

OPTIMAL CONFIGURATION AND PARTNER SELECTION IN DYNAMIC MANUFACTURING NETWORKS

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ABSTRACT

In this paper we develop a linear programming model for integrated partner selection and scheduling in a web-enabled global manufacturing network environment. We assume that all stakeholders in the supply chain share information on their capacities, schedules and cost structures. Based on this information, the model addresses the issue of partner selection for minimal cost of manufacturing and delivery. The model is solved using ILOG optimization tools.

1. INTRODUCTION

In this age of globalization, the ability of companies to meet rising customer expectations at lower operating costs has become a key competitive advantage. In order to enhance their competitiveness, companies no longer take ownership of all the assets and processes needed in delivering value to the customer. Instead they focus on their core competencies and partner with companies possessing complementary strengths. This together with a variety of other reasons has resulted in geographically distributed manufacturing, wherein, different components produced in different countries are assembled in another and the final product is customized at the customer's site in yet another country.

In this scenario, there is critical need for developing methods for partner selection and coordination among them and for integrated planning. Thankfully, the Internet provides the necessary platform to enable the seamless distribution of data, information, and knowledge across the entire value chain. The Internet thus has enabled effective monitoring of the activities executed by one's partners thereby further promoting and supporting the outsourcing of sub-processes and activities.

Our thinking in this paper is in line with emerging trends in collaborative e-commerce and the concept of value webs [1]. A value web is a dynamically changing network of independent companies, linked by the Internet to offer value to different customers [3]. The information linkages between companies are formed in real-time through the Internet, in response to market conditions and sometimes the formation of these linkages are facilitated by electronic marketplaces.

In the formation of effective value webs, the choice of partners for fulfillment of each and every order is important. This requires the development of optimization models and solutions, for partnership selection and value delivery, making full use of the information available on capacities, inventories, lead times, production-schedules and cost.

There is a significant amount of literature existing on partner selection in the operations research and management science literature. Weber and Current [4] discuss a multi-criteria analysis for vendor selection. They develop a model for minimizing total cost, late deliveries and supply rejection given the infrastructure constraints and constraints imposed by the company's policy. Arntzen et al [5] describe a global supply chain management model that was implemented at Digital Equipment Corporation. The model incorporates capacity constraints, import taxes, fixed charges, transportation constraints etc and recommends a production, distribution and supplier network. Erenguc et al [6] review and evaluates some of the relevant literature on production and distribution planning at each stage of the supply chain. The interested reader might find [7] useful for a comprehensive classification of publications on vendor selection criteria. Some other researchers have focused on the production scheduling aspects of the supply chain. Bretthauer and Cote [8] talk about a non-linear programming model for multi-period capacity planning.

Thus in the literature, most efforts have revolved around the selection of suppliers for a particular manufacturer. Our research here attempts to do much more. We select the supply chain configuration for every customer order and additionally provide the schedules for the manufacturing, assembly and inbound transportation within the supply chain. In fact, we embed the capacity availability and the fixed schedules of air/sea carriers into our algorithm and find the optimal component manufacture and assembly schedules. Our purpose in this paper is to develop a mathematical programming model for partner selection and supply chain design, and in the process build an integrated planning decision support system for channel-masters, supply chain process-owners and electronic market participants. We consider a four-tier supply chain with buyers, brand manufacturers, sub-assembly manufacturers, component suppliers and logistics service providers. The model determines the

optimal order quantities to be allocated to each of the manufacturers, suppliers and logistics service providers and determines the production and delivery schedules for each of them.

In the remaining four sections of this paper we develop a linear programming model for integrated partner selection and scheduling in a web-enabled global manufacturing network environment. We begin by describing the problem we wish to address. We also formulate a linear programming model for integrated partner selection and scheduling. In the subsequent section we briefly describe the ILOG tools used in solving the model. We then proceed to present and discuss some of our results under the section on computational results. And finally we conclude by jotting down some of our observations in the field of electronic supply chains.

2. PROBLEM FORMULATION

2.1 Problem Description

We assume that there are a number of component suppliers, sub-assembly manufacturers, brand manufacturers and logistics service providers in different geographical locations. They all share information on their production schedules, capacity, cost, quality, etc. We also assume that there are a number of buyers with orders for a range of finished goods. These orders can be fulfilled by different sets of manufacturers and suppliers at different costs and in different lead times with the support of the logistics service providers. The logistics service providers have their own costs, capacity constraints and fixed shipping schedules. With access to operational information on all the participants in an electronic supply chain the challenge is, how best to meet the demands of the buyers, using a combination of sellers and logistics providers with minimal operational cost. In particular, a collaborative approach in supply chain management and coordination is required to form an effective and efficient value web. The Internet has enabled economically viable real-time supply chain coordination in value webs as shown in Figure 2.

