# Network Design and Operations: Facility Location

6

## Learning Objectives

After reading this chapter, you will be able to answer the following questions:

> What is role of network design and operations in supply chain management?

> What are the key factors that drive network design decisions? How do firms make optimal network design decisions?

> How do firms make optimum supply chain operations planning decisions?

> What are the different types of roles that a facility can play within a supply chain network?

> In what way do network design decisions for the service sector differ from those of product businesses?

Reliance Retail,[1] the retail mega vision of Mukesh Ambani, started operations in the third quarter of 2006. When the first store was launched, Arvind Singhal, head of retail consultancy Technopak, remarked, “Nowhere in the world has a project started on such a grand scale—it has taken just 15 months from planning to execution.” However, before the retail operations were executed, a detailed blueprint for the entire operation was drawn up. Reliance Retail invested approximately Rs 300 billion in all, of which Rs 80 billion was earmarked for the supply chain network only. Fully aware of the fact that the success of a retail chain hinges on the efficiency of the supply chain network, Reliance Retail planned out its supply chain network meticulously.

Reliance plans to set up an integrated supply chain infrastructure, including a cold chain for frozen food. Currently, seven large wholesale terminals serve the entire retail chain. Eventually, RIL plans to set up over 150 distribution centres across the country to supply the retail chain. Reliance is also working on an exclusive contract-farming project in a few states, whereby it will procure the farm produce directly from the farmer. Reliance hopes that this system will enable it to offer products at low prices to the end customer and reduce wastage, which currently ranges from 30 to 40 per cent within the chain.

Reliance hopes that the supply chain network will become a key differentiator for the firm in the coming years. Reliance has taken into consideration the fact that network design decisions are strategic decisions that have long-term implications which are not easy to reverse.

Where to locate the plants and warehouses is an important strategic network design decision. A supply chain is essentially a network consisting of nodes and linkages, and in this chapter, we focus on strategic and tactical decisions regarding network design and operations. Network design focuses on the location of nodes for plants and storage points, for given customer nodes and network operations focus on identifying the optimal linkages between plants and markets.

# Introduction

Network design consists of decisions regarding the location of plants, suppliers and distribution centres so as to serve customers in a cost-effective way. Among the several elements of supply chain decisions, network design plays a crucial role and has significant implications on supply chain performance. Most global firms work with multiple plants and operate in multiple markets. The most important tactical issues that firms have to resolve include allocation of volumes to plants and allocation of plants to markets. Where to locate the plants is an important strategic network design decision. A supply chain is essentially a network consisting of nodes and linkages. Nodes represent conversion or storage points or demand points, and linkages represent transportation activities through which material flow takes place in the chain. Network design focuses on the location of nodes for plants and storage points for given customer nodes, and network operations focus on identifying the optimal linkages between plants and markets.

Sometimes, firms end up making long-term decisions on the basis of short-run considerations. Firms tend to focus on near-term issues and sometimes forget that the selected action is bound to have long-term strategic implications. When Tata decides to locate its small car factory in West Bengal, it has to live with that decision for a considerable point in time. Unlike other decisions, a network design decision is strategic in nature and has long-term implications and is not easy to reverse.

We start our discussion by focusing on network operations planning and subsequently look at network design decisions. Any change in the external or internal environment may force a firm to question the existing network, and redesigning may include the closure of some existing facilities or the starting of new facilities at a new site.

# Network Operations Planning

Decisions pertaining to operations planning are tactical in nature. When taking a decision on operations planning, the firm not only has to ensure establishing appropriate links between the various entities in the chain, but also has to consider many other related issues. A firm with a multi-plant network has to decide which suppliers should be linked to which plants, which plants should be linked to which warehouses, and which warehouses should be linked to which markets. The firm also has to decide the appropriate activity levels at each plant—that is, how much to produce at each of the plants.

Let us take the example of a global firm like Dell Computers, which manufactures its computer systems in seven locations around the world: Austin, Texas; Nashville, Tennessee; Winston-Salem, North Carolina; Eldorado do Sul, Brazil; Limerick, Ireland; Penang, Malaysia and Xiamen, China. Computer markets are dynamic in nature; demand across the globe keeps fluctuating. Hence, optimal service of the global market, using its seven facilities, is a complex planning operations decision that Dell has to make every quarter. Grasim, an Aditya Birla Group company, manages its cement business with seven facilities and faces similar problems.

We start by examining the relevant costs for network decisions. We proceed to scrutinize the two available approaches for the optimization of network operations.

## *Relevant Costs for Network Decisions*

Three types of costs are important for network design and operations-related decisions: fixed facility costs, variable production costs and transportation costs. Facility costs are fixed in nature and do not depend on the volume of production and storage. So, for tactical decisions like network operations planning, fixed facility costs will be incurred irrespective of the allocation


**Figure 6.1**

Location of plants and markets.

decision and hence are not relevant for decision making. If the supply chain production consists of multiple stages, then production costs will include costs involved in conversion as well as in transportation from a downstream stage to the upstream stage.

Let us look at the case of a hypothetical company called Indian Paints, a paint manufacturing firm, which has four manufacturing plants located at Ahmedabad, Hubli, Nagpur and Vishakapatnam. The firm has recently added one more plant at Baddi in Himachal Pradesh because of the attractive tax concessions available there. The firm primarily operates in six major markets. The geographical positioning of all the plants and markets is presented in Figure 6.1. The marketing group prepares market estimates every quarter and expects the supply chain to plan its operations so that the firm can deliver its products to all six markets at the lowest possible cost. Keeping in view the capacity constraints of each plant and the existing cost structure, the supply chain group has to decide the volume of produce at each plant and allocate market demands to plants. Table 6.1 presents the relevant data.

From Table 6.1, we can calculate that the firm faces a total demand of 1,060 units and has a capacity of 1,500 units; now with one more plant at Baddi, its capacity has gone up to 1,900 units.

***Table 6.1(a): Plant data.***

| Plant | Capacity | Fixed facility cost | Unit variable production cost |
|---|---|---|---|
| Ahmedabad | 350 | 78,000 | 675 |
| Baddi | 400 | 42,000 | 525 |
| Hubli | 450 | 36,000 | 650 |
| Nagpur | 300 | 38,000 | 625 |
| Vishakapatnam | 400 | 34,000 | 675 |

***Table 6.1(b): Market data.***

| Market | Bangalore | Chennai | Delhi | Mumbai | Lucknow | Kolkata |
|---|---|---|---|---|---|---|
| Quarterly demand | 165 | 135 | 280 | 200 | 125 | 155 |
| Price per unit | 1,030 | 950 | 1,000 | 975 | 900 | 850 |

***Table 6.1(c): Transportation cost matrix.***

| | Bangalore | Chennai | Delhi | Mumbai | Lucknow | Kolkata |
|---|---|---|---|---|---|---|
| Ahmedabad | 235 | 278 | 100 | 65 | 189 | 261 |
| Baddi | 511 | 558 | 97 | 328 | 216 | 305 |
| Hubli | 77 | 138 | 327 | 105 | 372 | 326 |
| Nagpur | 165 | 160 | 183 | 117 | 148 | 235 |
| Vishakapatnam | 163 | 107 | 328 | 217 | 303 | 203 |

## *Network Operations Optimization: Cost Minimization Model*

Given a fixed network design, it is possible to plan and execute network operations in such a manner so as to minimize the cost. This is achieved primarily by solving the demand allocation problem.

The demand allocation problem can be modelled as a linear programming problem and solved using standard linear programming packages. The general network operations planning problem can be formulated as follows:

$M$ = Number of plants; let $i = 1, \ldots, m$ describe $m$ respective manufacturing plants
$N$ = Number of markets; let $j = 1, \ldots, n$ describe $n$ respective markets
$Dem_j$ = quarterly demand at market $j$
$Cap_i$ = quarterly production capacity at plant $i$
$Cost_{ij}$ = Cost of producing and transporting one unit from plant $i$ to market $j$
$Fcost_i$ = Fixed cost of facility $i$

From the production and transportation data in Table 6.1, one can calculate the per unit production and transportation cost, shown in Table 6.2.

