,756 | 673,200 | 391,500 |
| Most Likely | Viet Nam | 1,008,984 | 576,563 | 320,313 |
| | China | 1,025,719 | 586,125 | 325,625 |
| | India | 1,010,166 | 577,238 | 320,688 |
| | Brazil | 1,373,063 | 748,000 | 435,000 |
| Pessimistic | Viet Nam | 1,210,781 | 691,875 | 384,375 |
| | China | 1,230,863 | 703,350 | 390,750 |
| | India | 1,212,199 | 692,685 | 384,825 |
| | Brazil | 1,647,675 | 897,600 | 522,000 |

Table 3.5 Process 1’s unit production cost of handle C ($/piece) – $\widetilde{P_{iko}}$

| Situations | Locations | Capacity Levels | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| Optimistic | Viet Nam | 0.0126 | 0.0139 | 0.0151 |
| | China | 0.0284 | 0.0312 | 0.0340 |
| | India | 0.0120 | 0.0132 | 0.0144 |
| | Brazil | 0.0432 | 0.0475 | 0.0518 |
| Most Likely | Viet Nam | 0.0140 | 0.0154 | 0.0168 |
| | China | 0.0315 | 0.0347 | 0.0378 |
| | India | 0.0133 | 0.0146 | 0.0160 |
| | Brazil | 0.0480 | 0.0528 | 0.0576 |
| Pessimistic | Viet Nam | 0.0168 | 0.0185 | 0.0202 |
| | China | 0.0378 | 0.0416 | 0.0454 |
| | India | 0.0160 | 0.0176 | 0.0192 |
| | Brazil | 0.0576 | 0.0634 | 0.0691 |

Since the considered business is operated in an uncertain environment, it is obvious to observe a situation in which supply capacity is surpassed by demand quantity. In such case, the losses due to unsatisfied demand is merely inevitable for the firm. Therefore, it is mandatory to estimate the shortage cost of not enough supply. Unit shortage cost of each SKU is estimated as in table 3.6.

Table 3.6 Unit shortage cost of each SKU ($/SKU) – $USC_k$

| Product | Shortage Rate |
|---|---|
| SKU C | 258.31 |
| SKU I | 129.16 |
| SKU K | 194.44 |

#### 3.2.2.3 Supply sources

Once raw materials are aggregated, it can be done similarly for supply sources. They can be grouped by categories of material and geographical location. Consequently, there are 28 suppliers providing material for the candidate production facilities. Each of them has limitation of supply and different prices, as shown in Table 3.7.

Table 3.7 Supplier data

| **Supplier location** | **Material** | **Capacity*** | **Price** ($)** | **UOM** |
|---|---|---|---|---|
| India | PP | 850,000 | 1.50 | Kg(s) |
| Saudi Arabia | PP | 970,000 | 1.52 | Kg(s) |
| China | TPE | 750,000 | 3.69 | Kg(s) |
| China | TPE | 610,000 | 3.68 | Kg(s) |
| VN | Colorant | 258,600 | 6.93 | Kg(s) |
| China | Colorant | 230,100 | 6.36 | Kg(s) |
| China | Aluminum Wire | 62,500 | 6.06 | Kg(s) |
| China | Aluminum Wire | 75,300 | 6.07 | Kg(s) |
| UK | Brass Wire | 24,200 | 14.48 | Kg(s) |
| Germany | Brass Wire | 25,500 | 14.47 | Kg(s) |
| China | Filament | 480,000 | 9.12 | Kg(s) |
| China | Filament | 570,000 | 9.28 | Kg(s) |
| Vietnam | PVC | 510,000 | 1.83 | Kg(s) |
| Taiwan | PVC | 660,000 | 1.84 | Kg(s) |
| VN | Shipper | 3,250 | 243.60 | KPcs |
| China | Shipper | 4,730 | 244.70 | KPcs |
| VN | Backer Card | 258,000 | 12.23 | KPcs |
| China | Backer Card | 276,000 | 11.59 | KPcs |
| US | BR | 700,000 | 3.78 | Kg(s) |

(* $Sup_{ik}$ , ** $B_{ik}$ )

#### 3.2.2.4 Demand origins

With defined families of products, it is inevitable to consolidate demand. Collected data reveals that demand could be organized by families and countries. Moreover, it is also implied that demand might be unpredictable in the coming years. Therefore, it is desirable to be designed as a fuzzy input. Aggregated fuzzy demand is displayed in Table 3.8.

Table 3.8 Customer Demand (in thousands of units) – $\widetilde{D_{ik}}$

| **Region** | **Country** | **Optimistic** | | | **Most Likely** | | | **Pessimistic** | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | **SKU C** | **SKU I** | **SKU K** | **SKU C** | **SKU I** | **SKU K** | **SKU C** | **SKU I** | **SKU K** |
| South Pacific | Australia | 32.36 | 0 | 38.19 | 35.95 | 0 | 42.44 | 43.14 | 0 | 50.93 |
| Euro-Asia | Russia | 30.96 | 0 | 22.92 | 34.40 | 0 | 25.46 | 41.28 | 0 | 30.56 |
| | Turkey | 16.85 | 0 | 0 | 18.72 | 0 | 0 | 22.46 | 0 | 0 |
| East Europe | Poland | 10.65 | 0 | 0 | 11.84 | 0 | 0 | 14.20 | 0 | 0 |
| | Romania | 17.93 | 0 | 0 | 19.92 | 0 | 0 | 23.90 | 0 | 0 |
| Asia | Thailand | 173.76 | 36.83 | 19.10 | 193.07 | 40.93 | 21.22 | 231.68 | 49.11 | 25.46 |
| | Philippines | 65.90 | 74.76 | 17.57 | 73.22 | 83.07 | 19.52 | 87.86 | 99.68 | 23.43 |
| | Vietnam | 17.57 | 0 | 15.28 | 19.53 | 0 | 16.98 | 23.43 | 0 | 20.37 |
| | China | 191.14 | 88.40 | 61.11 | 212.38 | 98.22 | 67.90 | 254.85 | 117.86 | 81.48 |
| | India | 199.83 | 73.45 | 35.14 | 222.03 | 81.61 | 39.04 | 266.43 | 97.93 | 46.85 |
| | Malaysia | 42.92 | 56.50 | 21.39 | 47.69 | 62.78 | 23.77 | 57.23 | 75.33 | 28.52 |
| | Taiwan | 22.61 | 7.13 | 24.44 | 25.12 | 7.92 | 27.16 | 30.14 | 9.50 | 32.59 |
| | Hong Kong | 0.69 | 45.79 | 27.50 | 0.76 | 50.87 | 30.56 | 0.92 | 61.05 | 36.67 |
| North America | US | 75.03 | 77.43 | 64.17 | 83.37 | 86.04 | 71.30 | 100.04 | 103.24 | 85.55 |
| | Canada | 62.53 | 53.43 | 55.00 | 69.47 | 59.36 | 61.11 | 83.37 | 71.24 | 73.33 |
| Latin American | Mexico | 4.23 | 0 | 5.96 | 4.70 | 0 | 6.62 | 5.64 | 0 | 7.94 |
| | Colombia | 10.06 | 0 | 14.51 | 11.18 | 0 | 16.13 | 13.41 | 0 | 19.35 |
| | Brazil | 0 | 269.58 | 44.31 | 0 | 299.53 | 49.23 | 0 | 359.43 | 59.07 |
| Africa and Middle East | GSS | 31.19 | 6.91 | 8.40 | 34.66 | 7.68 | 9.34 | 41.59 | 9.22 | 11.20 |
| | East Africa | 5.22 | 7.97 | 11.61 | 5.80 | 8.85 | 12.90 | 6.96 | 10.62 | 15.48 |

#### 3.2.2.5 Transportation cost

A transportation cost is incurred when moving a unit of commodity between any two nodes in the network. It is determined by relative distance as well as physical characteristics of commodity. Although multiple commodities are allowed on a single route in this case study, it is found that these commodities are somewhat homogeneous in term of physical appearances. Therefore, transportation cost, described in this section, is distance-based only and linearly related to amount of commodity which are shipped from one node to another. However, it is noteworthy that in other cases, transportation cost parameter could be extended to be dependent on both kind of items and distance without any loss of generality. Detailed transportation cost and other input data could be found in Appendix A.

### 3.2.3 Experimental Design

An experiment plan has been designed corresponding to developed models. At first, a base case solution, representing deterministic scenario, is determined by solving model I with Most Likely parameters. Secondly, model II, under fuzzy scenario, is solved with each objective function in (14) respectively to obtain solutions. These solutions are then converted to crisp values which are treated as selection criteria. After choosing the most favorable solution, it will be evaluated and an improvement may be carried out if there is any objective dominated in any situation. Finally, fuzzy scenario's solution is compared with deterministic scenario's to highlight the impact of uncertainty on the network.

# Chapter 4

# Result and Discussion

The mathematical models, which have been developed, are coded by Optimization Programming Language (OPL). The OPL models, exhibited in Appendix B, are solved by MIP solver in IBM ILOG CPLEX 12.6 system. According to the experimental design discussed in previous chapter, most likely parameters are referred as values for deterministic scenario and are applied to model I to obtain a base case solution. For the non-deterministic scenario, model II will be solved with each objective function to find the best network design for each possible situation known as optimistic, most likely, or pessimistic situations. Once the results have been determined, the objective value of other occasions are calculated. Afterward, a fuzzy (compromised) solution is chosen and subjected to evaluation of suitability. Finally, that solution is thoroughly compared with a base case one in detail to highlight the differences between them.

## 4.1 Deterministic Scenario

After running OPL model with base case data, it comes up with an optimal solution which costs $43,526,220, shown in Table 4.1. Over half of that are contributed by location, process, and production. The rest amount of expense comes from procurement and transportation.

Table 4.1 Total cost summary

| Category | Value ($) |
|---|---|
| Annualized fixed cost of Opening a location | 3,860,000 |
| Procurement Cost | 16,851,524 |
| Production Cost | 9,894,375 |
| Annualized fixed cost of Using a capacity level | 10,006,743 |
| Transportation Cost | 2,913,579 |
| Shortage Cost | - |
| Total Cost | 43,526,220 |

Three locations are selected in Asia according to Table 4.2. It is due to low production cost which can compensate transportation cost incurring from shipping to remote locations on the other side of the world. China location is configured as a dedicated plants with only tufting and packing processes because injection molding can be concentrated in Vietnam and India plants. Likewise, anchor-free process was established in only one location, China plant, as high capacity level of this process can handle occurred demand. On the other hand, anchor-wire tufting and pack are separated in all selected sites due to the fact that no single or combination of any capacity in any sites can be exploited to satisfy the demand.

Table 4.2 Decision summary

| | **Solution Summary** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Candidate Site** | Vietnam | | | China | | | India | | | Brazil | | |
| **Used?** | x | | | x | | | x | | | | | |
| **Capacity Level** / **Process** | High | Medium | Low | High | Medium | Low | High | Medium | Low | High | Medium | Low |
| 2-Phase-Injection-Molding (Semi-Auto) | x | | | | | | | x | | | | |
| 2-Phase-Injection-Molding (Automatic) | | | | | | | | | | | | |
| 3-Phase-Injection-Molding (Semi-Auto) | | | | | | | | | | | | |
| 3-Phase-Injection-Molding (Automatic) | | | | | | | | x | | | | |
| Tufting and Endrounding (Anchor-wire Semi-Auto) | | x | | | x | | | x | | | | |
| Tufting and Endrounding (Anchor-wire Automatic) | | | | | x | | | x | | | | |
| Tufting and Endrounding (Anchor-free) | | | | x | | | | | | | | |
| Packing (Semi-Auto) | | | x | | | x | | | x | | | |
| Packing (Automatic) | | | | | | | | | x | | | |

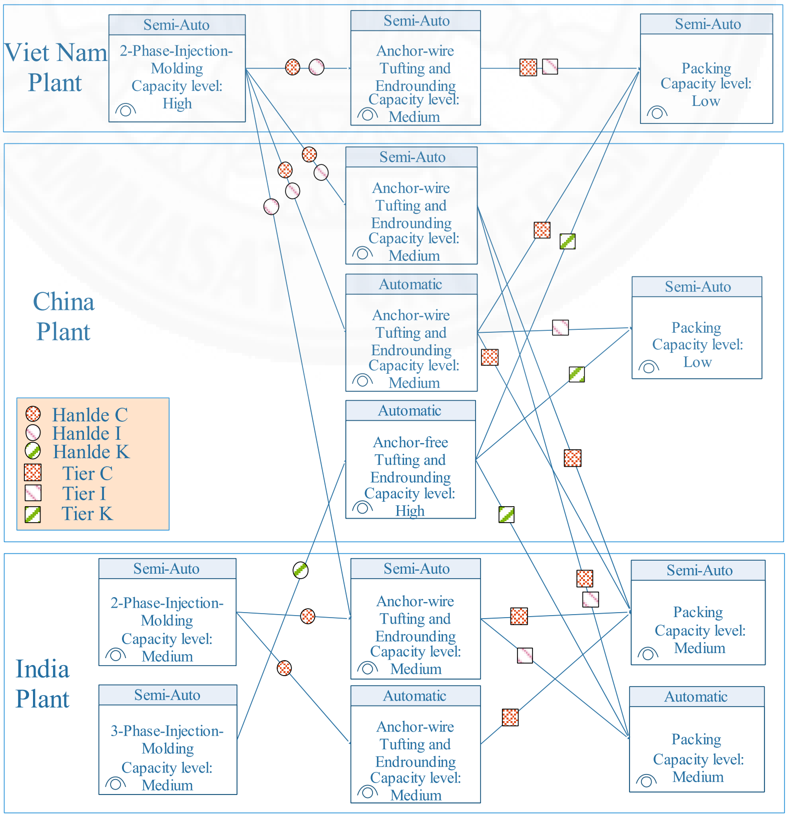

Figure 4.1 Plants’ portfolio and configuration

Consequently, Vietnam and India will focus on anchor-wire products. China will be in charge of manufacturing anchor-free products. Production portfolio and configuration of each site is illustrated in Figure 4.1. In addition, customers are assigned to each location as shown in Table 4.3.