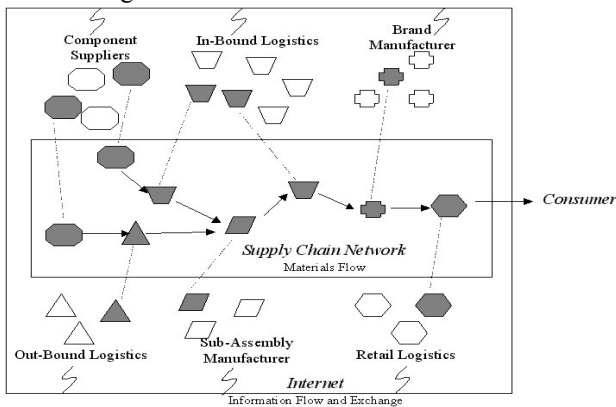


Figure 2: Supply Chain Configuration and Coordination between a set of partners using the Internet.

The challenge for a value web is the selection of the suppliers, assemblers and logistics service providers who can collectively meet the deadlines of the buyers and maximize the value delivered. Apart from incorporating the capacity constraints in the supply chain decisions, production activities need to be synchronized with the schedules of the logistics service providers, so that items can be ready for pickup in a just-in-time manner, instead of having to wait in inventory. There can be significant cost-savings in this exercise, through reduced inventory levels.

2.2 Notation

For development of a mathematical model for the above scenario, the following notations were used.

Identifiers

r	: Component type identifier.
R	: Number of component types.
v	: Component supplier identifier.
V	: Number of component suppliers.
i	: Sub-assembly type identifier.
I	: Number of sub-assembly types.
j	: Sub-assembly supplier identifier.
J	: Number of sub-assembly suppliers.
k	: Manufacturer Identifier.
K	: Number of Manufacturers.
m	: Buyer Identifier.
M	: Number of Buyers.
l	: Brand Identifier.
L	: Number of Brands.
t	: Time Period identifier.
T	: Total time horizon of the model.

Parameters

C_{abt}	: Maximum production capacity for component/sub-assembly/brand of type a offered by Component Supplier/Sub-Assembly Supplier/Manufacturer b in time period t .
P_{ab}	: Unit cost price for component/sub-assembly/brand of type a procured from Component Supplier/Sub-Assembly Supplier/Manufacturer b .
T_{abdt}	: Maximum transportation capacity for shipment of component/sub-assembly/brand of type a from Component Supplier/Sub-Assembly Supplier/Manufacturer b to its customer d in time period t .
U_{abdt}	: Unit transportation cost for shipment of component/sub-assembly/brand of type a from Component Supplier or Sub-Assembly Supplier or Manufacturer b to its customer d in time period t .
W_{ab}	: Unit inventory cost incurred for component/sub-assembly/brand of type a in the possession of Component Supplier or Sub-Assembly Supplier or Manufacturer b .
Q_{ab}	: Quantity for model type a required by Buyer b .

- D_{ab} : Time period by which required quantity for model type a is to be delivered to Buyer b .
 R_{ab} : Units of component type a required in the production of one unit of sub-assembly b .
 M_{ab} : Units of sub-assembly type a required in the production of one unit of model b .

Variables

- Q_{abt} : Quantity produced for component/sub-assembly/brand a by Component Supplier/Sub-Assembly Supplier/Manufacturer b in t .
 I_{abt} : Inventory of component/sub-assembly/brand a with Component Supplier or Sub-Assembly Supplier or Manufacturer b in time period t .
 S_{abdt} : Quantity shipped of component/sub-assembly/brand of type a from Component Supplier or Sub-Assembly Supplier or Manufacturer b to its customer d in time period t .

2.3 LP Model

We now develop a linear programming model for a dynamic manufacturing network. The objective of the model was to maximize the profit earned by the configurable manufacturing network subject to various capacity, production and logistics schedules and flow balancing constraints.