Given this cost structure, the firm has to allocate the demand from different markets to various plants. Let $Quant_{ij}$ = Quantity shipped from plant $i$ to market $j$ every quarter.

Since the firm likes to minimize the total cost, its objective function will be

$$\text{Minimize } \sum_{i=1}^{m}\sum_{j=1}^{n} Cost_{ij} \times Quant_{ij}$$

Subject to following constraints:

$$\sum_{i=1}^{m} Quant_{ij} = Dem_j \quad \text{for } j = 1, \ldots, n \tag{6.1}$$

$$\sum_{j=1}^{n} Quant_{ij} \le Cap_i \quad \text{for } j = 1, \ldots, m \tag{6.2}$$

$$Quant_{ij} \ge 0 \quad \text{for } j = 1, \ldots, m,\ j = 1, \ldots, n. \tag{6.3}$$

The constraints in Equation 6.1 ensure that demand at each of the market place is satisfied. Constraints in Equation 6.2 ensure that production at each factory does not violate the capacity constraint at the plants. Constraints in Equation 6.3 ensure that supply will always be non-negative.

***Table 6.2: Production plus transportation cost per unit.***

| | Bangalore | Chennai | Delhi | Mumbai | Lucknow | Kolkata |
|---|---|---|---|---|---|---|
| Ahmedabad | 910 | 953 | 775 | 740 | 864 | 936 |
| Baddi | 1,036 | 1,083 | 622 | 853 | 741 | 830 |
| Hubli | 727 | 788 | 977 | 755 | 1,022 | 976 |
| Nagpur | 790 | 785 | 808 | 742 | 773 | 860 |
| Vishakapatnam | 838 | 782 | 1,003 | 892 | 978 | 878 |

Of course, it is assumed that the aggregate capacity of the plants is more than the aggregate demand at all markets—otherwise the above constraints cannot be satisfied. This is a linear programming problem with the number of variables, $n \times m$, and the number of constraints equal to $n + m$ (not counting the non-negativity constraints in Equation 6.3). A simple linear programming software called Solver is available in MS Excel where linear programming problems can be modelled and solved easily from data kept in the Excel form. We have to define one cell for objective function, one cell for the right-hand side and another cell for the left-hand side of the constraint. (See Appendix A for details on how the above linear programming model can be formulated and solved in Excel.) In the Indian Paints example, we have five plants and six markets, so we have a linear programming problem with 30 variables and 11 constraints. Solver or any other linear programming software can handle problems of much larger size without any difficulty. Optimal allocation for Indian Paints from Excel Solver is shown in Table 6.3.

The allocation in Table 6.3 will result in the following financial performance for Indian Paints:

Revenue = 1,017,450
Variable cost = 773,770
Gross profit (revenue – variable cost) = 1,017,450 – 773,770 = 243,680
Net profit = Gross profit – Fixed cost = 243,680 – 228,000 = 15,680

While planning network operations, it is assumed that all the markets must be served, so we have worked with the constraint that supply is equal to demand (see Equation 6.1). It assumes that the marketing department has made necessary plans and that the supply chain is expected to fulfil the demand at each of the markets as specified by the marketing function. Now it is possible that some of the markets may not be profitable. Even in firms where the marketing department focuses on profits and not just revenues, they usually work with average cost of supply number and not specific cost of supply to individual markets and customers. Indian Paints incurs a cost of Rs 773,770 to deliver 1,060 units, so the average cost per unit of supply works out to be Rs 739.4, which is lower than the price realized in each of the markets. Even if marketing function had access to all the cost data, and not just average cost data, there is not going to be much concern because even a market like Kolkata, which has the lowest price realization per unit, can be served profitably from the Baddi plant, against a price realization of Rs 850. The cost of serving Kolkata market from Baddi is Rs 830. So the marketing department will make plans believing that it is worthwhile serving all markets. Unfortunately, this way of looking at each market and plant individually is not correct. In a complex network, it is not easy to figure out the cost of supply to any specific customer or market because each source of supply may have multiple opportunities and hence it is not the actual cost of supply but the opportunity cost of supply that is more important.

Progressive firms try and understand the inter-connectedness of relevant decisions. Instead of operating in silo, where marketing executives make their plans looking at the revenue target and ask the supply chain people to execute the plan with the least cost, a firm can make integrated plans so as to optimize performance. If marketing and supply chain departments decide

***Table 6.3: Network operations: optimal allocation with minimum cost as objective.***

| | Bangalore | Chennai | Delhi | Mumbai | Lucknow | Kolkata | Supply |
|---|---|---|---|---|---|---|---|
| Ahmedabad | 0 | 0 | 0 | 200 | 0 | 0 | 200 |
| Baddi | 0 | 0 | 280 | 0 | 120 | 0 | 400 |
| Hubli | 165 | 0 | 0 | 0 | 0 | 0 | 165 |
| Nagpur | 0 | 0 | 0 | 0 | 5 | 155 | 160 |
| Vishakapatnam | 0 | 135 | 0 | 0 | 0 | 0 | 135 |
| Demand met | 165 | 135 | 280 | 200 | 125 | 155 | 1,060 |

Objective function value = Total variable costs = 773,770.

to work jointly, it will be more sensible to solve the joint problem as a profit maximization issue; rather than serving all markets, the decision maker should be given the flexibility to serve only those markets that are profitable.

## *Network Operations Optimization: Profit Maximization Model*

So instead of cost minimization, a firm might solve the profit maximization problem, where the objective function includes a term for revenue, which is obtained by multiplying the volume of shipment to markets with their respective price. As fixed costs are not relevant for the decision, profit maximization is equivalent to the gross profit (revenue – variable cost) maximization problem.

The objective function is

$$\text{Maximize} \sum_{i=1}^{m}\sum_{j=1}^{n} Price_j \times Quant_{ij} - \sum_{i=1}^{m}\sum_{j=1}^{n} Cost_{ij} \times Quant_{ij}$$

$$\sum_{i=1}^{m} Quant_{ij} \le Dem_j \text{ for } j = 1,\ldots,n \tag{6.4}$$

$$\sum_{j=1}^{n} Quant_{ij} \le Cap_i \text{ for } i = 1,\ldots,m \tag{6.5}$$

$$Quant_{ij} \ge 0 \text{ for } i = 1,\ldots,m,\ j = 1,\ldots,n \tag{6.6}$$

The demand specified by the marketing department becomes the upper bound; that is, you cannot supply more than the volume specified by marketing group. If the market is not profitable or if the company has supply problems, company may decide not to serve that market. Constraint 6.1 will therefore be modified and the equality constraint will be changed to less than the equal constraint as shown in Equation 6.4.

The optimal allocation for Indian Paints from Excel Solver is shown in Table 6.4.

The allocation in Table 6.4 will result in following financial performance for Indian Paints:

Revenue = 885,700; Variable cost = 640,470
Gross profit (revenue – variable cost) = 885,700 – 640,470 = 245,230
Net profit = Gross profit – Fixed cost = 245,230 – 228,000 = 17,230

As we can see from the Solver output shown in Table 6.4, it is not profitable for Indian Paints to serve the Kolkata market. So even though the firm has a lower top line, it has higher profits and the profit has increased by almost 10 per cent. At first glance this will be counterintuitive. As one can see, it is more profitable for Baddi to supply to other markets, and forcing Baddi to supply to Kolkata will lower the profitability for the firm. In general, it is not straightforward to understand the profitability of individual markets. In Appendix A, we discuss the concept of shadow price, which can help firms in understanding the profitability of various markets.