Table 4.3 Demand allocation

| | | Vietnam | | | China | | | India | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Region** | **Country** | SKU C | SKU I | SKU K | SKU C | SKU I | SKU K | SKU C | SKU I | SKU K |
| South Pacific | Australia | x | | x | | | | | | |
| Euro-Asia | Russia | | | | | | x | x | | |
| | Turkey | | | | | | | x | | |
| East Europe | Poland | | | | | | | x | | |
| | Romania | | | | | | | x | | |
| Asia | Thailand | x | x | x | | | | x | | |
| | Philippines | x | x | x | | | | | | |
| | Vietnam | x | | x | | | | | | |
| | China | | | | | x | x | x | | |
| | India | | | | | | | x | x | x |
| | Malaysia | x | x | x | | | | | | |
| | Taiwan | x | | x | | x | | | | |
| | Hong Kong | x | | x | | x | | | | |
| North America | US | | | | | x | x | x | | x |
| | Canada | | | | | x | x | x | | |
| Latin American | Mexico | | | | | | x | x | | |
| | Colombia | | | | | | | x | | x |
| | Brazil | | | | | | | | x | x |
| Africa and Middle East | GSS | | | | | | | x | x | x |
| | East Africa | | | | | | | x | x | x |

### 4.2 Non-deterministic Scenario

Model II is solved sequentially with each objective function in equation (14) as described. The value of the objective function and its counter parts are revealed in Table 4.4. Since each solution could be treated as a membership function of a fuzzy set, they can be assessed by their crisp or defuzzified values. A number of defuzzifying methods has been introduced in fuzzy logic literature. Of all them, the centroid method is the most popular one. Therefore, it will be used to convert the fuzzy sets in this study. The detail of this method can be found in Ross (2010).

Table 4.4 Objective values in each state

| | **Situations** | | | |
|---|---|---|---|---|
| **Situation to be optimized** | **Optimistic** | **Most Likely** | **Pessimistic** | **Crisp Value** |
| Pessimistic | 48,043,527 | 50,799,666 | 65,392,421 | 54,745,205 |
| Most Likely | 41,150,108 | 43,526,220 | 150,264,845 | 78,313,725 |
| Optimistic | 36,897,516 | 90,034,157 | 196,315,838 | 107,749,171 |

The result highlights some characteristics of the problem. As the demand may contingently occurs somewhere between low (Optimistic) and high (Pessimistic) levels, it has significant effect on capacity of the network when the focus is shifted from one situation to another. Specifically, it would require larger capacity to be installed in order to match high demand if the model is optimized for the Pessimistic level. As a result, it would add more expense to the total cost. However, such additional cost has countered the severe loss incurred by unsatisfied demand as a result of insufficient capacity.

Pessimistic-optimized solution, in table 4.4, has a larger capacity than other two solutions because it relies on the demand in Pessimistic situation to determine the capacity for its network. Therefore, the total cost in Optimistic and Most Likely situations are worse than those in other solutions. Although Most Likely-optimized and Optimistic-optimized solutions require smaller capacity based on lower demand in Most Likely and Optimistic situations respectively, a large amount of sale is lost when the demand is relatively high during Pessimistic situation. This is the reason why their total costs in Pessimistic situation is greatly higher than that of Pessimistic-optimized solution.

In addition, it can be observed that the Pessimistic-optimized solution is the most preferable among the three based on its crisp value. The Pessimistic total cost is the smallest, even though Optimistic and Most Likely situations are worse than other solutions. Trying to improve this solution seems to be intuitively plausible. Consequently, Pessimistic-optimized solution is further investigated for improvement. There are many methods which may help to improve the current solution. In this study, a simple method, called $\varepsilon-\text{Constraint}$ method which was described in detail by Coello (1999), will be exploited. The concept of this method is that in a multi-objective mathematical model, it will minimize one objective regarded as the primary or the most preferable one while treating other objectives as constraints bounded by an $\varepsilon$ amounts. The solving process are carried out by changing the primary objective until there is no improvement of any other objective.

In this research, the $\varepsilon-\text{Constraint}$ will be applied in the same way. Initially, Optimistic objective in equation (14) is selected to be the preferred objective in model II. Since no improvement has been found, Most Likely objective is put in place. However, there is still no enhancement. Therefore, an alternative setting has been setup with a degree of relaxation in Pessimistic objective. By allowing Pessimistic objective to be 5% larger, two similar replications are carried out as the first setting. The replication in which the optimistic objective is firstly selected as preferred one still yields no betterment. The summary of the remaining replication, in which most likely function has been chosen in the first place, is illustrated in Table 4.5.

Table 4.5 $\varepsilon-\text{Constraint}$ Summary

| | | **State** | | | |
|---|---|---|---|---|---|
| **Iteration** | **Situation to be optimized** | **Optimistic** | **Most Likely** | **Pessimistic** | **Crisp Value** |
| 1 | Most Likely | 47,608,348 | 50,341,063 | 68,659,639 | 55,536,350 |
| 2 | Optimistic | No Improvement | | | |

It is apparent to recognize that though the solution in table 4.5 has lower total cost under Optimistic and Most Likely situations compared with the Pessimistic-optimized solution in table 4.4, the crisp value, however, is not better than Pessimistic-optimized solution. As a result, Pessimistic-optimized solution is the most suitable solution in this case.

### 4.3 Solution Comparison

Based on Table 4.2 and 4.6, while network structure (number of locations) in both deterministic and non-deterministic cases remains unchanged, the configuration (specification of processes) has been changed noticeably. Viet Nam plant has been expanded by three more processes, one injection molding, one tufting, and one packing. India plant has replaced a packing process by a tufting one in supporting for producing anchor-free product. Now, the two plants have become equivalent in terms of installed amount of capacity. China plant capacity has been shrunk although its configuration is kept untouched.

Table 4.6 Fuzzy Solution’s Decision Summary

| | **Solution Summary** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Candidate Site** | Vietnam | | | China | | | India | | | Brazil | | |
| **Used?** | x | | | x | | | x | | | | | |
| **Capacity Level** / **Process** | High | Medium | Low | High | Medium | Low | High | Medium | Low | High | Medium | Low |
| 2-Phase-Injection-Molding (Semi-Auto) | x | | | | | | x | | | | | |
| 2-Phase-Injection-Molding (Automatic) | | | | | | | | | | | | |
| 3-Phase-Injection-Molding (Semi-Auto) | | | x | | | | | | x | | | |
| 3-Phase-Injection-Molding (Automatic) | | | | | | | | | | | | |
| Tufting and Endrounding (Anchor-wire Semi-Auto) | | x | | | | x | | x | | | | |
| Tufting and Endrounding (Anchor-wire Automatic) | | x | | | x | | | x | | | | |
| Tufting and Endrounding (Anchor-free) | | | | | | x | | | x | | | |
| Packing (Semi-Auto) | | x | | | | x | | x | | | | |
| Packing (Automatic) | | | x | | | | | | | | | |

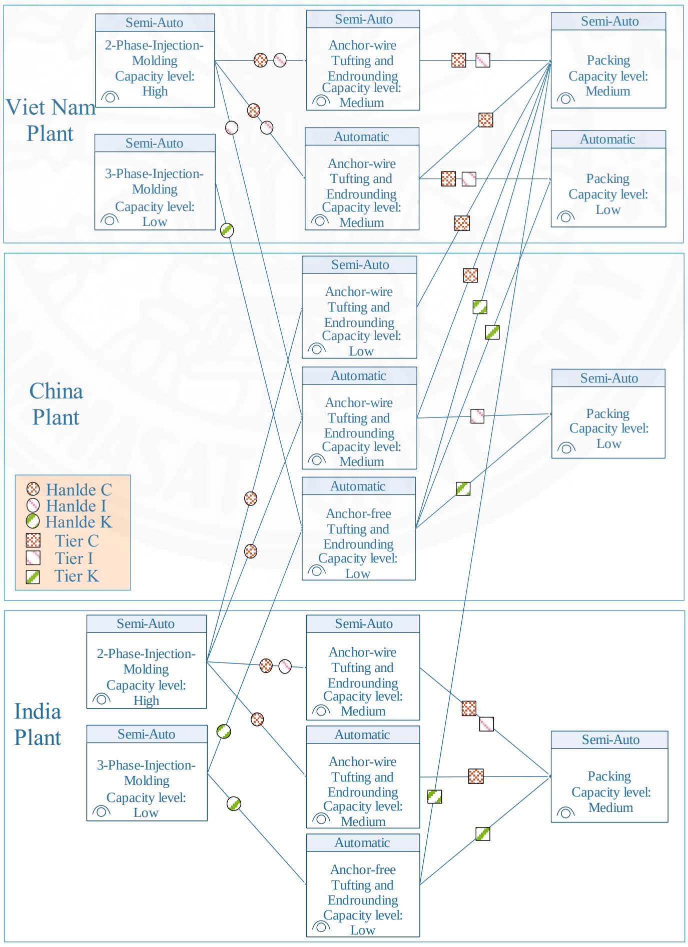

Figure 4.2 Fuzzy Solution’s Product Portfolio and Configuration

As the configuration of the network has been alternated, the product portfolio and internal relationship among facilities are varied as well. As can be observed in Figure 4.2, China is still a partial plant equipped with only tufting and packing processes. India has been assigned to manufacture anchor-free toothbrush which is previously handled by China alone. Viet Nam, jointly with India, has produced and supplied anchor-free handle for China. However, the main products manufactured in Viet Nam still are anchor-wire toothbrushes.

Table 4.7 Fuzzy Solution’s Demand Allocation

| | | Vietnam | | | China | | | India | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Region** | **Country** | SKU C | SKU I | SKU K | SKU C | SKU I | SKU K | SKU C | SKU I | SKU K |
| South Pacific | Australia | x | | x | | | | | | |
| Euro-Asia | Russia | | | | | | x | x | | |
| | Turkey | | | | | | | x | | |
| East Europe | Poland | | | | | | | x | | |
| | Romania | | | | | | | x | | |
| Asia | Thailand | x | x | x | | | | | | |
| | Philippines | x | x | x | | | | | | |
| | Vietnam | x | | x | | | | | | |
| | China | x | | x | | x | | | | |
| | India | | x | | | | | x | | x |
| | Malaysia | x | x | x | | | | | | |
| | Taiwan | x | x | x | | | | | | |
| | Hong Kong | x | x | x | | | | | | |
| North America | US | | | | | x | | x | | x |
| | Canada | | | x | | x | x | x | | x |
| Latin American | Mexico | | | x | | | | x | | |
| | Colombia | x | | x | | | | | | |
| | Brazil | | x | | | x | | | x | x |
| Africa and Middle East | GSS | | | | | | | x | x | x |
| | East Africa | | x | | | | | x | | x |

Besides of impacts on product assignment and internal relationship among plants, the network configuration has affected demand allocation significantly. Table 4.7 has shown that China now played a smaller role in delivering products because of shrunk capacity. Viet Nam, for the time being, has covered almost all the shipments in

Asia Region as its plant has been extended remarkably. Other regions has received products from India.

Generally, it can be seen that uncertainty has a substantial effect on the design of supply chain network. The design in deterministic or base case scenario tends to be smaller and less expensive than the one achieved in non-deterministic case. However, it is critical to note that if the demand varies considerably between Most Likely and Pessimistic demand levels or beyond, base case solution may result in an enormous amount of opportunity cost compared with the non-deterministic solution. For example, if demand is realized at Pessimistic situation, deterministic design may cost as high as 150,264,845, while non-deterministic design cost as much as 65,392,421. As a result, it is imperative to take uncertainty into consideration in order to neutralize the risk of financial loss.

# Chapter 5

# Conclusions and Recommendations

## 5.1 Conclusion

Throughout this study, a new modelling approach for production supply chain has been introduced. Two conceptual models, from which a mathematical model is developed, are completely constructed. Since the uncertainties are always an important issue for every supply chain design problem, they are also integrated into the model by means of possiblitic theory. As a result, the model, previously developed as a single-objective linear programming model, has been modified to be a multi-objective one. In addition to methodology, the developed models have also been validated by a case study derived from a toothbrush business. A base case solution, obtained by applying the Most Likely parameters, is compared with a solution, determined in fuzzy scenario. It is shown that the solution in fuzzy environment not only provides more flexibility to the network but lowers financial risk during the course of operation as well.

## 5.2 Recommendations for further studies

Though the model is a multi-objective one, it is not a result from the nature of the problem but of uncertainties integration. Therefore, it is plausible to explore how to extend the model with more objective functions than only the cost function which has been considered here. For instance, the new supply chain design not only cost less but also enhance sustainability as well. Moreover, since the model has just been validated by a case study of a medium size, it is valuable to test the model with larger supply chain in order to measure its performance. In case there is any large-scale problem which is unable to be handled by exact method, a heuristic approach may be preferable.