The profit was calculated, as given in Eqn. 1, as the sum of the revenue made from sales to the buyers, less the production costs and the costs incurred in the operation of the supply chain network, specifically transportation and inventory costs.

$$\begin{aligned}
 \text{MaxPROFIT} = & \sum_{l=1}^L \sum_{m=1}^M P_{lm} Q_{lm} \\
 & - \left[\sum_{r=1}^R \sum_{v=1}^V \sum_{j=1}^J \left(\sum_{t=1}^T S_{rvjt} U_{rvjt} + P_{rv} \sum_{t=1}^T S_{rvjt} \right) \right. \\
 & + \sum_{i=1}^I \sum_{j=1}^J \sum_{k=1}^K \left(\sum_{t=1}^T S_{ijkt} U_{ijkt} + P_{ij} \sum_{t=1}^T S_{ijkt} \right) \\
 & \left. + \sum_{l=1}^L \sum_{k=1}^K \sum_{m=1}^M \left(\sum_{t=1}^T S_{lkmt} U_{lkmt} + P_{lk} \sum_{t=1}^T S_{lkmt} \right) \right] \\
 & - \left[\sum_{i=1}^I \left(\sum_{r=1}^R \sum_{v=1}^V W_{rv} I_{rvt} + \sum_{r=1}^R \sum_{j=1}^J W_{rj} I_{rjt} \right) \right. \\
 & + \sum_{i=1}^I \sum_{j=1}^J W_{ij} I_{ijt} + \sum_{i=1}^I \sum_{k=1}^K W_{ik} I_{ikt} \\
 & \left. + \sum_{l=1}^L \sum_{k=1}^K W_{lk} I_{lkt} + \sum_{l=1}^L \sum_{m=1}^M W_{lm} I_{lmt} \right] \quad \dots (1)
 \end{aligned}$$

There are various capacity constraints in the virtual supply chain that make the solution non-trivial.

The component suppliers cannot produce more than their maximum production capacity. Hence,

$$Q_{rvt} \leq C_{rvt} \quad \text{forall } r \in R, v \in V \text{ \& } t \in T \quad \dots (2)$$

The components produced are held at the component suppliers end until they are shipped off to sub-assembly manufacturers. The production of new components adds to the inventory held by the supplier at the end of each time, while the products sold and shipped to the sub-assembly manufacturers in each time period reduces the suppliers inventory.

$$I_{rv(t-1)} + Q_{rvt} = \sum_{j=1}^J S_{rvjt} + I_{rvt} \quad \text{forall } r \in R, v \in V, j \in J \text{ \& } t \in T \quad \dots (3)$$

However, the quantity that can be transported in a single period is constrained by the maximum capacity of the transportation infrastructure. Considering our scenario with fixed shipping schedules, in time-periods when the service is available the transportation capacity is non-zero. However, for time-periods where particular flights or shipments are not scheduled the transportation capacity is zero. Hence the transportation of the component types from the component suppliers to the sub-assembly manufacturers site is bound by the below constraint.

$$S_{rvjt} \leq T_{rvjt} \quad \text{forall } r \in R, v \in V, j \in J \text{ \& } t \in T \quad \dots (4)$$

Once the components reach the sub-assembly manufacturer from the component supplier it adds to the manufacturer's inventory, which is then consumed by the production process. However before the manufacturing process can start and the component type can be consumed, the sub-assembly manufacturer will need to check adequate availability of all components that will be used in the sub-assembly production process. This imposes the following constraint on the component availability and the sub-assembly production.

$$I_{rj(t-1)} \geq \sum_{i=1}^I R_{ir} Q_{ijt} \quad \text{forall } r \in R, i \in I, j \in J, t \in T \quad \dots (5)$$

However once the production process begins the inventory drops. The inventory status for component types with the manufacturer can be determined as given below in Eqn. 6.

$$I_{rj(t-1)} + \sum_{v=1}^V S_{rvjt} = \sum_{i=1}^I R_{ir} Q_{ijt} + I_{rjt} \quad \text{forall } r \in R, v \in V, j \in J, i \in I \text{ \& } t \in T \quad \dots (6)$$

The capacity constraints and the inventory constraints that apply to the component suppliers apply to the sub-assembly manufacturers as well. The maximum production of sub-assemblies is constrained by the production capacity of the sub-assembler.

$$Q_{ijt} \leq C_{ijt} \quad \text{forall } i \in I, j \in J \text{ \& } t \in T \quad \dots (7)$$