***Table 6.4: Network operations: optimal allocation with maximum profit as objective.***

| | Bangalore | Chennai | Delhi | Mumbai | Lucknow | Kolkata | Supply |
|---|---|---|---|---|---|---|---|
| Ahmedabad | 0 | 0 | 0 | 200 | 0 | 0 | 200 |
| Baddi | 0 | 0 | 280 | 0 | 120 | 0 | 400 |
| Hubli | 165 | 0 | 0 | 0 | 0 | 0 | 165 |
| Nagpur | 0 | 0 | 0 | 0 | 5 | 0 | 5 |
| Vishakapatnam | 0 | 135 | 0 | 0 | 0 | 0 | 135 |
| Demand net | 165 | 135 | 280 | 200 | 125 | 0 | 905 |

Objective function = maximize total gross profit = 245,230.

For optimization of network operations, the firm has to ensure that all decisions made are in line with the firm's long-term strategy. Therefore, firms have to take into account other factors that may not appear to be immediately relevant. Some factors that firms take into consideration are discussed herewith.

### Handling New Markets

Often, a firm may like to serve a market even if it is not profitable, because it has been identified as a strategic market. Many global companies do not make profit in new markets in the initial years, but make a strategic decision to serve those markets for some years, willing to sustain losses. For example, Kelloggs, a cereal manufacturer, identified Japan as a strategic market and incurred losses during the first 10 years of operations. Similarly, it is incurring losses in the Indian market at present, but is continuing operations from a long-term strategic perspective. Thus, a company's structure and business strategy makes a difference in the way it models and handles network operations planning issues.

### Impact of Allocation Decision on Individual Plant Performance

In the above example, the assumption was that we are only interested in optimizing overall network performance and are not worried about its impact on the individual plant's performance. First, how does one determine the performance of each of these five plants? Each plant can be treated as a profit centre by allocating a transfer price to the plant, based on the price realized in the market that has been allocated to the plant. To understand the impact of such a scheme on different plants in the network, let us take the example of the Nagpur plant. If such a scheme is implemented, Nagpur will prefer to get an allocation from Mumbai because Mumbai has better price, and no plant manager likes to get allocated markets like Lucknow and Kolkata, which have lower price realizations. To avoid this problem, the firm may decide to work with transfer price, which is nothing but the weighted average price realized by the network. The unit transfer price will be determined by first deducting the total transport cost from the total revenue and subsequently the same will be divided by the total volume. This means that all plants will have the same unit transfer price, which will not be based on specific markets allocated to individual plants. Even with uniform transfer price, a plant like the one in Nagpur will show huge losses because it will not be able to cover its fixed cost due to the relatively lower volume of allocation made to it. Since the Nagpur plant is allocated only five units, it will show losses as far as financial performance is concerned. So even though Nagpur has the second lowest production cost (Baddi has the lowest production cost), it gets very low volume, which results in poor performance; hence, it is quite likely that the Nagpur plant manager will get a lower bonus compared to other plant managers. The only solution is to treat plants as cost centres rather than as profit centres. In that case, firms will try to optimize the overall network performance and each plant will take responsibility for its fixed and variable costs. Of course, this does not solve the problem completely because under this scheme each plant is measured on cost alone and will not have the motivation to come up with any value-added service. In case some customers require higher-quality service or want to work on collaborative product development, the plant will not be willing to provide the service unless it gets specific credit for same.

### Managing Allocation Decisions in a Multi-plant Global Firm

So far we have assumed that the entire network was under a centralized control and a firm could align the activities of individual plants through an appropriate performance measurement scheme. As discussed, creating alignment is not easy even in a firm that has complete control over its units, but issues get really complicated when dealing with a global multinational firm having a separate legal entity in each country of operation. Conflict will set in because the local unit manager will naturally be more interested in the performance of the local legal entity, as his or her performance in the local community will be determined by the local unit's performance. Most of the multinationals ensure that they do not judge the unit manager by the performance of the local legal entity. Usually, the important yardstick is the extent to which the individual entity manager is able to align his or her unit with the interest of the global network. This is possible only if the global firm has 100 per cent stake in the local legal entity. Unfortunately, in several countries, multinationals are forced to have local partners, either because the law does not permit 100 per cent foreign equity or at the market-entry stage the global firm may prefer to have a local partner so as to understand local issues. Suzuki, for example, entered India with the Government of India as partner. Similarly, Ford Motor Company entered India with Mahindras as partner. As long as local companies are taking care of only the local market and are not treated as part of the network, such arrangements work without too many difficulties. But the moment multinationals want to treat the local unit as part of a network, the local alliance partner objects if the local unit gets hurt in the process. Like the case of the Nagpur plant in the Indian Paints example, an Indian venture may get lower allocation in the network in the interest of the global network, and the allocation may have nothing to do with the productivity of the local unit. Let us take an example of a global firm that has two manufacturing facilities in South Asia, one in Colombo and one in Faridabad. In the past all customers in Chennai will to be assigned to the Faridabad plant managed by the Indian venture. Now with the reduction in custom tariff the global firm may decide to allocate the Chennai customer to the Colombo plant, which is geographically closer to the customer. So what may be good for a network is not necessarily good for individual units. It is a serious problem when each unit is a separate legal entity and may have local partners. This is the reason why multinational firms prefer 100 per cent control so that they can work with a network strategy and do not have to worry about individual units' profit performance.

In general, planning decisions of supply chain operations must be integrated with the strategic interest of the firm (Should Kolkata be treated as strategic market?) and management control systems and performance measures of individual units and managers managing various entities in the chain must be aligned with the overall business strategy. Otherwise it can create dysfunctional behaviour on the part of the various managers and they may sabotage the network planning operations system. Finally, the organization may end up with locally optimal but globally suboptimal decisions.

## Network Design Problem

So far we have looked at tactical problems of optimal demand allocation across plants for a given network. This problem is usually solved on a monthly or a quarterly basis. However, over a period of time market structures might change. For example, market demand in South India may increase at a faster place or the cost structures may change significantly. A differential rate of change in wages, utilities or transport cost alters the competitiveness of different plants. A firm

### *NETWORK RESTRUCTURING AT UNILEVER*[2]

Unilever is a European multinational with a turnover of 40 billion Euros. It is the market leader in home and personal care products, and foods and beverages in several global markets. The company has recently announced that it wants to streamline its manufacturing and supply chain operations. It plans to close about 50 of its 300 factories and to reduce its regional centres from about 100 to 25, as part of a bid to save 1.5 billion euro a year by 2010. The majority of restructuring is to be carried out in Europe, where structural costs are highest and where regional supply chain management offers the greatest opportunity. Network restructuring is an ongoing exercise in Unilever. After the European integration in the 1990s, Unilever Europe, carried out an analysis for three product lines for which they had 35 plants in Europe. Based on the analysis they had changed their network design, and the new network had only nine plants, resulting in substantial savings in costs.

may find new locations more attractive and might like to add capacities in these new emerging areas. In general, a firm should periodically question the existing network design and come up with a design that is optimal for the future demand projections and cost structures. Global firms like Unilever go through the exercise of major network restructuring every few years.

This is a common phenomenon in global firms, where they may want to add new capacities in Asia and shut down some facilities in Europe or America. Usually, fixed cost is not a function of volume, so if some plants are not getting enough volume because they are less productive and if there is excess capacity in the system, a firm may want to shut down certain facilities so that it can reduce total system costs. For example, Special Economic Zones in Mexico found that in 2002 about 200 firms had shut down their facilities because they had invested in facilities in China, which have much lower costs of production. With restructuring of the taxation system, India is likely to become one market and this is going to change the way distribution centres are located within the Indian market. In the pharmaceutical and the packaged-goods industries, mergers and acquisitions result in excess capacity for the system as a whole. Oil companies in Europe went through a major rationalization in the 1980s because of mergers and acquisitions. Several case studies have shown that firms use network design models for rationalizing facilities after a merger.

In the case of Indian Paints, let us assume that the firm decides to rationalize network design because it has surplus capacity in the network. As the firm has excess capacity and fixed costs account for a significant part of costs, the firm may explore the idea of closing some facilities so as to save some fixed costs in the process. Now the firm has to first decide whether to keep the plants open or closed, supply being possible only from plants that are open. Of course, if a plant is closed, the firm does not incur any fixed cost on that plant. So we make a modification in the model and introduce binary variables, which can take values of either 0 or 1. Apart from *nm* linear variables, the network design formulation will have *m* binary variables.