Besides, uncertainty has been integrated successfully into the model under possibilistic theory. It is observed that the model with a total cost function is not well-behave enough to come up with a compromised solution. Therefore, it is reasonable and necessary to examine the model’s behavior with an alternative objective function. Due to its popularity in possibilistic programming literature, a profit function may be worth to be considered as a substitute candidate in this case.

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# Appendices

# Appendix A

# Input Data

Table A1 Supplier Data

| No. | Location | Material | Capacity | Price | UOM |
|---|---|---|---|---|---|
| Supplier 1 (PP) | India | PP | 850,000 | 1.50 | Kg(s) |
| Supplier 2 (PP) | Saudi Arabia | PP | 970,000 | 1.52 | Kg(s) |
| Supplier 3 (TPE) | China | TPE | 750,000 | 3.69 | Kg(s) |
| Supplier 4 (TPE) | China | TPE | 610,000 | 3.68 | Kg(s) |
| Supplier 5 (Colorant) | VN | Colorant | 258,600 | 6.93 | Kg(s) |
| Supplier 6 (Colorant) | China | Colorant | 230,100 | 6.36 | Kg(s) |
| Supplier 7 (Colorant) | India | Colorant | 227,900 | 6.62 | Kg(s) |
| Supplier 8 (Aluminum Wire) | China | Aluminum Wire | 62,500 | 6.06 | Kg(s) |
| Supplier 9 (Aluminum Wire) | China | Aluminum Wire | 75,300 | 6.07 | Kg(s) |
| Supplier 10 (Brass Wire) | UK | Brass Wire | 24,200 | 14.48 | Kg(s) |
| Supplier 11 (Brass Wire) | Gemany | Brass Wire | 25,500 | 14.47 | Kg(s) |
| Supplier 12 (Filament) | China | Filament | 480,000 | 9.12 | Kg(s) |
| Supplier 13 (Filament) | China | Filament | 570,000 | 9.28 | Kg(s) |
| Supplier 14 (Filament) | China | Filament | 390,000 | 9.07 | Kg(s) |
| Supplier 15 (PVC) | Vietnam | PVC | 510,000 | 1.83 | Kg(s) |
| Supplier 16 (PVC) | Taiwan | PVC | 660,000 | 1.84 | Kg(s) |
| Supplier 17 (PVC) | China | PVC | 1,220,000 | 1.84 | Kg(s) |
| Supplier 18 (PVC) | Brazil | PVC | 550,000 | 1.84 | Kg(s) |
| Supplier 19 (PVC) | India | PVC | 1,148,000 | 1.83 | Kg(s) |
| Supplier 20 (Shipper) | VN | Shipper | 3,250 | 243.60 | KPcs |
| Supplier 21 (Shipper) | China | Shipper | 4,730 | 244.70 | KPcs |
| Supplier 22 (Shipper) | India | Shipper | 3,560 | 240.24 | KPcs |
| Supplier 23 (Shipper) | Brazil | Shipper | 3,150 | 238.04 | KPcs |
| Supplier 24 (Backer Card) | VN | Backer Card | 258,000 | 12.23 | KPcs |
| Supplier 25 (Backer Card) | China | Backer Card | 276,000 | 11.59 | KPcs |
| Supplier 26 (Backer Card) | India | Backer Card | 263,000 | 10.73 | KPcs |
| Supplier 27 (Backer Card) | Brazil | Backer Card | 234,000 | 12.18 | KPcs |
| Supplier 28 (BR) | US | BR | 700,000 | 3.78 | KPcs |

Table A2 Product data

| No | Master Item | Sub Item | Conversion | UOM |
|---|---|---|---|---|
| 1 | SKU C | Tier C | 100 | Piece(s) |
| | SKU C | Shipper C | 1 | Piece(s) |
| | SKU C | PVC C | 556 | Gram(s) |
| | SKU C | Backer Card C | 100 | Piece(s) |
| | Tier C | Filament C | 1 | Gram(s) |
| | Tier C | Aluminum Wire C | 1 | Gram(s) |
| | Tier C | Handle C | 1 | Piece(s) |
| | Handle C | PP C | 8 | Gram(s) |
| | Handle C | TPE C | 3 | Gram(s) |
| | Handle C | Colorant C | 1 | Gram(s) |
| 2 | SKU I | Tier I | 50 | Piece(s) |
| | SKU I | Shipper I | 1 | Piece(s) |
| | SKU I | PVC I | 278 | Gram(s) |
| | SKU I | Backer Card I | 50 | Piece(s) |
| | Tier I | Handle I | 1 | Piece(s) |
| | Tier I | Brass Wire I | 1 | Gram(s) |
| | Tier I | Filament I | 1 | Gram(s) |
| | Handle I | TPE I | 5 | Gram(s) |
| | Handle I | BR I | 14 | Gram(s) |
| | Handle I | Colorant I | 1 | Gram(s) |
| 3 | SKU K | Tier K | 75 | Piece(s) |
| | SKU K | Shipper K | 1 | Piece(s) |
| | SKU K | PVC K | 417 | Gram(s) |
| | SKU K | Backer Card K | 75 | Piece(s) |
| | Tier K | Handle K | 1 | Piece(s) |
| | Tier K | Filament K | 1 | Gram(s) |
| | Handle K | PP K | 11 | Gram(s) |
| | Handle K | TPE K | 8 | Gram(s) |
| | Handle K | Colorant K | 1 | Gram(s) |

Table A3 Process capacity (mil. of units)

| | | Capacity Level | | |
|---|---|---|---|---|
| Location | Process No. | 1 | 2 | 3 |
| Viet Nam | 1 | 95.00 | 59.00 | 43.50 |
| | 2 | 50.00 | 28.00 | 16.00 |
| | 3 | 51.00 | 39.50 | 33.50 |
| | 4 | 52.40 | 40.80 | 35.20 |
| | 5 | 42.00 | 34.00 | 24.00 |
| | 6 | 40.00 | 31.00 | 20.00 |
| | 7 | 39.00 | 32.40 | 26.80 |
| | 8 | 1.21 | 0.91 | 0.70 |
| | 9 | 0.86 | 0.67 | 0.59 |
| China | 1 | 90.00 | 62.00 | 43.50 |
| | 2 | 50.00 | 28.00 | 16.00 |
| | 3 | 54.00 | 41.90 | 35.60 |
| | 4 | 52.40 | 40.80 | 35.20 |
| | 5 | 42.00 | 34.00 | 24.00 |
| | 6 | 40.00 | 31.00 | 20.00 |
| | 7 | 42.00 | 34.00 | 28.00 |
| | 8 | 1.09 | 0.88 | 0.72 |
| | 9 | 0.86 | 0.67 | 0.59 |
| India | 1 | 95.00 | 62.00 | 43.50 |
| | 2 | 50.00 | 28.00 | 16.00 |
| | 3 | 48.00 | 36.50 | 30.50 |
| | 4 | 52.40 | 40.80 | 35.20 |
| | 5 | 42.00 | 34.00 | 24.00 |
| | 6 | 40.00 | 31.00 | 20.00 |
| | 7 | 40.50 | 31.00 | 27.60 |
| | 8 | 1.12 | 0.92 | 0.75 |
| | 9 | 0.86 | 0.67 | 0.59 |
| Brazil | 1 | 85.00 | 61.00 | 41.50 |
| | 2 | 50.00 | 28.00 | 16.00 |
| | 3 | 41.00 | 36.50 | 29.60 |
| | 4 | 52.40 | 40.80 | 35.20 |
| | 5 | 42.00 | 34.00 | 24.00 |
| | 6 | 40.00 | 31.00 | 20.00 |
| | 7 | 41.50 | 32.90 | 29.10 |
| | 8 | 0.92 | 0.71 | 0.60 |
| | 9 | 1.16 | 0.97 | 0.79 |

Table A4 Process investment cost (mil. $)

| | | Situation | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Optimistic | | | Most Likely | | | Pessimistic | | |
| Location | Process No. | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| Viet Nam | 1 | 1.21 | 0.69 | 0.38 | 1.01 | 0.58 | 0.32 | 0.91 | 0.52 | 0.29 |
| | 2 | 1.72 | 0.98 | 0.55 | 1.44 | 0.82 | 0.46 | 1.29 | 0.74 | 0.41 |
| | 3 | 2.05 | 1.29 | 0.91 | 1.71 | 1.07 | 0.76 | 1.53 | 0.96 | 0.68 |
| | 4 | 2.86 | 1.64 | 1.18 | 2.39 | 1.36 | 0.99 | 2.15 | 1.23 | 0.89 |
| | 5 | 1.39 | 0.80 | 0.62 | 1.16 | 0.66 | 0.52 | 1.04 | 0.60 | 0.46 |
| | 6 | 1.95 | 1.11 | 0.79 | 1.62 | 0.93 | 0.66 | 1.46 | 0.84 | 0.59 |
| | 7 | 2.22 | 1.72 | 1.24 | 1.85 | 1.43 | 1.03 | 1.66 | 1.29 | 0.93 |
| | 8 | 0.84 | 0.44 | 0.37 | 0.70 | 0.37 | 0.31 | 0.63 | 0.33 | 0.28 |
| | 9 | 1.17 | 0.62 | 0.51 | 0.98 | 0.51 | 0.43 | 0.88 | 0.46 | 0.39 |
| China | 1 | 1.23 | 0.70 | 0.39 | 1.03 | 0.59 | 0.33 | 0.92 | 0.53 | 0.29 |
| | 2 | 1.72 | 0.98 | 0.55 | 1.44 | 0.82 | 0.46 | 1.29 | 0.74 | 0.41 |
| | 3 | 2.08 | 1.31 | 0.92 | 1.73 | 1.09 | 0.77 | 1.56 | 0.98 | 0.69 |
| | 4 | 2.91 | 1.66 | 1.20 | 2.43 | 1.39 | 1.00 | 2.18 | 1.25 | 0.90 |
| | 5 | 1.42 | 0.81 | 0.63 | 1.18 | 0.67 | 0.52 | 1.06 | 0.61 | 0.47 |
| | 6 | 1.98 | 1.13 | 0.81 | 1.65 | 0.94 | 0.67 | 1.49 | 0.85 | 0.60 |
| | 7 | 2.20 | 1.63 | 1.18 | 1.83 | 1.36 | 0.98 | 1.65 | 1.22 | 0.88 |
| | 8 | 0.86 | 0.45 | 0.38 | 0.72 | 0.38 | 0.31 | 0.64 | 0.34 | 0.28 |
| | 9 | 1.20 | 0.63 | 0.53 | 1.00 | 0.53 | 0.44 | 0.90 | 0.47 | 0.40 |
| India | 1 | 1.21 | 0.69 | 0.38 | 1.01 | 0.58 | 0.32 | 0.91 | 0.52 | 0.29 |
| | 2 | 1.70 | 0.97 | 0.54 | 1.41 | 0.81 | 0.45 | 1.27 | 0.73 | 0.40 |
| | 3 | 2.05 | 1.29 | 0.91 | 1.71 | 1.07 | 0.76 | 1.54 | 0.97 | 0.68 |
| | 4 | 2.87 | 1.64 | 1.18 | 2.39 | 1.37 | 0.99 | 2.15 | 1.23 | 0.89 |
| | 5 | 1.39 | 0.80 | 0.62 | 1.16 | 0.66 | 0.52 | 1.05 | 0.60 | 0.46 |
| | 6 | 1.95 | 1.12 | 0.79 | 1.63 | 0.93 | 0.66 | 1.46 | 0.84 | 0.59 |
| | 7 | 2.17 | 1.61 | 1.16 | 1.81 | 1.34 | 0.97 | 1.62 | 1.20 | 0.87 |
| | 8 | 0.83 | 0.44 | 0.36 | 0.69 | 0.36 | 0.30 | 0.62 | 0.33 | 0.27 |
| | 9 | 1.16 | 0.61 | 0.51 | 0.97 | 0.51 | 0.42 | 0.87 | 0.46 | 0.38 |
| Brazil | 1 | 1.65 | 0.90 | 0.52 | 1.37 | 0.75 | 0.44 | 1.24 | 0.67 | 0.39 |
| | 2 | 1.72 | 0.97 | 0.55 | 1.43 | 0.81 | 0.46 | 1.29 | 0.73 | 0.41 |
| | 3 | 2.97 | 2.00 | 1.65 | 2.48 | 1.66 | 1.37 | 2.23 | 1.50 | 1.24 |
| | 4 | 2.99 | 2.04 | 1.59 | 2.49 | 1.70 | 1.32 | 2.24 | 1.53 | 1.19 |
| | 5 | 1.71 | 0.97 | 0.87 | 1.42 | 0.81 | 0.72 | 1.28 | 0.73 | 0.65 |
| | 6 | 1.99 | 1.13 | 0.81 | 1.66 | 0.95 | 0.67 | 1.49 | 0.85 | 0.60 |
| | 7 | 2.18 | 1.78 | 1.30 | 1.82 | 1.48 | 1.09 | 1.64 | 1.34 | 0.98 |
| | 8 | 1.05 | 0.62 | 0.53 | 0.87 | 0.51 | 0.44 | 0.79 | 0.46 | 0.40 |
| | 9 | 1.25 | 0.68 | 0.57 | 1.05 | 0.57 | 0.47 | 0.94 | 0.51 | 0.43 |