The inventory of sub-assemblies at the sub-assembly manufacturers end increases at the end of each period by the quantity produced and decreases by the amount of sub-assemblies shipped out to customers, in that time period.

$$I_{ijt(t-1)} + Q_{ijt} = \sum_{k=1}^K S_{ijkt} + I_{ijt} \quad \text{for all } i \in I, j \in J, k \in K \& t \in T \quad \dots (8)$$

The quantity of sub-assemblies that can be shipped is constrained by the capacity of the transportation infrastructure.

$$S_{ijkt} \leq T_{ijkt} \quad \text{for all } i \in I, j \in J, k \in K \& t \in T \quad \dots (9)$$

The shipped sub-assemblies will be stored at the manufacturer's end. Only in the case of sufficient availability of all the needed sub-assemblies, will production of the brands begin.

$$I_{ik(t-1)} \geq \sum_{l=1}^L M_{li} Q_{lkt} \quad \text{for all } i \in I, l \in L, k \in K, t \in T \quad \dots (10)$$

As regards the inventory levels of sub-assemblies at the manufacturer's end incoming stocks will add to the inventory and sub-assemblies stocks will be used in the production of the brands. The inventory status for sub-assembly types with the manufacturer can be determined as given below in Eqn. 11.

$$I_{ik(t-1)} + \sum_{j=1}^J S_{ijkt} = \sum_{l=1}^L M_{li} Q_{lkt} + I_{ikt} \quad \text{for all } i \in I, j \in J, k \in K, l \in L \& t \in T \quad \dots (11)$$

The manufacturer cannot manufacture the different brand types in a quantity more than their maximum capacity.

$$Q_{lkt} \leq C_{lkt} \quad \text{for all } l \in L, k \in K \& t \in T \quad \dots (12)$$

The manufactured brands are stored at the assemblers warehouse so that they may then be delivered to the buyer on his requested date and time.

$$I_{lk(t-1)} + Q_{lkt} = \sum_{m=1}^M S_{lkm} + I_{lkt} \quad \text{for all } l \in L, k \in K, m \in M \& t \in T \quad \dots (13)$$

The transportation capacity constraint for the movement of the models from the assembly sites to the buyers will be governed by the below transportation capacity constraint.

$$S_{lkm} \leq T_{lkm} \quad \text{for all } l \in L, k \in K, m \in M \& t \in T \quad \dots (14)$$

The models will be stored at the buyer's warehouse or will be kept aside by the assembler within his own premises for subsequent delivery.

$$I_{lm(t-1)} + \sum_{k=1}^K S_{lkm} = I_{lmt} \quad \text{for all } l \in L, k \in K, m \in M \& t \in T \quad \dots (15)$$

Finally, the entire process of procuring the product types, assembling and delivering the finished brands to the buyers needs to be completed by the date specified by the buyer, or equivalently the inventory level at the buyer's end on the due date for his order should equal the quantity ordered by the buyer.

$$I_{lm(t+D_{lm})} = Q_{lm} \quad \text{for all } l \in L, m \in M \& t \in [1, T - D_{lm}] \quad \dots (16)$$

The solution of this model determines the selection of suitable suppliers and assemblers for each order and also provides a schedule for production and assembly activities within the supply chain.

With the above mathematical model any of the available optimization toolkits might be used in order to determine the firms involved in the dynamic supply chain for a given set of orders.

3. SOLUTION

3.1 ILOG OPL Studio

The above linear model was developed and optimized in the commercial optimization program, OPL Studio available from ILOG. ILOG provides a very comprehensive library of optimization algorithms implemented in C++. These algorithms can be used for the solution of a varied number of large-scale linear, integer or constraint programming models. ILOG also incorporates a set of modeling concepts, such as activities and resources, which are very useful in the solution of scheduling and allocation problems. ILOG studio utilizes the Optimization Programming Language (OPL) for modeling of problems. User-defined search strategies for each model can be specified in order to reduce the computational power required for the solution.

3.2 Computational Complexity

The above model LP model was developed in ILOG and solved for a scenario with 3 component suppliers, 5 sub-assembly manufacturers supplying 2 different product types to 3 manufacturers, who sell 2 different model types to 2 buyers. Not all manufacturers manufacture all models or all suppliers supply all product types. The time horizon for the model was taken as 12 periods. The number of variables that were encountered was 2535 and the constraints numbered 2899. The solution time was less than 10 seconds.