## Network Design Model: Cost Minimization Model

If a firm wants to work with an objective of cost minimization for the network, the revised objective function will be as follows:

$$\text{Minimize} \quad \sum Fac-open_i \times Fcost_i + \sum_{i=1}^{m}\sum_{j=1}^{n} Cost_{ij} \times Quant_{ij}$$

$$\sum_{i=1}^{m} Quant_{ij} = Dem_j \quad \text{for } j = 1,\ldots,n \tag{6.7}$$

$$\sum_{j=1}^{n} Quant_{ij} \le Fac\text{-}open_i \times Cap_i \quad \text{for } i = 1,\ldots,m \tag{6.8}$$

$$Quant_{ij} \ge 0 \quad \text{for } i = 1,\ldots,m \quad \text{for } j = 1,\ldots,n \tag{6.9}$$

$$Fac-open_i = 0 \text{ or } 1 \text{ binary variable} \quad \text{for } i = 1,\ldots,m \tag{6.10}$$

Unlike a network operation planning case, fixed costs are the relevant costs of decision making and have been included in the objective function. Only if the binary variable $Fac\text{-}open_i$ takes the value of 1 does the fixed cost for that plant get added to the total cost in the objective function. Similarly, the right-hand side of Equation 6.8 ensures that the effective capacity of a plant is 0 if the relevant binary variable takes the value of 0 and that the effective capacity is equal to the plant capacity if the binary variable takes the value of 1.

For solving the above problem, we need a software that can handle binary decision variables also. Pure linear programming software will not be able to handle binary variables. Excel Solver

*Table 6.5: Network design: optimal allocation with minimum cost as objective.*

| | Bangalore | Chennai | Delhi | Mumbai | Lucknow | Kolkata | Supply | Plant (open/close) |
|---|---|---|---|---|---|---|---|---|
| Ahmedabad | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Close |
| Baddi | 0 | 0 | 280 | 0 | 120 | 0 | 400 | Open |
| Hubli | 165 | 135 | 0 | 60 | 0 | 0 | 360 | Open |
| Nagpur | 0 | 0 | 0 | 140 | 5 | 155 | 300 | Open |
| Vishakapatnam | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Close |
| Demand met | 165 | 135 | 280 | 200 | 125 | 155 | 0 | |

Objective function = Total costs = 891,760.

can handle binary decision variables and the relevant details are discussed in Appendix A. Optimal allocation for Indian Paints from Excel Solver is as shown in Table 6.5.

The allocation shown in Table 6.5 will result in the following financial performance for Indian Paints:

Revenue = 1,017,450
Variable cost = 775,760
Gross profit (Revenue – Variable cost) = 1,017,450 – 775,760 = 241,690
Net profit = Gross profit – Fixed cost = 241,690 – 116,000 = 125,690

This suggests that the Ahmedabad and Vishakapatnam plants should be closed. Ahmedabad has significantly high fixed cost and Vishakapatnam has relatively lower volume of allocation, so they are ideal candidates for closure, given the excess capacity in the system. Comparison with Table 6.3 shows that these changes lead to an increase in the net profit, despite the increase in the total variable cost in the system. Since fixed costs have come down because of the closure of the two plants, the overall profit has increased significantly.

## Network Design Model: Profit Maximization Model

If the network design problem is solved as a profit maximization problem (all markets need not be served), the objective function will be as follows:

$$\sum\sum Price_j \times Quant_{ij} - \sum Fac\text{-}open_i \times F\cos t_i - \sum_{i=1}^{m}\sum_{j=1}^{n} Cost_{ij} \times Quant_{ij}$$

$$\sum_{i=1}^{m} Quant_{ij} \le Dem_j \quad \text{for } j = 1,\ldots,n \tag{6.11}$$

$$\sum_{j=1}^{n} Quant_{ij} \le Fac\text{-}open_i \times Cap_i \quad \text{for } i = 1,\ldots,m \tag{6.12}$$

$$Quant_{ij} \ge 0 \quad \text{for } i = 1,\ldots,m,\ j = 1,\ldots,n \tag{6.13}$$

$$Fac\text{-}open_i = 0 \text{ or } 1 \text{ binary variable} \quad \text{for } i = 1,\ldots,n \tag{6.14}$$

The optimal allocation for Indian Paints from Excel Solver is as shown in Table 6.6.

The allocation in Table 6.6 will result in the following financial performance for Indian Paints:

Revenue = 833,700
Variable cost = 601,015
Gross profit (Revenue – Variable cost) = 833,700 – 601,015 = 232,685
Net profit = Gross profit –Fixed cost = 232,685 – 78,000 = 154,685

*Table 6.6: Network design: optimal allocation with maximum profit as objective.*

| | Bangalore | Chennai | Delhi | Mumbai | Lucknow | Kolkata | Supply | Plant (open/close) |
|---|---|---|---|---|---|---|---|---|
| Ahmedabad | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Close |
| Baddi | 0 | 0 | 280 | 0 | 120 | 0 | 400 | Open |
| Hubli | 165 | 85 | 0 | 200 | 0 | 0 | 450 | Open |
| Nagpur | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Close |
| Vishakapatnam | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Close |
| Demand met | 165 | 85 | 280 | 200 | 120 | 0 | | |

Objective function= Total net profit = 154,685.

This suggests that the Ahmedabad, Vishakapatnam and Nagpur plants should be closed. The Ahmedabad plant has significantly high fixed cost and the Vishakapatnam plant has relatively lower volume of allocation, so they are ideal candidates for closure given the excess capacity in the system. Further, if it is not necessary to serve the Kolkata market, the Nagpur facility can also be closed to save the relevant fixed cost. Comparison of Table 6.6 with Table 6.4 shows that the net profit has increased and thus the overall profit has increased significantly.

As presented in Table 6.7, we can compare all the four approaches discussed above in terms of profitability. As we can see, network redesign significantly improves the profitability of a firm. Further, integrated problem solving has greater profitability when compared to a situation when marketing and supply chain decisions are made independently. Of course, following the profit maximization model for both network design and operations will lead to higher profitability at the cost of the top-line. Sometimes firms may have some top-line objectives and may be willing to sacrifice their bottom-line objectives in the process.

Though network design decisions help bring down overall costs and improve profitability, the firm has to consider all related issues and take into account the possible consequences of the decision on such issues. For example, network design decisions have a tremendous impact on the performance of individual plants. We briefly discuss such issues here.

## Political Dimensions of Network Design Decisions

Network design decisions definitely improve the performance of the network, but such measures also put much pressure on individual plants. It is possible that a plant might be closed because of issues that are not under the control of the plant manager. For example, the Nagpur plant, which was the lowest cost producer before Indian Paints decided to put up the Baddi plant, is now on the chopping block. This issue is quite tricky in multi-product situations. Different ways of cost allocation across products result in different costs and this, in turn, results in different decisions. Usually, plant managers try and play around with numbers so that they can retain more products in their portfolio and they can spread their fixed cost over a larger number of products. Also, within a firm, the plant with a bigger portfolio will have more political clout in the system. So if one is not careful, network design decisions can become

*Table 6.7: Performance comparison of different decisions.*

| Decision problem | Type of decision | Objective | Revenue | Net profit | % Net profit/ sales |
|---|---|---|---|---|---|
| I | Network operations | Cost minimization | 1,017,450 | 15,680 | 1.54 |
| II | Network operations | Profit maximization | 885,700 | 17,230 | 1.95 |
| III | Network design | Cost minimization | 1,017,450 | 125,690 | 12.35 |
| IV | Network design | Profit maximization | 833,700 | 154,685 | 18.55 |

highly political in nature. Further, some plants have a historical legacy—older plants have higher energy cost, older labour force and high labour cost. Will it be fair to compare plants that are not comparable in the first place? Again, if a global firm has local alliance partners, they are not going to be comfortable with extreme decisions of this kind. In general, frequent network redesign decisions will give a clear signal to plant managers that they are competing against each other. If plant managers are rewarded on how well they perform relative to other plant managers, there will be no incentives for knowledge sharing. Minimizing cost on a short-run basis may result in loss of opportunity for long-term cost reduction through the sharing of best practices. BMW, a global automobile major, has designed a strategic planning model that provides decision support to the firm whenever it has to make these allocation-related decisions.