## Table A5 Process production cost ($/unit)

| | | Optimistitic | | | Most Likely | | | Pessimistic | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Location | Process No. | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| Viet Nam | 1 | 0.0126 | 0.0139 | 0.0151 | 0.0140 | 0.0154 | 0.0168 | 0.0168 | 0.0185 | 0.0202 |
| | 2 | 0.0117 | 0.0129 | 0.0140 | 0.0130 | 0.0143 | 0.0156 | 0.0156 | 0.0172 | 0.0187 |
| | 3 | 0.0144 | 0.0158 | 0.0173 | 0.0160 | 0.0176 | 0.0192 | 0.0192 | 0.0211 | 0.0230 |
| | 4 | 0.0137 | 0.0150 | 0.0164 | 0.0152 | 0.0167 | 0.0182 | 0.0182 | 0.0200 | 0.0218 |
| | 5 | 0.0308 | 0.0338 | 0.0369 | 0.0342 | 0.0376 | 0.0410 | 0.0410 | 0.0451 | 0.0492 |
| | 6 | 0.0267 | 0.0294 | 0.0320 | 0.0297 | 0.0327 | 0.0356 | 0.0356 | 0.0392 | 0.0427 |
| | 7 | 0.0350 | 0.0385 | 0.0420 | 0.0389 | 0.0428 | 0.0467 | 0.0467 | 0.0514 | 0.0560 |
| | 8 | 0.0187 | 0.0206 | 0.0225 | 0.0208 | 0.0229 | 0.0250 | 0.0250 | 0.0275 | 0.0300 |
| | 9 | 0.0174 | 0.0191 | 0.0209 | 0.0193 | 0.0212 | 0.0232 | 0.0232 | 0.0254 | 0.0278 |
| China | 1 | 0.0284 | 0.0312 | 0.0340 | 0.0315 | 0.0347 | 0.0378 | 0.0378 | 0.0416 | 0.0454 |
| | 2 | 0.0099 | 0.0109 | 0.0119 | 0.0110 | 0.0121 | 0.0132 | 0.0132 | 0.0145 | 0.0158 |
| | 3 | 0.0268 | 0.0294 | 0.0321 | 0.0298 | 0.0327 | 0.0357 | 0.0358 | 0.0392 | 0.0428 |
| | 4 | 0.0133 | 0.0147 | 0.0160 | 0.0148 | 0.0163 | 0.0178 | 0.0178 | 0.0196 | 0.0214 |
| | 5 | 0.0313 | 0.0345 | 0.0376 | 0.0348 | 0.0383 | 0.0418 | 0.0418 | 0.0460 | 0.0502 |
| | 6 | 0.0239 | 0.0263 | 0.0286 | 0.0265 | 0.0292 | 0.0318 | 0.0318 | 0.0350 | 0.0382 |
| | 7 | 0.0348 | 0.0383 | 0.0418 | 0.0387 | 0.0426 | 0.0464 | 0.0464 | 0.0511 | 0.0557 |
| | 8 | 0.0306 | 0.0337 | 0.0367 | 0.0340 | 0.0374 | 0.0408 | 0.0408 | 0.0449 | 0.0490 |
| | 9 | 0.0247 | 0.0271 | 0.0296 | 0.0274 | 0.0301 | 0.0329 | 0.0329 | 0.0361 | 0.0395 |
| India | 1 | 0.0120 | 0.0131 | 0.0144 | 0.0133 | 0.0146 | 0.0160 | 0.0160 | 0.0175 | 0.0192 |
| | 2 | 0.0090 | 0.0099 | 0.0108 | 0.0100 | 0.0110 | 0.0120 | 0.0120 | 0.0132 | 0.0144 |
| | 3 | 0.0140 | 0.0154 | 0.0168 | 0.0156 | 0.0171 | 0.0187 | 0.0187 | 0.0205 | 0.0224 |
| | 4 | 0.0125 | 0.0138 | 0.0150 | 0.0139 | 0.0153 | 0.0167 | 0.0167 | 0.0184 | 0.0200 |
| | 5 | 0.0302 | 0.0333 | 0.0363 | 0.0336 | 0.0370 | 0.0403 | 0.0403 | 0.0444 | 0.0484 |
| | 6 | 0.0248 | 0.0274 | 0.0298 | 0.0276 | 0.0304 | 0.0331 | 0.0331 | 0.0365 | 0.0397 |
| | 7 | 0.0344 | 0.0378 | 0.0412 | 0.0382 | 0.0420 | 0.0458 | 0.0458 | 0.0504 | 0.0550 |
| | 8 | 0.0173 | 0.0190 | 0.0207 | 0.0192 | 0.0211 | 0.0230 | 0.0230 | 0.0253 | 0.0276 |
| | 9 | 0.0163 | 0.0179 | 0.0195 | 0.0181 | 0.0199 | 0.0217 | 0.0217 | 0.0239 | 0.0260 |
| Brazil | 1 | 0.0432 | 0.0475 | 0.0518 | 0.0480 | 0.0528 | 0.0576 | 0.0576 | 0.0634 | 0.0691 |
| | 2 | 0.0351 | 0.0386 | 0.0421 | 0.0390 | 0.0429 | 0.0468 | 0.0468 | 0.0515 | 0.0562 |
| | 3 | 0.0446 | 0.0491 | 0.0535 | 0.0495 | 0.0545 | 0.0594 | 0.0594 | 0.0654 | 0.0713 |
| | 4 | 0.0360 | 0.0396 | 0.0432 | 0.0400 | 0.0440 | 0.0480 | 0.0480 | 0.0528 | 0.0576 |
| | 5 | 0.0342 | 0.0376 | 0.0410 | 0.0380 | 0.0418 | 0.0456 | 0.0456 | 0.0502 | 0.0547 |
| | 6 | 0.0257 | 0.0283 | 0.0308 | 0.0285 | 0.0314 | 0.0342 | 0.0342 | 0.0377 | 0.0410 |
| | 7 | 0.0352 | 0.0387 | 0.0422 | 0.0391 | 0.0430 | 0.0469 | 0.0469 | 0.0516 | 0.0563 |
| | 8 | 0.0320 | 0.0353 | 0.0384 | 0.0356 | 0.0392 | 0.0427 | 0.0427 | 0.0470 | 0.0512 |
| | 9 | 0.0266 | 0.0293 | 0.0320 | 0.0296 | 0.0326 | 0.0355 | 0.0355 | 0.0391 | 0.0426 |

Table A6 Node representations

| Set | Descriptions | Node No. |
|---|---|---|
| Suppliers | Supplier 1 (PP) | 1 |
| | Supplier 2 (PP) | 2 |
| | Supplier 3 (TPE) | 3 |
| | Supplier 4 (TPE) | 4 |
| | Supplier 5 (Colorant) | 5 |
| | Supplier 6 (Colorant) | 6 |
| | Supplier 7 (Colorant) | 7 |
| | Supplier 8 (Aluminum Wire) | 8 |
| | Supplier 9 (Aluminum Wire) | 9 |
| | Supplier 10 (Brass Wire) | 10 |
| | Supplier 11 (Brass Wire) | 11 |
| | Supplier 12 (Filament) | 12 |
| | Supplier 13 (Filament) | 13 |
| | Supplier 14 (Filament) | 14 |
| | Supplier 15 (PVC) | 15 |
| | Supplier 16 (PVC) | 16 |
| | Supplier 17 (PVC) | 17 |
| | Supplier 18 (PVC) | 18 |
| | Supplier 19 (PVC) | 19 |
| | Supplier 20 (Shipper) | 20 |
| | Supplier 21 (Shipper) | 21 |
| | Supplier 22 (Shipper) | 22 |
| | Supplier 23 (Shipper) | 23 |
| | Supplier 24 (Backer Card) | 24 |
| | Supplier 25 (Backer Card) | 25 |
| | Supplier 26 (Backer Card) | 26 |
| | Supplier 27 (Backer Card) | 27 |
| | Supplier 28 (BR) | 84 |
| Vietnam Location | 2-Phase-Injection-Molding (Semi-Auto) | 28 |
| | 2-Phase-Injection-Molding (Automatic) | 29 |
| | 3-Phase-Injection-Molding (Semi-Auto) | 30 |
| | 3-Phase-Injection-Molding (Automatic) | 31 |
| | Tufting and Endrounding (Anchor-wire Semi-Auto) | 32 |
| | Tufting and Endrounding (Anchor-wire Automatic) | 33 |
| | Tufting and Endrounding (Anchor-free) | 34 |
| | Packing (Semi-Auto) | 35 |
| | Packing (Automatic) | 36 |
| China Location | 2-Phase-Injection-Molding (Semi-Auto) | 37 |
| | 2-Phase-Injection-Molding (Automatic) | 38 |
| | 3-Phase-Injection-Molding (Semi-Auto) | 39 |
| | 3-Phase-Injection-Molding (Automatic) | 40 |
| | Tufting and Endrounding (Anchor-wire Semi-Auto) | 41 |
| | Tufting and Endrounding (Anchor-wire Automatic) | 42 |

| | | |
|---|---|---|
| | Tufting and Endrounding (Anchor-free) | 43 |
| | Packing (Semi-Auto) | 44 |
| | Packing (Automatic) | 45 |
| India Location | 2-Phase-Injection-Molding (Semi-Auto) | 46 |
| | 2-Phase-Injection-Molding (Automatic) | 47 |
| | 3-Phase-Injection-Molding (Semi-Auto) | 48 |
| | 3-Phase-Injection-Molding (Automatic) | 49 |
| | Tufting and Endrounding (Anchor-wire Semi-Auto) | 50 |
| | Tufting and Endrounding (Anchor-wire Automatic) | 51 |
| | Tufting and Endrounding (Anchor-free) | 52 |
| | Packing (Semi-Auto) | 53 |
| | Packing (Automatic) | 54 |
| Brazil Location | 2-Phase-Injection-Molding (Semi-Auto) | 55 |
| | 2-Phase-Injection-Molding (Automatic) | 56 |
| | 3-Phase-Injection-Molding (Semi-Auto) | 57 |
| | 3-Phase-Injection-Molding (Automatic) | 58 |
| | Tufting and Endrounding (Anchor-wire Semi-Auto) | 59 |
| | Tufting and Endrounding (Anchor-wire Automatic) | 60 |
| | Tufting and Endrounding (Anchor-free) | 61 |
| | Packing (Semi-Auto) | 62 |
| | Packing (Automatic) | 63 |
| Customers | Australia | 64 |
| | Russia | 65 |
| | Turkey | 66 |
| | Poland | 67 |
| | Romania | 68 |
| | Thailand | 69 |
| | Philippines | 70 |
| | Vietnam | 71 |
| | China | 72 |
| | India | 73 |
| | Malaysia | 74 |
| | Taiwan | 75 |
| | Hong Kong | 76 |
| | US | 77 |
| | Canada | 78 |
| | Mexico | 79 |
| | Colombia | 80 |
| | Brazil | 81 |
| | GSS | 82 |
| | East Africa | 83 |

Table A7 Network arcs

| From Node | To Node | Commodity | Transportation Cost |
|---|---|---|---|
| 1 | 28 | {"PP"} | 0.00012 |
| 2 | 28 | {"PP"} | 0.00023 |
| 3 | 28 | {"TPE"} | 0.00009 |
| 4 | 28 | {"TPE"} | 0.00009 |
| 84 | 28 | {"BR"} | 0.00051 |
| 5 | 28 | {"Colorant"} | 0.00001 |
| 6 | 28 | {"Colorant"} | 0.00009 |
| 7 | 28 | {"Colorant"} | 0.00012 |
| 1 | 29 | {"PP"} | 0.00012 |
| 2 | 29 | {"PP"} | 0.00023 |
| 3 | 29 | {"TPE"} | 0.00009 |
| 4 | 29 | {"TPE"} | 0.00009 |
| 84 | 29 | {"BR"} | 0.00051 |
| 5 | 29 | {"Colorant"} | 0.00001 |
| 6 | 29 | {"Colorant"} | 0.00009 |
| 7 | 29 | {"Colorant"} | 0.00012 |
| 1 | 30 | {"PP"} | 0.00012 |
| 2 | 30 | {"PP"} | 0.00023 |
| 3 | 30 | {"TPE"} | 0.00009 |
| 4 | 30 | {"TPE"} | 0.00009 |
| 84 | 30 | {"BR"} | 0.00051 |
| 5 | 30 | {"Colorant"} | 0.00001 |
| 6 | 30 | {"Colorant"} | 0.00009 |
| 7 | 30 | {"Colorant"} | 0.00012 |
| 1 | 31 | {"PP"} | 0.00012 |
| 2 | 31 | {"PP"} | 0.00023 |
| 3 | 31 | {"TPE"} | 0.00009 |
| 4 | 31 | {"TPE"} | 0.00009 |
| 84 | 31 | {"BR"} | 0.00051 |
| 5 | 31 | {"Colorant"} | 0.00001 |
| 6 | 31 | {"Colorant"} | 0.00009 |
| 7 | 31 | {"Colorant"} | 0.00012 |
| 1 | 37 | {"PP"} | 0.00011 |
| 2 | 37 | {"PP"} | 0.00020 |
| 3 | 37 | {"TPE"} | 0.00001 |
| 4 | 37 | {"TPE"} | 0.00001 |
| 84 | 37 | {"BR"} | 0.00043 |
| 5 | 37 | {"Colorant"} | 0.00009 |
| 6 | 37 | {"Colorant"} | 0.00001 |
| 7 | 37 | {"Colorant"} | 0.00011 |
| 1 | 38 | {"PP"} | 0.00011 |
| 2 | 38 | {"PP"} | 0.00020 |
| 3 | 38 | {"TPE"} | 0.00001 |