4. COMPUTATIONAL RESULTS

In order to verify the dynamic nature of the model that was developed in earlier sections, the model was solved for orders placed by each of the buyers and the supply chain configuration for each was observed and compared.

It was assumed that each buyer required 500 units of a model at the end of the 10th time-period and was willing to pay the price of \$400, same as the rest of the buyers. The orders were to be fulfilled by the manufacturing network part of which is described in Appendix A. Each unit of the finished model requires 1 unit of sub-assembly 1 and 2 units of sub-assembly 2. Both the sub-assemblies are in turn made of 1 unit of component 1 and 1 unit of component 2. The manufacturing network can be designed to output more than one models. In such a situation it is very much possible to gain from economies of scale in the collective ordering and transportation of materials, which are used in the manufacture of multiple models. However, for ease of explanation the manufacture of only model has been considered in this experiment.

The optimal supply chain configuration for the fulfillment of 500 units of the finished goods required by buyer 1, consolidated over the entire time horizon, is obtained as given in Figure 3 below.

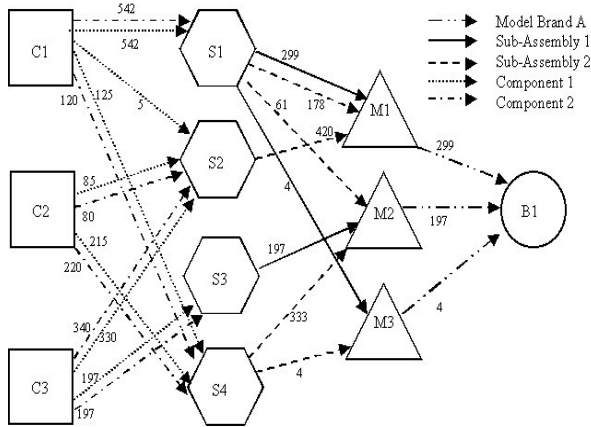


Figure 3. Configuration to meet Buyer 1 demand.

Similarly, the manufacturing network configuration for the fulfillment of any combination of orders from Buyer 1, Buyer 2 and Buyer 3 may also be obtained.

From the three scenarios it is noticed that, depending on where the buyer is, an appropriate manufacturing center is selected to fulfill the order. In case the demand is more than the quantity the manufacturer's supply chain is able to handle, the remainder of the demand will be fulfilled through other manufacturers. One of the bottlenecks in the supply chain that might arise is that the manufacturers are not able to manufacture at full capacity due to the lack of adequate sub-assembly and component supply from the suppliers, who cannot produce any more sub-assemblies or components. Consideration is also given to the schedules of the logistics service provider, so that item are produced just in time for pickup and delivery, instead of having to wait in the inventory.

The profit earned through the operation of the supply chain in each of the three cases is presented below.

Table 2: Profits in sales made to each of the three buyers

Revenues for sales	Profit from supply chain operations
Buyer 1 purchase 500 units @ \$400	\$85,724
Buyer 2 purchase 500 units @ \$400	\$87,935
Buyer 3 purchase 500 units @ \$400	\$79,593

Hence, the model suggests that it would be most profitable to accept orders from Buyer 2 as compared to orders from Buyer 1 or Buyer 3.

In the lack of any capacity constraints at the suppliers' and manufacturers' facility and the availability of transportation infrastructure the problem leads to the trivial solution where the cheapest complete link from the supplier to the buyer is chosen.

The solution of the LP model discussed earlier provides a breakdown of the optimum raw material production quantity, inventory holding and manufacturing capacity utilization for each time period. This information is key to scheduling supply chain activities to perform at optimal levels. Hence, the LP model provides an integrated strategic level partnership tool and a low level operational scheduling tool as well.

In order to simulate the large number of participants simultaneously trading in a marketplace, a solution was obtained for the manufacturing network configuration for multiple buyer requests. With multiple buyers trading on the marketplaces, the supply chain gets more complicated, with larger number of interconnections between the various participants in the value web.

5. CONCLUSIONS

In this paper, we have formulated and solved the partner selection problem in global manufacturing networks. This problem is very important in the current time of globalized manufacturing, proliferating electronic marketplaces and Internet enabled collaborative commerce. We specifically demonstrate how integrated supply chain planning can be conducted using standard optimization tools. We are developing a decision support tool for use in electronic marketplaces.