### *STRATEGIC PLANNING MODEL AT BMW*[3]

The BMW group manufactures and sells three premium car brands, BMW, MINI and Rolls Royce, globally. It sold about 1.25 million cars in 2006. BMW has eight full-fledged manufacturing plants and seven complete knockdown manufacturing plants located in different parts of the world. Allocating global volumes to these different units used to be a tough and challenging problem for the group. To optimize its volume-allocation decision, BMW has developed a strategic planning model. This model includes supply of raw material as well as the distribution of finished goods and works with a planning horizon of 12 years. Apart from allocation decisions, it also helps the firm in making optimal investment decisions in major departments like body assembly, paint shop and final assembly. This strategic model allows BMW to understand the impact of investment decisions on cost drivers of the supply chain.

The crucial issue here will be to insulate plant managers' performance measures from the plant closure decision. As mentioned earlier, many plants in Mexico were closed as firms had put up new facilities in China. Even if one attempts to insulate the plant manager of a Mexico plant from the closure decision, he or she may not be willing to move to China if the opportunity is provided, and even if he or she is willing to move, the firm may not be interested in shifting the manager because of cultural differences.

Even if firms may not use the solution suggested by optimization models, the recommendation of the models can help the firms in establishing right benchmarks in evaluating alternative solutions. It is possible that a model does not capture all the intangibles and the firm may choose locations other than the ones suggested by the model. It is necessary to remember that a firm will have to live with the facility decision for a long time to come. Thus, it is important that the firm generates several scenarios based on the world view of likely developments in the future. Asian Paints is trying to move away from country-focused manufacturing to a network approach but is aware of the sensitivities involved and wants to gradually move to the idea of regional hubs before moving to a full-fledged global network.

### *ASIAN PAINTS' INTERNATIONAL OPERATIONS*[4]

Asian Paints is India's largest paint company, with a turnover of Rs 36.7 billion. Over a period of time, it has increased its international operations with a strong focus on developing countries. It operates in 21 countries and has a manufacturing facility in each of these countries. With reduction in import duties, Asian Paints wants to explore the idea of redesigning its plant network and work with the idea of regional manufacturing units rather than country-specific units. Asian Paints has divided its global market into five regions, viz, South Asia, South-East Asia, South Pacific, the Middle East and the Caribbean.

Setting up regional manufacturing units in place of country-specific units will allow the company to get better economies of scale in manufacturing. They have already invested in the necessary IT infrastructure and other processes that will allow them to successfully achieve the complex integration of manufacturing and distribution under the new setup.

In general, plant closures are extremely painful for a firm and this issue also has political dimensions as local governments are extremely concerned about facility closures and job cuts. Thus, progressive multinationals do not look at facility location decisions as short-term decisions because they are aware of the difficulties involved in closing facilities. It also creates an image of bad management and may have certain implications for the kind of people the firm is likely to attract. One of the ways in which firms try and avoid extreme decisions like closure is by assigning a higher strategic role to each facility, thereby avoiding chances of extreme decisions like closure. At a later stage in this chapter we discuss how firms can assign different strategic roles to different units so that each unit brings more value to the network than just being a node in the network.

# Network Design and Operations Models: Extensions

In this section, we discuss the network design and operations models that may be applicable in situations with increased limitation on account of factors like seasonality of supply and short life cycle of the product. As discussed earlier, the ability of a plant to deal with complex network designs or operations planning problems puts it at a strategic point in the supply chain, thereby enabling it to avoid consequences like closure.

## *Seasonal Products: Tactical Planning Problems*

In normal tactical situations, it is assumed that opening inventory is the same as closing inventory; hence, inventory is removed from the model. But in seasonal products, inventory does not remain the same throughout the year. So depending on the period of the year, the opening inventory will be expected to be different from the closing inventory. At the relevant stock point, Equation 6.15 will ensure that planned increase or decrease in inventory takes place in the relevant period.

$$\text{Opening inventory} + \text{Inflow} - \text{Outflow} = \text{Closing inventory} \tag{6.15}$$

## *Multiple Capacity: Deciding on the Best Option*

Let us assume that Indian Paints is exploring two options while putting up a new facility at Baddi, to put up either a facility with a moderate capacity of 400 units or a high-capacity one with 600 units. The firm expects economies of scale; therefore, the higher-capacity option will have lower variable cost as well as fixed cost per unit of capacity. But if the plant is not going to get enough volume, then excess investments will be a wasteful expenditure. To handle this case, the model will have six possible plants in its network design instead of five plants. The Baddi site will be represented by two rows: Baddi-moderate and Baddi-high. One additional constraint (6.16) will be added to ensure that at most one plant (either moderate or high capacity) should be kept open at Baddi:

$$\textit{Fac-Open}_{\text{Baddi-Moderate}} + \textit{Fac-Open}_{\text{Baddi-High}} \leq 1 \tag{6.16}$$

Similar logic can be used in case the firm has options of three or more types of facilities, using binary variable for each facility type for each site, and by introducing a constraint like 6.16, one can ensure that at most one type of facility is opened at each site.

So far we have only studied plants and markets. It is possible that to ensure better response time to markets, intermediate warehouses will be needed; and the optimal mix of warehouses in a network design problem need to be identified. Similar to plant variables, we will introduce binary variables at each potential warehouse location. Additional data will be needed on the plant-to-warehouse transport cost matrix, warehouse-to-market transportation cost matrix and fixed cost of opening a warehouse. We will have to introduce a constraint to ensure that the inflow to the warehouse is the same as the outflow from the warehouse.

## *Short Life Cycle Products: A Suitable Network Design*

For firms dealing with products that have a short life cycle, cost considerations do not form the only important factor in the network. Changing fashion trends and rapid technological advances force the firms to align themselves quickly to reflect the changes. In such an environment, a firm has to be prepared for either volume variability or mix variability or a combination of both, and this cannot be handled by holding a high safety stock of finished goods. The entire network must have a short lead time so that it can respond fast to market or technology shocks. So the network design for short life cycle products must balance the cost and time involved in the sourcing, production, storage and transportation activities in the supply chain. Two different ways can be used to capture time in the network: cycle time and weighted activity time.

Cycle time is the time taken on the longest path of the network. Weighted activity time is sum of the processing/transporting times for each individual segment of the network multiplied by the number of units processed by the node or shipped through the link. This includes all the paths and not just the longest path in network. Digital Equipment Corporation had developed an elaborate decision support system for global supply chain analysis, where it minimized cost or weighted activity time or a combination of both. As shown below, the objective function is a composite of time and cost:

$$\alpha \times \text{Cost} + (1 - \alpha) \times \text{Time}, \quad 0 \le \alpha \le 1$$

The difference between the two different concepts of time (weighted activity time and cycle time) are illustrated with an example.

Consider the case of a simplified version of the PC supply chain described in Figure 6.2. The supply chain involves manufacturing disks and motherboards, assembling PCs and shipping them to the North American market. The firm is trying to make location decisions for each of the three manufacturing centres. As shown in Figure 6.2, the firm has two choices for each of the manufacturing locations. Relevant data for the problem are presented in Table 6.8.

We want to measure the time element in the chain using both the concepts of weighted time and cycle time.