|  |  |  |  |
|---|---|---|---|
| 4 | 38 | {"TPE"} | 0.00001 |
| 84 | 38 | {"BR"} | 0.00043 |
| 5 | 38 | {"Colorant"} | 0.00009 |
| 6 | 38 | {"Colorant"} | 0.00001 |
| 7 | 38 | {"Colorant"} | 0.00011 |
| 1 | 39 | {"PP"} | 0.00011 |
| 2 | 39 | {"PP"} | 0.00020 |
| 3 | 39 | {"TPE"} | 0.00001 |
| 4 | 39 | {"TPE"} | 0.00001 |
| 84 | 39 | {"BR"} | 0.00043 |
| 5 | 39 | {"Colorant"} | 0.00009 |
| 6 | 39 | {"Colorant"} | 0.00001 |
| 7 | 39 | {"Colorant"} | 0.00011 |
| 1 | 40 | {"PP"} | 0.00011 |
| 2 | 40 | {"PP"} | 0.00020 |
| 3 | 40 | {"TPE"} | 0.00001 |
| 4 | 40 | {"TPE"} | 0.00001 |
| 84 | 40 | {"BR"} | 0.00043 |
| 5 | 40 | {"Colorant"} | 0.00009 |
| 6 | 40 | {"Colorant"} | 0.00001 |
| 7 | 40 | {"Colorant"} | 0.00011 |
| 1 | 46 | {"PP"} | 0.00001 |
| 2 | 46 | {"PP"} | 0.00012 |
| 3 | 46 | {"TPE"} | 0.00011 |
| 4 | 46 | {"TPE"} | 0.00011 |
| 84 | 46 | {"BR"} | 0.00050 |
| 5 | 46 | {"Colorant"} | 0.00012 |
| 6 | 46 | {"Colorant"} | 0.00011 |
| 7 | 46 | {"Colorant"} | 0.00001 |
| 1 | 47 | {"PP"} | 0.00001 |
| 2 | 47 | {"PP"} | 0.00012 |
| 3 | 47 | {"TPE"} | 0.00011 |
| 4 | 47 | {"TPE"} | 0.00011 |
| 84 | 47 | {"BR"} | 0.00050 |
| 5 | 47 | {"Colorant"} | 0.00012 |
| 6 | 47 | {"Colorant"} | 0.00011 |
| 7 | 47 | {"Colorant"} | 0.00001 |
| 1 | 48 | {"PP"} | 0.00001 |
| 2 | 48 | {"PP"} | 0.00012 |
| 3 | 48 | {"TPE"} | 0.00011 |
| 4 | 48 | {"TPE"} | 0.00011 |
| 84 | 48 | {"BR"} | 0.00050 |
| 5 | 48 | {"Colorant"} | 0.00012 |
| 6 | 48 | {"Colorant"} | 0.00011 |
| 7 | 48 | {"Colorant"} | 0.00001 |
| 1 | 49 | {"PP"} | 0.00001 |

|  |  |  |  |
|---|---|---|---|
| 2 | 49 | {"PP"} | 0.00012 |
| 3 | 49 | {"TPE"} | 0.00011 |
| 4 | 49 | {"TPE"} | 0.00011 |
| 84 | 49 | {"BR"} | 0.00050 |
| 5 | 49 | {"Colorant"} | 0.00012 |
| 6 | 49 | {"Colorant"} | 0.00011 |
| 7 | 49 | {"Colorant"} | 0.00001 |
| 1 | 55 | {"PP"} | 0.00054 |
| 2 | 55 | {"PP"} | 0.00040 |
| 3 | 55 | {"TPE"} | 0.00061 |
| 4 | 55 | {"TPE"} | 0.00061 |
| 84 | 55 | {"BR"} | 0.00027 |
| 5 | 55 | {"Colorant"} | 0.00066 |
| 6 | 55 | {"Colorant"} | 0.00061 |
| 7 | 55 | {"Colorant"} | 0.00054 |
| 1 | 56 | {"PP"} | 0.00054 |
| 2 | 56 | {"PP"} | 0.00040 |
| 3 | 56 | {"TPE"} | 0.00061 |
| 4 | 56 | {"TPE"} | 0.00061 |
| 84 | 56 | {"BR"} | 0.00027 |
| 5 | 56 | {"Colorant"} | 0.00066 |
| 6 | 56 | {"Colorant"} | 0.00061 |
| 7 | 56 | {"Colorant"} | 0.00054 |
| 1 | 57 | {"PP"} | 0.00054 |
| 2 | 57 | {"PP"} | 0.00040 |
| 3 | 57 | {"TPE"} | 0.00061 |
| 4 | 57 | {"TPE"} | 0.00061 |
| 84 | 57 | {"BR"} | 0.00027 |
| 5 | 57 | {"Colorant"} | 0.00066 |
| 6 | 57 | {"Colorant"} | 0.00061 |
| 7 | 57 | {"Colorant"} | 0.00054 |
| 1 | 58 | {"PP"} | 0.00054 |
| 2 | 58 | {"PP"} | 0.00040 |
| 3 | 58 | {"TPE"} | 0.00061 |
| 4 | 58 | {"TPE"} | 0.00061 |
| 84 | 58 | {"BR"} | 0.00027 |
| 5 | 58 | {"Colorant"} | 0.00066 |
| 6 | 58 | {"Colorant"} | 0.00061 |
| 7 | 58 | {"Colorant"} | 0.00054 |
| 8 | 32 | {"Aluminum Wire"} | 0.00009 |
| 9 | 32 | {"Aluminum Wire"} | 0.00009 |
| 10 | 32 | {"Brass Wire"} | 0.00035 |
| 11 | 32 | {"Brass Wire"} | 0.00033 |
| 12 | 32 | {"Filament"} | 0.00009 |
| 13 | 32 | {"Filament"} | 0.00009 |
| 14 | 32 | {"Filament"} | 0.00009 |

|  |  |  |  |
|---|---|---|---|
| 8 | 33 | {"Aluminum Wire"} | 0.00009 |
| 9 | 33 | {"Aluminum Wire"} | 0.00009 |
| 10 | 33 | {"Brass Wire"} | 0.00035 |
| 11 | 33 | {"Brass Wire"} | 0.00033 |
| 12 | 33 | {"Filament"} | 0.00009 |
| 13 | 33 | {"Filament"} | 0.00009 |
| 14 | 33 | {"Filament"} | 0.00009 |
| 8 | 34 | {"Aluminum Wire"} | 0.00009 |
| 9 | 34 | {"Aluminum Wire"} | 0.00009 |
| 10 | 34 | {"Brass Wire"} | 0.00035 |
| 11 | 34 | {"Brass Wire"} | 0.00033 |
| 12 | 34 | {"Filament"} | 0.00009 |
| 13 | 34 | {"Filament"} | 0.00009 |
| 14 | 34 | {"Filament"} | 0.00009 |
| 8 | 41 | {"Aluminum Wire"} | 0.00001 |
| 9 | 41 | {"Aluminum Wire"} | 0.00001 |
| 10 | 41 | {"Brass Wire"} | 0.00027 |
| 11 | 41 | {"Brass Wire"} | 0.00025 |
| 12 | 41 | {"Filament"} | 0.00001 |
| 13 | 41 | {"Filament"} | 0.00001 |
| 14 | 41 | {"Filament"} | 0.00001 |
| 8 | 42 | {"Aluminum Wire"} | 0.00001 |
| 9 | 42 | {"Aluminum Wire"} | 0.00001 |
| 10 | 42 | {"Brass Wire"} | 0.00027 |
| 11 | 42 | {"Brass Wire"} | 0.00025 |
| 12 | 42 | {"Filament"} | 0.00001 |
| 13 | 42 | {"Filament"} | 0.00001 |
| 14 | 42 | {"Filament"} | 0.00001 |
| 8 | 43 | {"Aluminum Wire"} | 0.00001 |
| 9 | 43 | {"Aluminum Wire"} | 0.00001 |
| 10 | 43 | {"Brass Wire"} | 0.00027 |
| 11 | 43 | {"Brass Wire"} | 0.00025 |
| 12 | 43 | {"Filament"} | 0.00001 |
| 13 | 43 | {"Filament"} | 0.00001 |
| 14 | 43 | {"Filament"} | 0.00001 |
| 8 | 50 | {"Aluminum Wire"} | 0.00011 |
| 9 | 50 | {"Aluminum Wire"} | 0.00011 |
| 10 | 50 | {"Brass Wire"} | 0.00027 |
| 11 | 50 | {"Brass Wire"} | 0.00024 |
| 12 | 50 | {"Filament"} | 0.00011 |
| 13 | 50 | {"Filament"} | 0.00011 |
| 14 | 50 | {"Filament"} | 0.00011 |
| 8 | 51 | {"Aluminum Wire"} | 0.00011 |
| 9 | 51 | {"Aluminum Wire"} | 0.00011 |
| 10 | 51 | {"Brass Wire"} | 0.00027 |
| 11 | 51 | {"Brass Wire"} | 0.00024 |

|  |  |  |  |
|---|---|---|---|
| 12 | 51 | {"Filament"} | 0.00011 |
| 13 | 51 | {"Filament"} | 0.00011 |
| 14 | 51 | {"Filament"} | 0.00011 |
| 8 | 52 | {"Aluminum Wire"} | 0.00011 |
| 9 | 52 | {"Aluminum Wire"} | 0.00011 |
| 10 | 52 | {"Brass Wire"} | 0.00027 |
| 11 | 52 | {"Brass Wire"} | 0.00024 |
| 12 | 52 | {"Filament"} | 0.00011 |
| 13 | 52 | {"Filament"} | 0.00011 |
| 14 | 52 | {"Filament"} | 0.00011 |
| 8 | 59 | {"Aluminum Wire"} | 0.00061 |
| 9 | 59 | {"Aluminum Wire"} | 0.00061 |
| 10 | 59 | {"Brass Wire"} | 0.00031 |
| 11 | 59 | {"Brass Wire"} | 0.00033 |
| 12 | 59 | {"Filament"} | 0.00061 |
| 13 | 59 | {"Filament"} | 0.00061 |
| 14 | 59 | {"Filament"} | 0.00061 |
| 8 | 60 | {"Aluminum Wire"} | 0.00061 |
| 9 | 60 | {"Aluminum Wire"} | 0.00061 |
| 10 | 60 | {"Brass Wire"} | 0.00031 |
| 11 | 60 | {"Brass Wire"} | 0.00033 |
| 12 | 60 | {"Filament"} | 0.00061 |
| 13 | 60 | {"Filament"} | 0.00061 |
| 14 | 60 | {"Filament"} | 0.00061 |
| 8 | 61 | {"Aluminum Wire"} | 0.00061 |
| 9 | 61 | {"Aluminum Wire"} | 0.00061 |
| 10 | 61 | {"Brass Wire"} | 0.00031 |
| 11 | 61 | {"Brass Wire"} | 0.00033 |
| 12 | 61 | {"Filament"} | 0.00061 |
| 13 | 61 | {"Filament"} | 0.00061 |
| 14 | 61 | {"Filament"} | 0.00061 |
| 15 | 35 | {"PVC"} | 0.00001 |
| 16 | 35 | {"PVC"} | 0.00006 |
| 17 | 35 | {"PVC"} | 0.00009 |
| 18 | 35 | {"PVC"} | 0.00066 |
| 19 | 35 | {"PVC"} | 0.00012 |
| 20 | 35 | {"Shipper"} | 0.00735 |
| 21 | 35 | {"Shipper"} | 0.09045 |
| 22 | 35 | {"Shipper"} | 0.11737 |
| 23 | 35 | {"Shipper"} | 0.65786 |
| 24 | 35 | {"Backer Card"} | 0.00735 |
| 25 | 35 | {"Backer Card"} | 0.09045 |
| 26 | 35 | {"Backer Card"} | 0.11737 |
| 27 | 35 | {"Backer Card"} | 0.65786 |
| 15 | 36 | {"PVC"} | 0.00001 |
| 16 | 36 | {"PVC"} | 0.00006 |

| | | | |
|---|---|---|---|
| 17 | 36 | {"PVC"} | 0.00009 |
| 18 | 36 | {"PVC"} | 0.00066 |
| 19 | 36 | {"PVC"} | 0.00012 |
| 20 | 36 | {"Shipper"} | 0.00735 |
| 21 | 36 | {"Shipper"} | 0.09045 |
| 22 | 36 | {"Shipper"} | 0.11737 |
| 23 | 36 | {"Shipper"} | 0.65786 |
| 24 | 36 | {"Backer Card"} | 0.00735 |
| 25 | 36 | {"Backer Card"} | 0.09045 |
| 26 | 36 | {"Backer Card"} | 0.11737 |
| 27 | 36 | {"Backer Card"} | 0.65786 |
| 15 | 44 | {"PVC"} | 0.00009 |
| 16 | 44 | {"PVC"} | 0.00005 |
| 17 | 44 | {"PVC"} | 0.00001 |
| 18 | 44 | {"PVC"} | 0.00061 |
| 19 | 44 | {"PVC"} | 0.00011 |
| 20 | 44 | {"Shipper"} | 0.09045 |
| 21 | 44 | {"Shipper"} | 0.01103 |
| 22 | 44 | {"Shipper"} | 0.10978 |
| 23 | 44 | {"Shipper"} | 0.61194 |
| 24 | 44 | {"Backer Card"} | 0.09045 |
| 25 | 44 | {"Backer Card"} | 0.01103 |
| 26 | 44 | {"Backer Card"} | 0.10978 |
| 27 | 44 | {"Backer Card"} | 0.61194 |
| 15 | 45 | {"PVC"} | 0.00009 |
| 16 | 45 | {"PVC"} | 0.00005 |
| 17 | 45 | {"PVC"} | 0.00001 |
| 18 | 45 | {"PVC"} | 0.00061 |
| 19 | 45 | {"PVC"} | 0.00011 |
| 20 | 45 | {"Shipper"} | 0.09045 |
| 21 | 45 | {"Shipper"} | 0.01103 |
| 22 | 45 | {"Shipper"} | 0.10978 |
| 23 | 45 | {"Shipper"} | 0.61194 |
| 24 | 45 | {"Backer Card"} | 0.09045 |
| 25 | 45 | {"Backer Card"} | 0.01103 |
| 26 | 45 | {"Backer Card"} | 0.10978 |
| 27 | 45 | {"Backer Card"} | 0.61194 |
| 15 | 53 | {"PVC"} | 0.00012 |
| 16 | 53 | {"PVC"} | 0.00015 |
| 17 | 53 | {"PVC"} | 0.00011 |
| 18 | 53 | {"PVC"} | 0.00054 |
| 19 | 53 | {"PVC"} | 0.00001 |
| 20 | 53 | {"Shipper"} | 0.11737 |
| 21 | 53 | {"Shipper"} | 0.10978 |
| 22 | 53 | {"Shipper"} | 0.00809 |
| 23 | 53 | {"Shipper"} | 0.54360 |