Our formulation here is linear and uses a LP model. We are planning to solve supply chain problems where the number of buyers and sellers are large and there are more tiers in the chain. We also want to impose more realistic constraints such as those forced by transportation lead times and solve the resulting mixed integer-programming problem.

6. REFERENCES

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7. Appendix A

Presented below is representative data on the manufacturing capacity, transportation capacity, production costs, transportation costs and inventory holding costs for a particular brand delivered by the supply chain network. Similar information is also assumed to be available for all the supply chain participants for all the components and sub-assemblies and components used.

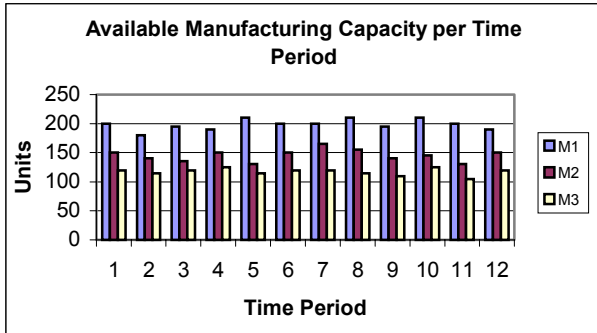


Fig. A-1: Manufacturer capacity information

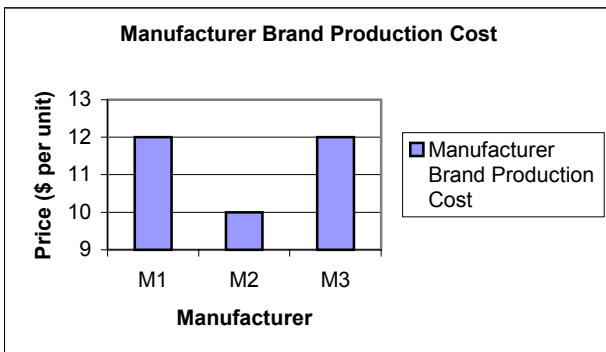


Fig A-2: Brand production costs

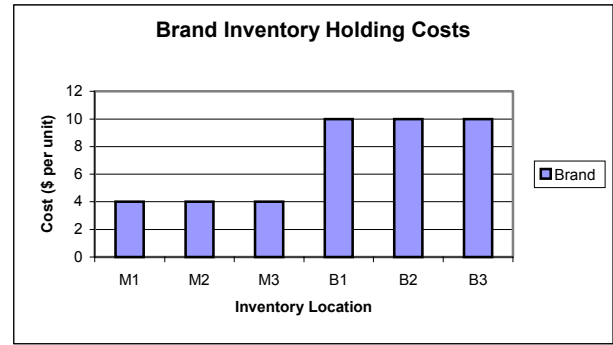


Fig A-3: Brand Inventory Holding Cost

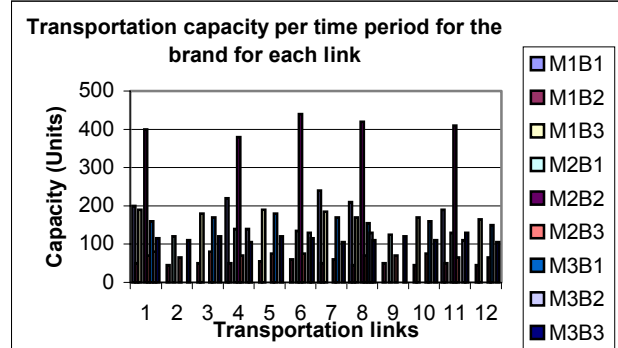


Fig A-4: Transportation capacity per time period for the brand from the brand manufacturers to the buyers.

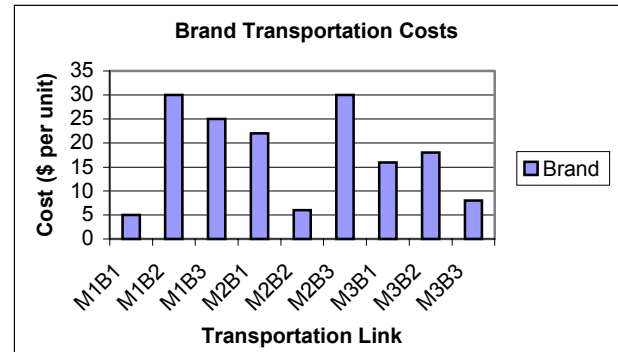


Fig A-5: Brand transportation cost for each link from the brand manufacturers to the buyers.