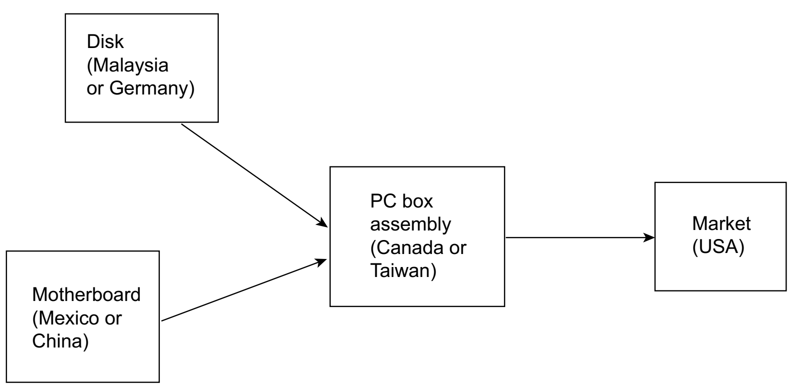



**Figure 6.2**

PC supply chain.

*Table 6.8(a): Production cost (value added) and lead time data.*

| Product/component | Location | Production lead time (PLT) (in weeks) | Value added (VA) (US$) |
|---|---|---|---|
| PC box | Canada | 2 | 50 |
| PC box | Taiwan | 1 | 35 |
| Disk | Malaysia | 3 | 50 |
| Disk | Germany | 2 | 68 |
| Mother board | Mexico | 3 | 150 |
| Mother board | China | 2 | 130 |

*Table 6.8(b): Transportation time and transportation cost.*

| Component/ subassembly | | Transportation time (TLT) (weeks) | Transportation cost (TCST) (US$) |
|---|---|---|---|
| PC box (PB) | Canada–USA | 1 | 8 |
| PC box | Taiwan–USA | 3 | 20 |
| Disk (DK) | Malaysia–Canada | 2 | 7 |
| Disk | Malaysia–Taiwan | 1 | 4 |
| Disk | Germany–Canada | 2 | 5 |
| Disk | Germany–Taiwan | 1 | 3 |
| Mother board (MB) | Mexico–Canada | 1 | 5 |
| Mother board | Mexico–Taiwan | 2 | 10 |
| Mother board | China–Canada | 3 | 13 |
| Mother board | China–Taiwan | 1 | 5 |

## Comparing Supply Chain Configurations

There are eight supply chain configurations possible. But we examine just the two configurations described below:

Configuration 1: Disk—Germany; Motherboard—Mexico; PC Box—Canada

Configuration 2: Disk—Malaysia; Motherboard—China; PC Box—Taiwan

For the two configurations described above we work out cost, cycle time and weighted activity time using following formulas:

$$\text{Cost (Configuration)} = VA(DK) + TCST(DK - PC) + VA(MB) + TCST(MB - PC) + VA(PC) + TCST(PC - USA)$$

$$\text{Cycle time (Configuration)} = \text{Max}\{[PLT(DK) + TLT(DK - PC)], [PLT(MB) + TLT(MB - PC)]\} + PLT(PC) + TLT(PC - USA)$$

$$\begin{aligned}\text{Weighted activity time (Configuration)} = {} & VA(DK) \times PLT(DK) + [(VA(DK) + TCST(DK - PC)]TRLT(DK - PC) \\ & + VA(MB)PLT(MB) + [(VA(MB) + TCST(MB - PB)]TRLT(DK - PB) + [VA(DK) \\ & + TCST(DK - PB) + VA(MB) + TCST(MB - PB) + VA(PB)] \times PLT(PB) + [VA(DK) \\ & + TCST(DK - PB) + VA(MB) + TCST(MB - PB) + VA(PB) + TCST(PB - USA)] \\ & \times PLT(PB)\end{aligned}$$

Cost (Configuration 1) = 68 + 5 + 150 + 5 + 50 + 8 = 286

Cost (Configuration 2) = 50 + 4 + 130 + 5 + 35 + 20 = 244

Cycle time (Configuration 1) = Max[(2 + 2), (3 + 1)] + 2 + 1 = 7 weeks

Cycle time (Configuration 2) = Max[(3 + 1), (2 + 1)] + 1 + 3 = 8 weeks

Weighted activity time (Configuration 1) = $68 \times 2 + (68 + 5) \times 2 + 150 \times 3 + (150 + 5) \times 1 + (68 + 5 + 150 + 5 + 50) \times 2 + (68 + 5 + 150 + 5 + 50 + 8) \times 1 = 1,729$

Weighted activity time (Configuration 2) = $50 \times 3 + (50 + 4) \times 1 + 130 \times 2 + (130 + 5) \times 1 + (50 + 4 + 130 + 5 + 35) \times 1 + (50 + 4 + 130 + 5 + 35 + 20) \times 3 = 1,555$

Thus, depending on the importance of cost versus time (value of $\alpha$ in the objective function), a firm can make appropriate choices. Of course, Configuration 2 provides better performance on the cost front, while performance on the time front will depend on the choice of performance measures. If one uses weighted activity time as a measure of time, Configuration 2 will perform better; but if cycle time is used as a measure of time, Configuration 1 will perform better. Cycle time as a measure of time will capture responsiveness of the chain while weighted activity time will capture the pipeline inventory in the chain. Though Digital Corporation had used weighted activity time in its decision support system because it is easier to compute, cycle time may be more appropriate for capturing measures related to the responsiveness of a chain.

## Impact of Lead Time on Supply Chain Performance

As discussed in the chapter on inventory, lead time in production and transportation has implications for pipeline and safety stock inventory. Pipeline inventory is a direct function of the lead time of the process, while safety stock is a function of the square root of the lead time. But

**INTERVIEW WITH**

**SUPRAKASH MUKHERJEE**

*Deere & Company (usually known by its brand name John Deere) is an American corporation with a presence in 27 countries and a revenue of $22.148 billion (2006). Mr Suprakash Mukherjee is the Senior General Manager, Global Sourcing, Enterprise Supply Management, at John Deere India.*

*What are the issues related to specifically global supply chain networks?*

**Suprakash Mukherjee**: Unlike local supply chains, global supply chain networks function under multiple sources of uncertainty and different types of risk, including raw material prices, product prices, product demand, and foreign exchange rates amongst others, which vary across countries. This makes managing a global supply chain a very dynamic and resource-intensive process. For example, the India plants manufacture 5,000 series tractors of which only 50 per cent are for the domestic market. The remaining 50 per cent are exported to more than 50 countries. Similar tractors are manufactured at six other locations in the world. Hence, we need to ensure that we meet the demand in each of the markets while ensuring minimum costs and adequate utilization at each of the facilities.

*How do you manage the uncertainties you mentioned above?*

**Suprakash Mukherjee:** Along with its challenges, global supply chain also throws open the opportunities of lowering costs by allowing access to low-cost suppliers. For example, the cost advantages of India sourcing are significant and the Regional Supply Management Centre at the John Deere Technology Centre leverages those sources. The supply base in India supports factories globally as India's steel and plastics go into products for sale worldwide.

Recently, we also compiled a model to ascertain the impact of foreign exchange fluctuations on revenues across different markets. The model helped us to reassess our allocation across different plants in order to ensure minimal fluctuation in the revenue because of exchange rate fluctuations in different markets.

*How important do you think is it for an organization to optimize on its supply chain network?*

**Suprakash Mukherjee:** The growth in globalization has led to supply chain management being a key focus area for management of top multinational enterprises. A lot of companies fail in the present context because of the inability to configure global manufacturing plants and markets. Hence, I believe global supply chain management, based on enhanced integration of suppliers and customers, not only makes better business sense but is also a source of competitive advantage.

a shorter lead time allows a firm to respond to changes in an environment that cannot be predicated. Further, in the fashion industry, maintaining large safety stock is not the optimal way of dealing with a highly uncertain demand situation. As discussed later, "sense and respond" is the most effective strategy in the fashion industry, and a short lead time is the most important characteristic of such a strategy. Sony, to its horror, found that it had landed with an unresponsive supplier who could not deliver a few minor components at short notice, and this resulted in huge losses of sales for its PlayStation II during Christmas in 2000.

# Data for Network Design

Network design will require cost- and demand-related data. Though an organization may have relevant transactions data, converting the same into meaningful data is an important task and requires some considerations. A discussion of this issue is presented in this section.