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|---|---|---|---|
| 24 | 53 | {"Backer Card"} | 0.11737 |
| 25 | 53 | {"Backer Card"} | 0.10978 |
| 26 | 53 | {"Backer Card"} | 0.00809 |
| 27 | 53 | {"Backer Card"} | 0.54360 |
| 15 | 54 | {"PVC"} | 0.00012 |
| 16 | 54 | {"PVC"} | 0.00015 |
| 17 | 54 | {"PVC"} | 0.00011 |
| 18 | 54 | {"PVC"} | 0.00054 |
| 19 | 54 | {"PVC"} | 0.00001 |
| 20 | 54 | {"Shipper"} | 0.11737 |
| 21 | 54 | {"Shipper"} | 0.10978 |
| 22 | 54 | {"Shipper"} | 0.00809 |
| 23 | 54 | {"Shipper"} | 0.54360 |
| 24 | 54 | {"Backer Card"} | 0.11737 |
| 25 | 54 | {"Backer Card"} | 0.10978 |
| 26 | 54 | {"Backer Card"} | 0.00809 |
| 27 | 54 | {"Backer Card"} | 0.54360 |
| 15 | 62 | {"PVC"} | 0.00066 |
| 16 | 62 | {"PVC"} | 0.00065 |
| 17 | 62 | {"PVC"} | 0.00061 |
| 18 | 62 | {"PVC"} | 0.00001 |
| 19 | 62 | {"PVC"} | 0.00054 |
| 20 | 62 | {"Shipper"} | 0.65786 |
| 21 | 62 | {"Shipper"} | 0.61194 |
| 22 | 62 | {"Shipper"} | 0.54360 |
| 23 | 62 | {"Shipper"} | 0.00992 |
| 24 | 62 | {"Backer Card"} | 0.65786 |
| 25 | 62 | {"Backer Card"} | 0.61194 |
| 26 | 62 | {"Backer Card"} | 0.54360 |
| 27 | 62 | {"Backer Card"} | 0.00992 |
| 15 | 63 | {"PVC"} | 0.00066 |
| 16 | 63 | {"PVC"} | 0.00065 |
| 17 | 63 | {"PVC"} | 0.00061 |
| 18 | 63 | {"PVC"} | 0.00001 |
| 19 | 63 | {"PVC"} | 0.00054 |
| 20 | 63 | {"Shipper"} | 0.65786 |
| 21 | 63 | {"Shipper"} | 0.61194 |
| 22 | 63 | {"Shipper"} | 0.54360 |
| 23 | 63 | {"Shipper"} | 0.00992 |
| 24 | 63 | {"Backer Card"} | 0.65786 |
| 25 | 63 | {"Backer Card"} | 0.61194 |
| 26 | 63 | {"Backer Card"} | 0.54360 |
| 27 | 63 | {"Backer Card"} | 0.00992 |
| 35 | 64 | {"SKU C","SKU I","SKU K"} | 0.19033 |
| 35 | 65 | {"SKU C","SKU I","SKU K"} | 0.19438 |
| 35 | 66 | {"SKU C","SKU I","SKU K"} | 0.27863 |

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|---|---|---|---|
| 35 | 67 | {"SKU C","SKU I","SKU K"} | 0.32093 |
| 35 | 68 | {"SKU C","SKU I","SKU K"} | 0.30820 |
| 35 | 69 | {"SKU C","SKU I","SKU K"} | 0.02973 |
| 35 | 70 | {"SKU C","SKU I","SKU K"} | 0.05927 |
| 35 | 71 | {"SKU C","SKU I","SKU K"} | 0.00735 |
| 35 | 72 | {"SKU C","SKU I","SKU K"} | 0.09045 |
| 35 | 73 | {"SKU C","SKU I","SKU K"} | 0.11737 |
| 35 | 74 | {"SKU C","SKU I","SKU K"} | 0.04764 |
| 35 | 75 | {"SKU C","SKU I","SKU K"} | 0.06816 |
| 35 | 76 | {"SKU C","SKU I","SKU K"} | 0.04064 |
| 35 | 77 | {"SKU C","SKU I","SKU K"} | 0.50764 |
| 35 | 78 | {"SKU C","SKU I","SKU K"} | 0.42577 |
| 35 | 79 | {"SKU C","SKU I","SKU K"} | 0.56044 |
| 35 | 80 | {"SKU C","SKU I","SKU K"} | 0.57087 |
| 35 | 81 | {"SKU C","SKU I","SKU K"} | 0.65786 |
| 35 | 82 | {"SKU C","SKU I","SKU K"} | 0.20782 |
| 35 | 83 | {"SKU C","SKU I","SKU K"} | 0.29041 |
| 36 | 64 | {"SKU C","SKU I","SKU K"} | 0.19033 |
| 36 | 65 | {"SKU C","SKU I","SKU K"} | 0.19438 |
| 36 | 66 | {"SKU C","SKU I","SKU K"} | 0.27863 |
| 36 | 67 | {"SKU C","SKU I","SKU K"} | 0.32093 |
| 36 | 68 | {"SKU C","SKU I","SKU K"} | 0.30820 |
| 36 | 69 | {"SKU C","SKU I","SKU K"} | 0.02973 |
| 36 | 70 | {"SKU C","SKU I","SKU K"} | 0.05927 |
| 36 | 71 | {"SKU C","SKU I","SKU K"} | 0.00735 |
| 36 | 72 | {"SKU C","SKU I","SKU K"} | 0.09045 |
| 36 | 73 | {"SKU C","SKU I","SKU K"} | 0.11737 |
| 36 | 74 | {"SKU C","SKU I","SKU K"} | 0.04764 |
| 36 | 75 | {"SKU C","SKU I","SKU K"} | 0.06816 |
| 36 | 76 | {"SKU C","SKU I","SKU K"} | 0.04064 |
| 36 | 77 | {"SKU C","SKU I","SKU K"} | 0.50764 |
| 36 | 78 | {"SKU C","SKU I","SKU K"} | 0.42577 |
| 36 | 79 | {"SKU C","SKU I","SKU K"} | 0.56044 |
| 36 | 80 | {"SKU C","SKU I","SKU K"} | 0.57087 |
| 36 | 81 | {"SKU C","SKU I","SKU K"} | 0.65786 |
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| 36 | 83 | {"SKU C","SKU I","SKU K"} | 0.29041 |
| 44 | 64 | {"SKU C","SKU I","SKU K"} | 0.27499 |
| 44 | 65 | {"SKU C","SKU I","SKU K"} | 0.10502 |
| 44 | 66 | {"SKU C","SKU I","SKU K"} | 0.21890 |
| 44 | 67 | {"SKU C","SKU I","SKU K"} | 0.24430 |
| 44 | 68 | {"SKU C","SKU I","SKU K"} | 0.23827 |
| 44 | 69 | {"SKU C","SKU I","SKU K"} | 0.08262 |
| 44 | 70 | {"SKU C","SKU I","SKU K"} | 0.11848 |
| 44 | 71 | {"SKU C","SKU I","SKU K"} | 0.09045 |
| 44 | 72 | {"SKU C","SKU I","SKU K"} | 0.01103 |

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|---|---|---|---|
| 44 | 73 | {"SKU C","SKU I","SKU K"} | 0.10978 |
| 44 | 74 | {"SKU C","SKU I","SKU K"} | 0.12976 |
| 44 | 75 | {"SKU C","SKU I","SKU K"} | 0.05145 |
| 44 | 76 | {"SKU C","SKU I","SKU K"} | 0.01838 |
| 44 | 77 | {"SKU C","SKU I","SKU K"} | 0.42852 |
| 44 | 78 | {"SKU C","SKU I","SKU K"} | 0.34532 |
| 44 | 79 | {"SKU C","SKU I","SKU K"} | 0.49279 |
| 44 | 80 | {"SKU C","SKU I","SKU K"} | 0.57087 |
| 44 | 81 | {"SKU C","SKU I","SKU K"} | 0.61194 |
| 44 | 82 | {"SKU C","SKU I","SKU K"} | 0.17569 |
| 44 | 83 | {"SKU C","SKU I","SKU K"} | 0.29044 |
| 45 | 64 | {"SKU C","SKU I","SKU K"} | 0.27499 |
| 45 | 65 | {"SKU C","SKU I","SKU K"} | 0.10502 |
| 45 | 66 | {"SKU C","SKU I","SKU K"} | 0.21890 |
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| 45 | 68 | {"SKU C","SKU I","SKU K"} | 0.23827 |
| 45 | 69 | {"SKU C","SKU I","SKU K"} | 0.08262 |
| 45 | 70 | {"SKU C","SKU I","SKU K"} | 0.11848 |
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| 45 | 79 | {"SKU C","SKU I","SKU K"} | 0.49279 |
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| 53 | 64 | {"SKU C","SKU I","SKU K"} | 0.28747 |
| 53 | 65 | {"SKU C","SKU I","SKU K"} | 0.18343 |
| 53 | 66 | {"SKU C","SKU I","SKU K"} | 0.17039 |
| 53 | 67 | {"SKU C","SKU I","SKU K"} | 0.22684 |
| 53 | 68 | {"SKU C","SKU I","SKU K"} | 0.20679 |
| 53 | 69 | {"SKU C","SKU I","SKU K"} | 0.08767 |
| 53 | 70 | {"SKU C","SKU I","SKU K"} | 0.17565 |
| 53 | 71 | {"SKU C","SKU I","SKU K"} | 0.11737 |
| 53 | 72 | {"SKU C","SKU I","SKU K"} | 0.10978 |
| 53 | 73 | {"SKU C","SKU I","SKU K"} | 0.00809 |
| 53 | 74 | {"SKU C","SKU I","SKU K"} | 0.11347 |
| 53 | 75 | {"SKU C","SKU I","SKU K"} | 0.16100 |
| 53 | 76 | {"SKU C","SKU I","SKU K"} | 0.13420 |
| 53 | 77 | {"SKU C","SKU I","SKU K"} | 0.49950 |
| 53 | 78 | {"SKU C","SKU I","SKU K"} | 0.42196 |

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|---|---|---|---|
| 53 | 79 | {"SKU C","SKU I","SKU K"} | 0.57245 |
| 53 | 80 | {"SKU C","SKU I","SKU K"} | 0.58763 |
| 53 | 81 | {"SKU C","SKU I","SKU K"} | 0.54360 |
| 53 | 82 | {"SKU C","SKU I","SKU K"} | 0.09101 |
| 53 | 83 | {"SKU C","SKU I","SKU K"} | 0.18455 |
| 54 | 64 | {"SKU C","SKU I","SKU K"} | 0.28747 |
| 54 | 65 | {"SKU C","SKU I","SKU K"} | 0.18343 |
| 54 | 66 | {"SKU C","SKU I","SKU K"} | 0.17039 |
| 54 | 67 | {"SKU C","SKU I","SKU K"} | 0.22684 |
| 54 | 68 | {"SKU C","SKU I","SKU K"} | 0.20679 |
| 54 | 69 | {"SKU C","SKU I","SKU K"} | 0.08767 |
| 54 | 70 | {"SKU C","SKU I","SKU K"} | 0.17565 |
| 54 | 71 | {"SKU C","SKU I","SKU K"} | 0.11737 |
| 54 | 72 | {"SKU C","SKU I","SKU K"} | 0.10978 |
| 54 | 73 | {"SKU C","SKU I","SKU K"} | 0.00809 |
| 54 | 74 | {"SKU C","SKU I","SKU K"} | 0.11347 |
| 54 | 75 | {"SKU C","SKU I","SKU K"} | 0.16100 |
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| 54 | 77 | {"SKU C","SKU I","SKU K"} | 0.49950 |
| 54 | 78 | {"SKU C","SKU I","SKU K"} | 0.42196 |
| 54 | 79 | {"SKU C","SKU I","SKU K"} | 0.57245 |
| 54 | 80 | {"SKU C","SKU I","SKU K"} | 0.58763 |
| 54 | 81 | {"SKU C","SKU I","SKU K"} | 0.54360 |
| 54 | 82 | {"SKU C","SKU I","SKU K"} | 0.09101 |
| 54 | 83 | {"SKU C","SKU I","SKU K"} | 0.18455 |
| 62 | 64 | {"SKU C","SKU I","SKU K"} | 0.57316 |
| 62 | 65 | {"SKU C","SKU I","SKU K"} | 0.53169 |
| 62 | 66 | {"SKU C","SKU I","SKU K"} | 0.39577 |
| 62 | 67 | {"SKU C","SKU I","SKU K"} | 0.36810 |
| 62 | 68 | {"SKU C","SKU I","SKU K"} | 0.37378 |
| 62 | 69 | {"SKU C","SKU I","SKU K"} | 0.62925 |
| 62 | 70 | {"SKU C","SKU I","SKU K"} | 0.71512 |
| 62 | 71 | {"SKU C","SKU I","SKU K"} | 0.65786 |
| 62 | 72 | {"SKU C","SKU I","SKU K"} | 0.61194 |
| 62 | 73 | {"SKU C","SKU I","SKU K"} | 0.54360 |
| 62 | 74 | {"SKU C","SKU I","SKU K"} | 0.62345 |
| 62 | 75 | {"SKU C","SKU I","SKU K"} | 0.68539 |
| 62 | 76 | {"SKU C","SKU I","SKU K"} | 0.67333 |
| 62 | 77 | {"SKU C","SKU I","SKU K"} | 0.26920 |
| 62 | 78 | {"SKU C","SKU I","SKU K"} | 0.34232 |
| 62 | 79 | {"SKU C","SKU I","SKU K"} | 0.23471 |
| 62 | 80 | {"SKU C","SKU I","SKU K"} | 0.11899 |
| 62 | 81 | {"SKU C","SKU I","SKU K"} | 0.00992 |
| 62 | 82 | {"SKU C","SKU I","SKU K"} | 0.45569 |
| 62 | 83 | {"SKU C","SKU I","SKU K"} | 0.36750 |
| 63 | 64 | {"SKU C","SKU I","SKU K"} | 0.57316 |

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|---|---|---|---|
| 63 | 65 | {"SKU C","SKU I","SKU K"} | 0.53169 |
| 63 | 66 | {"SKU C","SKU I","SKU K"} | 0.39577 |
| 63 | 67 | {"SKU C","SKU I","SKU K"} | 0.36810 |
| 63 | 68 | {"SKU C","SKU I","SKU K"} | 0.37378 |
| 63 | 69 | {"SKU C","SKU I","SKU K"} | 0.62925 |
| 63 | 70 | {"SKU C","SKU I","SKU K"} | 0.71512 |
| 63 | 71 | {"SKU C","SKU I","SKU K"} | 0.65786 |
| 63 | 72 | {"SKU C","SKU I","SKU K"} | 0.61194 |
| 63 | 73 | {"SKU C","SKU I","SKU K"} | 0.54360 |
| 63 | 74 | {"SKU C","SKU I","SKU K"} | 0.62345 |
| 63 | 75 | {"SKU C","SKU I","SKU K"} | 0.68539 |
| 63 | 76 | {"SKU C","SKU I","SKU K"} | 0.67333 |
| 63 | 77 | {"SKU C","SKU I","SKU K"} | 0.26920 |
| 63 | 78 | {"SKU C","SKU I","SKU K"} | 0.34232 |
| 63 | 79 | {"SKU C","SKU I","SKU K"} | 0.23471 |
| 63 | 80 | {"SKU C","SKU I","SKU K"} | 0.11899 |
| 63 | 81 | {"SKU C","SKU I","SKU K"} | 0.00992 |
| 63 | 82 | {"SKU C","SKU I","SKU K"} | 0.45569 |
| 63 | 83 | {"SKU C","SKU I","SKU K"} | 0.36750 |
| 28 | 32 | {"Handle C","Handle I"} | 0.00000 |
| 28 | 33 | {"Handle C","Handle I"} | 0.00000 |
| 28 | 41 | {"Handle C","Handle I"} | 0.00090 |
| 28 | 42 | {"Handle C","Handle I"} | 0.00090 |
| 28 | 50 | {"Handle C","Handle I"} | 0.00117 |
| 28 | 51 | {"Handle C","Handle I"} | 0.00117 |
| 28 | 59 | {"Handle C","Handle I"} | 0.00658 |
| 28 | 60 | {"Handle C","Handle I"} | 0.00658 |
| 29 | 32 | {"Handle C","Handle I"} | 0.00000 |
| 29 | 33 | {"Handle C","Handle I"} | 0.00000 |
| 29 | 41 | {"Handle C","Handle I"} | 0.00090 |
| 29 | 42 | {"Handle C","Handle I"} | 0.00090 |
| 29 | 50 | {"Handle C","Handle I"} | 0.00117 |
| 29 | 51 | {"Handle C","Handle I"} | 0.00117 |
| 29 | 59 | {"Handle C","Handle I"} | 0.00658 |
| 29 | 60 | {"Handle C","Handle I"} | 0.00658 |
| 30 | 34 | {"Handle K"} | 0.00000 |
| 30 | 43 | {"Handle K"} | 0.00090 |
| 30 | 52 | {"Handle K"} | 0.00117 |
| 30 | 61 | {"Handle K"} | 0.00658 |
| 31 | 34 | {"Handle K"} | 0.00000 |
| 31 | 43 | {"Handle K"} | 0.00090 |
| 31 | 52 | {"Handle K"} | 0.00117 |
| 31 | 61 | {"Handle K"} | 0.00658 |
| 32 | 35 | {"Tier C","Tier I"} | 0.00000 |
| 32 | 36 | {"Tier C","Tier I"} | 0.00000 |
| 32 | 44 | {"Tier C","Tier I"} | 0.00090 |

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|---|---|---|---|
| 32 | 45 | {"Tier C","Tier I"} | 0.00090 |
| 32 | 53 | {"Tier C","Tier I"} | 0.00117 |
| 32 | 54 | {"Tier C","Tier I"} | 0.00117 |
| 32 | 62 | {"Tier C","Tier I"} | 0.00658 |
| 32 | 63 | {"Tier C","Tier I"} | 0.00658 |
| 33 | 35 | {"Tier C","Tier I"} | 0.00000 |
| 33 | 36 | {"Tier C","Tier I"} | 0.00000 |
| 33 | 44 | {"Tier C","Tier I"} | 0.00090 |
| 33 | 45 | {"Tier C","Tier I"} | 0.00090 |
| 33 | 53 | {"Tier C","Tier I"} | 0.00117 |
| 33 | 54 | {"Tier C","Tier I"} | 0.00117 |
| 33 | 62 | {"Tier C","Tier I"} | 0.00658 |
| 33 | 63 | {"Tier C","Tier I"} | 0.00658 |
| 34 | 35 | {"Tier K"} | 0.00000 |
| 34 | 36 | {"Tier K"} | 0.00000 |
| 34 | 44 | {"Tier K"} | 0.00090 |
| 34 | 45 | {"Tier K"} | 0.00090 |
| 34 | 53 | {"Tier K"} | 0.00117 |
| 34 | 54 | {"Tier K"} | 0.00117 |
| 34 | 62 | {"Tier K"} | 0.00658 |
| 34 | 63 | {"Tier K"} | 0.00658 |
| 37 | 32 | {"Handle C","Handle I"} | 0.00090 |
| 37 | 33 | {"Handle C","Handle I"} | 0.00090 |
| 37 | 41 | {"Handle C","Handle I"} | 0.00000 |
| 37 | 42 | {"Handle C","Handle I"} | 0.00000 |
| 37 | 50 | {"Handle C","Handle I"} | 0.00110 |
| 37 | 51 | {"Handle C","Handle I"} | 0.00110 |
| 37 | 59 | {"Handle C","Handle I"} | 0.00612 |
| 37 | 60 | {"Handle C","Handle I"} | 0.00612 |
| 38 | 32 | {"Handle C","Handle I"} | 0.00090 |
| 38 | 33 | {"Handle C","Handle I"} | 0.00090 |
| 38 | 41 | {"Handle C","Handle I"} | 0.00000 |
| 38 | 42 | {"Handle C","Handle I"} | 0.00000 |
| 38 | 50 | {"Handle C","Handle I"} | 0.00110 |
| 38 | 51 | {"Handle C","Handle I"} | 0.00110 |
| 38 | 59 | {"Handle C","Handle I"} | 0.00612 |
| 38 | 60 | {"Handle C","Handle I"} | 0.00612 |
| 39 | 34 | {"Handle K"} | 0.00090 |
| 39 | 43 | {"Handle K"} | 0.00000 |
| 39 | 52 | {"Handle K"} | 0.00110 |
| 39 | 61 | {"Handle K"} | 0.00612 |
| 40 | 34 | {"Handle K"} | 0.00090 |
| 40 | 43 | {"Handle K"} | 0.00000 |
| 40 | 52 | {"Handle K"} | 0.00110 |
| 40 | 61 | {"Handle K"} | 0.00612 |
| 41 | 35 | {"Tier C","Tier I"} | 0.00090 |

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|---|---|---|---|
| 41 | 36 | {"Tier C","Tier I"} | 0.00090 |
| 41 | 44 | {"Tier C","Tier I"} | 0.00000 |
| 41 | 45 | {"Tier C","Tier I"} | 0.00000 |
| 41 | 53 | {"Tier C","Tier I"} | 0.00110 |
| 41 | 54 | {"Tier C","Tier I"} | 0.00110 |
| 41 | 62 | {"Tier C","Tier I"} | 0.00612 |
| 41 | 63 | {"Tier C","Tier I"} | 0.00612 |
| 42 | 35 | {"Tier C","Tier I"} | 0.00090 |
| 42 | 36 | {"Tier C","Tier I"} | 0.00090 |
| 42 | 44 | {"Tier C","Tier I"} | 0.00000 |
| 42 | 45 | {"Tier C","Tier I"} | 0.00000 |
| 42 | 53 | {"Tier C","Tier I"} | 0.00110 |
| 42 | 54 | {"Tier C","Tier I"} | 0.00110 |
| 42 | 62 | {"Tier C","Tier I"} | 0.00612 |
| 42 | 63 | {"Tier C","Tier I"} | 0.00612 |
| 43 | 35 | {"Tier K"} | 0.00090 |
| 43 | 36 | {"Tier K"} | 0.00090 |
| 43 | 44 | {"Tier K"} | 0.00000 |
| 43 | 45 | {"Tier K"} | 0.00000 |
| 43 | 53 | {"Tier K"} | 0.00110 |
| 43 | 54 | {"Tier K"} | 0.00110 |
| 43 | 62 | {"Tier K"} | 0.00612 |
| 43 | 63 | {"Tier K"} | 0.00612 |
| 46 | 32 | {"Handle C","Handle I"} | 0.00117 |
| 46 | 33 | {"Handle C","Handle I"} | 0.00117 |
| 46 | 41 | {"Handle C","Handle I"} | 0.00110 |
| 46 | 42 | {"Handle C","Handle I"} | 0.00110 |
| 46 | 50 | {"Handle C","Handle I"} | 0.00000 |
| 46 | 51 | {"Handle C","Handle I"} | 0.00000 |
| 46 | 59 | {"Handle C","Handle I"} | 0.00544 |
| 46 | 60 | {"Handle C","Handle I"} | 0.00544 |
| 47 | 32 | {"Handle C","Handle I"} | 0.00117 |
| 47 | 33 | {"Handle C","Handle I"} | 0.00117 |
| 47 | 41 | {"Handle C","Handle I"} | 0.00110 |
| 47 | 42 | {"Handle C","Handle I"} | 0.00110 |
| 47 | 50 | {"Handle C","Handle I"} | 0.00000 |
| 47 | 51 | {"Handle C","Handle I"} | 0.00000 |
| 47 | 59 | {"Handle C","Handle I"} | 0.00544 |
| 47 | 60 | {"Handle C","Handle I"} | 0.00544 |
| 48 | 34 | {"Handle K"} | 0.00117 |
| 48 | 43 | {"Handle K"} | 0.00110 |
| 48 | 52 | {"Handle K"} | 0.00000 |
| 48 | 61 | {"Handle K"} | 0.00544 |
| 49 | 34 | {"Handle K"} | 0.00117 |
| 49 | 43 | {"Handle K"} | 0.00110 |
| 49 | 52 | {"Handle K"} | 0.00000 |