## *Demand Data*

A firm may have numerous SKUs in its product portfolio, but it will be counter-productive to include all of them in its network design models. For example, an auto company could offer 200 product variants consisting of various combinations. However, these variants may also be aggregated into three families: large, medium and small. We should keep in mind the supply chain related characteristics like transportation cost, inventory cost and demand placed on capacity. For example, if two different models are manufactured at two different types of facilities, then one cannot aggregate them, and both have to maintain separate identities for the sake of network design. The problem of aggregation is likely to be more serious for retailers like Food World or Pantaloon, where one may work with thousands of SKUs in the product portfolio.

Like they do with products, a firm will have to aggregate its customers and markets also. A firm may be dealing with thousands of customers, and those in close proximity of one another are good candidates for aggregation. Few large A-category customers can be treated individually while all the B-category and C-category customers can be aggregated on a geographical basis. There is a trade-off involved in the aggregation process. Whenever data are aggregated, there is loss of some information, but for any meaningful analysis there should not be too many binary variables. Also with too large a model, a firm will be unable to communicate with the decision makers in a meaningful way. There may also be problems in getting the required data.

## *Supply Side Cost Data*

Relevant data from the supply perspective is necessary to capture production- and transportation-related costs. The production cost is incurred at nodes (facilities) and transportation cost is incurred at arcs (between facilities) in the network

### Production Cost: Comparable Costs Across Facilities

Different plants may have different accounting systems and may use different methodologies while allocating common cost (e.g., overhead allocation) across product categories. In many instances where firms have been merged, these problems are more serious and unless costs are used in a comparable way, the results will not be meaningful and will also create problems of credibility. Since the results of the network design can have serious implications like plant closure, it is important that production costs are comparable across plants. If firms are using activity based costing, they can identify cost drivers for each product category and allocate costs on a reasonably fair and accurate basis.

### Transportation Costs

Allocation of transportation costs is relatively easy because for most of the links data will be available from the logistics provider. But in the case of a new network, firms can use distance as proxy for cost. When dealing with rural and semi-urban areas where the details of distance may not be available, then firms can calculate Euclidian distances from the coordinates of the nodes of the network.

# Strategic Role of Units in the Network

So far in our discussion we assumed that a network is optimized only to minimize costs. This is a very narrow and short-term view of plant capability. In this section, we introduce a framework to examine the role of a unit from a broader perspective.

## *Strategic Role Framework*

Ferdows has suggested that we should look at the role of a plant from a long-term perspective and it is possible that each unit within the network may play a different role. As shown in Figure 6.3, individual plants can play a lower strategic role where it is primarily located for accessing either market or low-cost resources or knowledge or a plant can play higher strategic role and make multiple contributions to the overall network. As shown in Figure 6.3, a plant can play six possible roles in a network and each of them is described below.

### Offshore Plant

An offshore facility is established to take advantage of low-cost labour or material in the region. It produces products/services for export markets. Global multinationals have been establishing low-cost manufacturing plants in Asia. China accounts for 70 per cent of the world's toys, 60 per cent of its bicycles, 50 per cent of shoes and 33 per cent of luggage. Global software companies have been setting up offshore facilities for backend services in India. Many countries in Asia have established free trade zones where labour costs are low, infrastructure is good, facilities are close to a port and all the import tariffs are waived provided the goods are exported and are not used for the domestic market. Offshore plants play a limited strategic role and investments in technical and managerial resources are usually quite low.

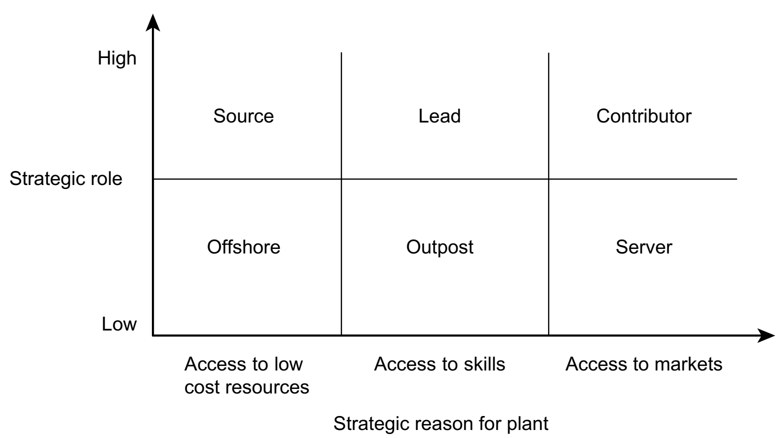



**Figure 6.3**
Role of plant in network.

### Server Facility

Server facility is established with an objective of supplying products/services to specific national or regional markets. It provides relatively lower-cost market access. A server facility is useful in a situation of tariff barriers, local content requirements or high logistics cost to supply to that region. Many multinationals established plants in India in the 1980s to serve local market because of high import tariffs prevalent in India. A server facility has a higher strategic role than an offshore plant because it may be allowed to make some changes in the products to cater to local tastes; similarly, it may be allowed to make changes in some processes to take advantage of the differential capital and labour costs. But it is not expected to play any role beyond that region, so in that sense it plays a limited strategic role.

### Outpost Plant

An outpost is established to tap into the local knowledge available in that region. There are advanced clusters in any industry where advanced suppliers, competitors, research laboratories and customers are located. Being present in that region allows a firm access to tacit information and knowledge, which is difficult to access from other places. For example, many companies dealing with cutting edge technology and hi-tech items are located in Silicon valley, the United States, and in Bangalore, India. Similarly, many pharmaceutical companies like Glenmark Pharma have set up labs in Switzerland, which though being a high cost economy is most likely to provide state-of-the-art information and knowledge to the organization.

### Source Plant

The main objective of establishing a source facility is low-cost production. But it plays a broader and more strategic role in a network than an offshore facility. A source plant might be the primary source of a product for the global network. A source facility will usually start as an offshore facility and will then gradually start playing a bigger and more strategic role in the network. Offshore facilities that show technical and managerial capability are usually upgraded to source status. ABB has centres of excellence for each product category. Source factories are located in regions where not only are the production costs low but adequate number of people with technical and managerial skills are available and the necessary infrastructure is in place.

### Contributor Plant

The main objective of establishing a source facility is low-cost market access. But it plays a strategic role in the network, which is broader than that of the server facility. Apart from serving specific regional or national markets, its responsibility extends to product and process engineering as well as supplier development. Over a period of time a server plant that develops those capabilities and takes necessary responsibilities becomes a contributor plant. For example, multinationals in India, like Unilever, have stared playing the role of contributor where they have made necessary investments in the relevant research and development labs.

### Lead Facility

A lead facility creates new processes, products and technologies for the entire network. It not only collects data for the headquarters, but also taps into local resources and becomes a hub, performing critical value-added activities.

## *Role Evolution Within a Network*

Typically, any new plant will start with a rather low strategic role and will provide market access, resource access or knowledge access. Whatever may be the rationale behind establishing a manufacturing facility at a specific location, the strategic role of the plant is likely to change over a period of time. Many multinationals had established offshore facilities in East Asia and Mexico to manufacture electronic parts, because of the low labour cost in that region. But over a period of time, labour cost went up and only those plants that had anticipated theses changes and managed to change the strategic role of facilities survived. Otherwise, over a period of time, firms have moved to China where labour costs are still relatively low. HP Singapore is an interesting case of a facility that has managed the transition very well.

### *EVOLUTION OF THE SINGAPORE FACILITY AT HP*[5]

HP Singapore started with manufacturing basic electronic components, and over a period of time demonstrated its capability to handle the entire product and not just the components. When the Singapore plant was asked to find ways of reducing the manufacturing costs for hand-held computers, they argued that since the bulk of manufacturing costs get decided at the design stage, they had to get the mandate to design the product to be in a position to reduce the manufacturing costs. Once they got the broader role, they managed to reduce the manufacturing costs by 50 per cent, as a consequence of which they got the additional responsibility of design and manufacturing. Over a period of time, through a series of capability building projects, the HP Singapore facility has established itself as a leader plant in the HP network.