| | | | |
|---|---|---|---|
| 49 | 61 | {"Handle K"} | 0.00544 |
| 50 | 35 | {"Tier C","Tier I"} | 0.00117 |
| 50 | 36 | {"Tier C","Tier I"} | 0.00117 |
| 50 | 44 | {"Tier C","Tier I"} | 0.00110 |
| 50 | 45 | {"Tier C","Tier I"} | 0.00110 |
| 50 | 53 | {"Tier C","Tier I"} | 0.00000 |
| 50 | 54 | {"Tier C","Tier I"} | 0.00000 |
| 50 | 62 | {"Tier C","Tier I"} | 0.00544 |
| 50 | 63 | {"Tier C","Tier I"} | 0.00544 |
| 51 | 35 | {"Tier C","Tier I"} | 0.00117 |
| 51 | 36 | {"Tier C","Tier I"} | 0.00117 |
| 51 | 44 | {"Tier C","Tier I"} | 0.00110 |
| 51 | 45 | {"Tier C","Tier I"} | 0.00110 |
| 51 | 53 | {"Tier C","Tier I"} | 0.00000 |
| 51 | 54 | {"Tier C","Tier I"} | 0.00000 |
| 51 | 62 | {"Tier C","Tier I"} | 0.00544 |
| 51 | 63 | {"Tier C","Tier I"} | 0.00544 |
| 52 | 35 | {"Tier K"} | 0.00117 |
| 52 | 36 | {"Tier K"} | 0.00117 |
| 52 | 44 | {"Tier K"} | 0.00110 |
| 52 | 45 | {"Tier K"} | 0.00110 |
| 52 | 53 | {"Tier K"} | 0.00000 |
| 52 | 54 | {"Tier K"} | 0.00000 |
| 52 | 62 | {"Tier K"} | 0.00544 |
| 52 | 63 | {"Tier K"} | 0.00544 |
| 55 | 32 | {"Handle C","Handle I"} | 0.00658 |
| 55 | 33 | {"Handle C","Handle I"} | 0.00658 |
| 55 | 41 | {"Handle C","Handle I"} | 0.00612 |
| 55 | 42 | {"Handle C","Handle I"} | 0.00612 |
| 55 | 50 | {"Handle C","Handle I"} | 0.00544 |
| 55 | 51 | {"Handle C","Handle I"} | 0.00544 |
| 55 | 59 | {"Handle C","Handle I"} | 0.00000 |
| 55 | 60 | {"Handle C","Handle I"} | 0.00000 |
| 56 | 32 | {"Handle C","Handle I"} | 0.00658 |
| 56 | 33 | {"Handle C","Handle I"} | 0.00658 |
| 56 | 41 | {"Handle C","Handle I"} | 0.00612 |
| 56 | 42 | {"Handle C","Handle I"} | 0.00612 |
| 56 | 50 | {"Handle C","Handle I"} | 0.00544 |
| 56 | 51 | {"Handle C","Handle I"} | 0.00544 |
| 56 | 59 | {"Handle C","Handle I"} | 0.00000 |
| 56 | 60 | {"Handle C","Handle I"} | 0.00000 |
| 57 | 34 | {"Handle K"} | 0.00658 |
| 57 | 43 | {"Handle K"} | 0.00612 |
| 57 | 52 | {"Handle K"} | 0.00544 |
| 57 | 61 | {"Handle K"} | 0.00000 |
| 58 | 34 | {"Handle K"} | 0.00658 |

|  |  |  |  |
|---|---|---|---|
| 58 | 43 | {"Handle K"} | 0.00612 |
| 58 | 52 | {"Handle K"} | 0.00544 |
| 58 | 61 | {"Handle K"} | 0.00000 |
| 59 | 35 | {"Tier C","Tier I"} | 0.00658 |
| 59 | 36 | {"Tier C","Tier I"} | 0.00658 |
| 59 | 44 | {"Tier C","Tier I"} | 0.00612 |
| 59 | 45 | {"Tier C","Tier I"} | 0.00612 |
| 59 | 53 | {"Tier C","Tier I"} | 0.00544 |
| 59 | 54 | {"Tier C","Tier I"} | 0.00544 |
| 59 | 62 | {"Tier C","Tier I"} | 0.00000 |
| 59 | 63 | {"Tier C","Tier I"} | 0.00000 |
| 60 | 35 | {"Tier C","Tier I"} | 0.00658 |
| 60 | 36 | {"Tier C","Tier I"} | 0.00658 |
| 60 | 44 | {"Tier C","Tier I"} | 0.00612 |
| 60 | 45 | {"Tier C","Tier I"} | 0.00612 |
| 60 | 53 | {"Tier C","Tier I"} | 0.00544 |
| 60 | 54 | {"Tier C","Tier I"} | 0.00544 |
| 60 | 62 | {"Tier C","Tier I"} | 0.00000 |
| 60 | 63 | {"Tier C","Tier I"} | 0.00000 |
| 61 | 35 | {"Tier K"} | 0.00658 |
| 61 | 36 | {"Tier K"} | 0.00658 |
| 61 | 44 | {"Tier K"} | 0.00612 |
| 61 | 45 | {"Tier K"} | 0.00612 |
| 61 | 53 | {"Tier K"} | 0.00544 |
| 61 | 54 | {"Tier K"} | 0.00544 |
| 61 | 62 | {"Tier K"} | 0.00000 |
| 61 | 63 | {"Tier K"} | 0.00000 |

# Appendix B

# OPL Model

```
*********************************************
 * OPL 12.6.0.0 Model
 * Author: Administrator
 * Creation Date: Aug 25, 2015 at 10:43:40 AM
 *********************************************/

{int} V =...; //set of nodes in the network
{int} S =...; //set of nodes representing suppliers
{int} C =...; //set of nodes representing customers
{int} O =...; //set of capacity options
{string} States ={"pessimistic","most likely","optimistic"};

//BOM Structure
tuple BOM {
	string Master_Item;
	string Sub_Item;
	float Conversion;
}

{BOM} BOM_Data=...;

//Material
tuple Material{
	string Item_Name;
	string Category;
}

{Material} Material_Data=...;

{string} K =...; //set of components (or commodites)
{string} K_Dummy=...; //set of dummy components
{string} F =...; //set of finished goods


tuple Process{
	int Node;
	{string} Output; // Components or Product produced by the Process
}

{Process} P =...; //information about requirement of each process;


tuple Edge{
	int fromnode; //Origin Node
	int tonode;   //Destination Node
	{string} commodity; //Required Components
	float transport_cost; //Transportation cost
};

{Edge} Edges=...; //Arc connecting nodes over the network
```

```
tuple Location{
      {int}Associated_Nodes;
};

{Location} L=...;

float Ultilization_Target=...;

float Production_Limit_Ratio=...;

float Unit_Sourcing_Cost[S][K]=...;//Sourcing cost of component k using
supplier s

float Unit_Production_Cost [States][O][V diff (S union C)][K union
F]=...;//Production cost of component k using a capacity level at a
location

float Unit_Shortage_Cost[F]=...; //Cost for each unsatisfied demand

int Demand[States][C][F]=...; //Demand at each customer location

int Open[States][L]=...; // Cost of Opening a location

int Setup[States][ V diff (S union C)][O]=...; // Cost of installing a kind
of capacity in a location

int Cap[V diff (S union C)][O]=...; // Capacity for each option in a
location

int Sup[S][K]=...; // Supply capacity of suppliers

//Decision Variables
dvar boolean Y[L]; //Location Decision

dvar boolean Z[V diff (S union C)][O]; //Option Decision

dvar int+ X[Edges][K_Dummy union F][O]; //Flow Quantity

dvar int+ Shortage[States][C][F]; //Shortage Demand

dvar float+ alpha;

//Cost Expression

//Opening Cost term in most likely situation
dexpr float Opening_Cost_M = sum (event in States:event=="most likely",l in
L)Y[l]*Open[event][l];

//Opening Cost term in optimistic situation
dexpr float Opening_Cost_O = sum (event in States:event=="optimistic",l in
L)Y[l]*Open[event][l];

//Opening Cost term in pessimistic situation
```

```
dexpr float Opening_Cost_P = sum (event in States:event=="pessimistic",l in
L)Y[l]*Open[event][l];

//Setup Cost term in most likely situation
dexpr float Setup_Cost_M = sum (event in States:event=="most likely",i in V
diff (S union C), o in O)Z[i][o]*Setup[event][i][o];

//Setup Cost term in optimistic situation
dexpr float Setup_Cost_O = sum (event in States:event=="optimistic",i in V
diff (S union C), o in O)Z[i][o]*Setup[event][i][o];

//Setup Cost term in pessimistic situation
dexpr float Setup_Cost_P = sum (event in States:event=="pessimistic",i in V
diff (S union C), o in O)Z[i][o]*Setup[event][i][o];

dexpr float Transportation_Cost = sum (e in Edges,k in K_Dummy union F,o in
O)X[e][k][o]*e.transport_cost;

dexpr float Procurement_Cost = sum (s in S, e in Edges:
e.fromnode==s,k_dummy in K_Dummy,m in Material_Data:m.Item_Name==k_dummy, k
in e.commodity:k==m.Category, o in
O)X[e][k_dummy][o]*Unit_Sourcing_Cost[e.fromnode][k];

//Production Cost term in most likely situation
dexpr float Production_Cost_M = sum (event in States:event=="most likely",i
in V diff (S union C), e in Edges: e.fromnode==i, k in e.commodity,o in
O)X[e][k][o]*Unit_Production_Cost[event][o][e.fromnode][k];

//Production Cost term in optimistic situation
dexpr float Production_Cost_O = sum (event in States:event=="optimistic",i
in V diff (S union C), e in Edges: e.fromnode==i, k in e.commodity,o in
O)X[e][k][o]*Unit_Production_Cost[event][o][e.fromnode][k];

//Production Cost term in pessimistic situation
dexpr float Production_Cost_P = sum (event in States:event=="pessimistic",i
in V diff (S union C), e in Edges: e.fromnode==i, k in e.commodity,o in
O)X[e][k][o]*Unit_Production_Cost[event][o][e.fromnode][k];

//Shortage Cost term in pessimistic situation
dexpr float Shortage_Cost_P=sum(event in States:event=="pessimistic",i in
C,k in F)Shortage[event][i][k]*Unit_Shortage_Cost[k];

//Shortage Cost term in most likely situation
dexpr float Shortage_Cost_M=sum(event in States:event=="most likely",i in
C,k in F)Shortage[event][i][k]*Unit_Shortage_Cost[k];

//Opening Cost term in optimistic situation
dexpr float Shortage_Cost_O=sum(event in States:event=="optimistic",i in
C,k in F)Shortage[event][i][k]*Unit_Shortage_Cost[k];

//Total Cost in pessimistic situation
dexpr float z_p =
Opening_Cost_P+Setup_Cost_P+Transportation_Cost+Procurement_Cost+Production
_Cost_P+Shortage_Cost_P;

//Total Cost in most likely situation
```

```
dexpr float z_m =
Opening_Cost_M+Setup_Cost_M+Transportation_Cost+Procurement_Cost+Production
_Cost_M+Shortage_Cost_M;

//Total Cost in optimistic situation
dexpr float z_o =
Opening_Cost_O+Setup_Cost_O+Transportation_Cost+Procurement_Cost+Production
_Cost_O+Shortage_Cost_O;

//Objective Function
//minimize
Opening_Cost+Setup_Cost+Transportation_Cost+Procurement_Cost+Production_Cos
t+Shortage_Cost_P;

//*******************************
// Epsilon Approach
//*******************************

//minimize z_o; // Iteration 1

//minimize z_m; // Iteration 2


//Replication 1
minimize z_o; // Iteration 1 - relax pessimistic by 5%

//Replication 2
//minimize z_m; // Iteration 1 - relax pessimistic by 5%

//minimize z_o; // Iteration 2 - relax pessimistic by 5%
//*******************************
//
//*******************************

//Constraints
subject to{

//*******************************
// Epsilon Approach
//*******************************

	//z_o<= 48043527;

	//Iternation 1 - relax pessimistic by 5%
	//z_p<= 65392421*1.05;
	//z_o<= 48043527;

	//Iternation 2 - relax pessimistic by 5%
	z_p<= 65392421*1.05;
	z_m<= 50799666;

//*******************************
//
//*******************************
```

```
       //Supply
       ctSupply:
       forall (i in S, k in K)
         sum (e in Edges: e.fromnode==i, k1 in K_Dummy, m in 
Material_Data:m.Item_Name==k1, c in e.commodity:c==m.Category&&c==k,o in 
O:o==1)X[e][k1][o]<=Sup[i][k];

       forall (i in S, k in K)
         sum (e in Edges: e.fromnode==i, k1 in K_Dummy, m in 
Material_Data:m.Item_Name==k1, c in e.commodity:c==m.Category&&c==k,o in 
O:o!=1)X[e][k1][o]<=0;

       //Demand
       ctDemand:
       forall (event in States, i in C, k in F)
         sum (e in Edges: e.tonode==i, c in e.commodity:c==k, o in 
O)X[e][k][o]>=Demand[event][i][k]-Shortage[event][i][k];

       forall (event in States, i in C, k in F)
         Shortage[event][i][k]<=Demand[event][i][k];

       //Balance
       ctBalance:
       forall (h in V diff (S union C))
         forall (p in P: p.Node==h, comp in p.Output,b in BOM_Data: 
b.Master_Item==comp)
           sum (e1 in Edges:e1.tonode==h, c1 in K_Dummy: c1==b.Sub_Item, m 
in Material_Data:m.Item_Name==c1, c in e1.commodity:c==m.Category, o in 
O)X[e1][c1][o]/b.Conversion==
           sum (e2 in Edges:e2.fromnode==h,c2 in e2.commodity:c2==comp,o in 
O)X[e2][c2][o];

       //Node constraint
       ctUpper_Capacity_Limit:
       forall (h in V diff (S union C), o in O)
         sum (e in Edges:e.fromnode==h,c in 
e.commodity)X[e][c][o]<=Z[h][o]*Cap[h][o];

       //Location Constraint
       ctLocation:
       forall (l in L, l1 in l.Associated_Nodes, i in V diff(S union 
C):i==l1, o in O)Z[i][o]<=Y[l];

       //Capacity Selection
       ctCapacity:
       forall (i in V diff (S union C))
         sum (o in O)Z[i][o]<=1;


}
```