Many software facilities in India are concerned with similar issues. They know that multinationals have located their facility here because of the low cost of skilled labour. But given the increasing cost (about 15 per cent per annum), there is concern that eventually these multinational might move to either Eastern Europe or to some other part of world. Local managers of these facilities are trying to ensure that these facilities are justified by their quality of work and innovations so that in the future they are not justified by labour cost alone. The chief of Dell India[6] recently said, "We came to India for quality and stayed back because of innovations".

LG had identified India as big potential market and decided in 1995 to set up manufacturing facilities here. The Indian facility started as a server, but over a period of time it has started playing the role of a contributor. In 2005, LG India spent about 1 billion rupees on research alone. LG India still imports the basic technology from South Korea, but 90 per cent of the required R&D work for new products is done locally.

Countries like Singapore have invested heavily in the education sector to ensure that local units in Singapore start playing a more strategic role in their respective networks. They have invited world-class institutes from around the globe to set up campuses in Singapore so that they can offer skilled labour in the IT and finance sectors, which can absorb the high cost of labour.

## Location of Service Systems

The discussion thus far on network design and operations has focused on ways of maximizing profits, minimizing costs, locating plants, handling complexities within the network and extracting the relevant data. We have not considered the location of service systems within the scope of our discussions. Such decisions are important strategic and tactical decisions that are of paramount importance in the retail and other similar sectors. In this section, we look at various issues associated with the location of service systems.

Deciding optimal locations for services where the facility will be visited by customers involves considerations that are very different from decisions related to plant networks for product businesses. Since the services sector consists of diverse sets of services, we focus our discussion on retail, public system services and aftermarket services.

Customer convenience is one of the key considerations in the retail network design. Unlike Dell Computers, which manages its global operations with just seven plants, Wal-Mart works with 3,900 stores in the United States alone and 2,700 stores in the rest of the world. Currently, Wal-Mart operates in 15 countries other than the United States, and the number of international stores is bound to go up significantly if Wal-Mart wants to have a global reach like Dell Computers. Within India, Food World, the market leader in organized retailing with a turnover of Rs 3 billion, owns more than 80 stores across 12 metros in southern India and has 29 stores in Bangalore.

## *Locating Retail Outlets*

The technique of locating retail outlets has been studied extensively, and the most popular model is the spatial interaction model developed by Huff. Huff's model groups population within a geographical region in clusters and the probability of a customer from one cluster visiting a store located in some other cluster is as shown below:

$$P_{ij} = \frac{S_j/(D_{ij})^2}{\Sigma_j S_j/(D_{ij})^2}$$

where $P_{ij}$ is the probability of customer from cluster $i$ travelling to retail location $j$, $S_j$ is the size of retail location $j$ and $D_{ij}$ is the distance from population cluster $i$ to retail location $j$.

The probability of attracting a customer to a store is directly proportionate to the size of the retail outlet and inversely proportionate to the distance travelled by the customer. Finally, a retailer is in a competitive market, and the probability that a customer will visit the store is a function of the relative attractiveness of the store. Let us assume that a firm wants to design a retail network for Bangalore city. Bangalore's population of 6.52 million is located over an area of about 700 km$^2$. So Bangalore can be divided into 70 clusters of 10 km$^2$ each. It is assumed that the entire population within a cluster is located at the centre of that cluster. Once the clustering is done, a firm can capture relevant data like customer population and distances from the GIS of the relevant region. Given the locations of competitors and the cost economics involved in locating a facility, a firm can use the above model in designing an appropriate network structure.

### Impact of a New Outlet on the Existing Network

Adding a new unit at a different location in the existing network will definitely attract a whole lot of new customers, but at the same time it might eat into the customer base of the existing units. Some customers of the existing units, finding the new unit more conveniently located, might switch to the new unit and in the process hurt the business and financial prospects of some of the existing units. On the positive side, the new unit will add to the system-wide revenue but might hurt some of the existing individual units in the network. Issues of conflict in service networks design are very similar to the one discussed earlier in the case of a global multinational's manufacturing business. In services, this issue is even more relevant because a lot of services operate with the franchise model. In franchise service operations, increasing one more outlet with a new franchisee in same city will hurt the franchisees of existing outlets. For its retail oil business, Reliance Industries Ltd is planning to build a network of about 2,000 retail outlets. Out of these 2,000 outlets, about 75 per cent will be run by franchisee partners and the balance will be company-owned outlets. As Reliance goes on increasing the number of outlets in the same geographical area like a city, we are sure to see issues of conflicting interest on the part of Reliance and its different franchisee partners. Any additional outlet in the network will add to business for the network but it will also eat into the business of existing units and franchisees.

While designing customer retail outlets where there will be interaction with customers, firms have to ensure that the backend network is able to serve these retail outlets, placed close to customers, in an efficient manner. Wal-Mart designed clusters of stores near distribution centres to facilitate frequent replenishments at the lowest cost. This was extremely important because Wal-Mart competed primarily on cost, and its overall network design and business practices were designed and operated so that it can offer products at the lowest possible prices in the retail outlets.

## *Locating Public Service Systems*

The model discussed above will not be applicable while designing networks for emergency and public service systems. In an emergency service system, instead of the average distance, one has to minimize the maximum distance for all the users who are likely to use the emergency system. See Box 6.1 for a discussion on the issue of designing a comprehensive trauma system at Bangalore. Similarly, while designing health care systems and deciding primary school locations in rural areas, the focus will have to be on equity and not just efficiency issues. While designing a network of schools it may be important that no child will have to walk more than three kilometres to reach school. In designing public systems, apart from efficiency considerations we will have to worry about equity issues also.

## *Designing Aftermarket Service System Network*

Designing aftermarket service systems involves issues similar to those discussed in designing of retail network systems. The design of an aftermarket service network is likely to receive much attention from manufacturers once they realize its importance from a business perspective. In developed markets, businesses earn 45 per cent of gross profit from aftermarket services, although it accounts for only 24 per cent of the revenue. Unlike in the case of retail outlets where the customer travels to a retail outlet for aftermarket services, a service provider will have to travel to the customers' premises (along with necessary parts). Since a customer is usually promised guaranteed service delivery time, decisions regarding location of after-service facilities with necessary resources (people and parts) are of vital importance. Unlike in retail services, an after-market service firm can work with geographical hierarchy of facilities. Firms like Tata Motors work with three-tier stocking centres and different categories of parts are located at different tiers. Tata Motors has one central distribution facility, where expensive parts required at low frequency are stocked. It maintains four regional service centres, where moderately expensive parts with moderate frequency requirements are stocked; and fast-moving,

**BOX 6.1** Comprehensive Trauma Consortium at Bangalore: Operation Sanjeevani[7]

Every year about 7,000 to 8,000 accidents take place in Bangalore and about 800 of them are fatal. Unfortunately, like in any other city, it used to take a couple of hours before medical help could be made available to victims after the accident. It is a well-known fact that when accident victims receive treatment within an hour of being injured, life can be saved in most of the cases and the extent of damage to organs also can be controlled significantly. To provide this service, the Comprehensive Trauma Consortium (CTC), a voluntary organization, was formed.

This initiative provides paramedical help to all medial emergencies and accidents and liaises with 22 hospitals to ensure that the best help is available to the victim within the "golden hour" of the accident/emergency. CTC has 25 ambulances and these are stationed at different locations around the city and are always on call, complete with preliminary medical equipment and a paramedic. On receiving a call, the CTC call centre directs the nearest ambulance to the accident spot. Through a global positioning system and wireless facility (installed in all CTC ambulances and partner hospitals), the control room directs the ambulance to the accident spot.

As per CTC estimates, after CTC came into being, the rate of patients being declared "dead on arrival" has gone down drastically from a high of 32 per cent (including 10 per cent in transit) to just 3 per cent.

CTC is working towards its mission of reaching its victims to the nearest hospital within 10 minutes.

low-valued parts are stocked in decentralized stock points located in every state. Of course, the firm may not offer the same service to all customers. Firms offer differentiated services like the platinum service, where a customer is assured of response in less than 24 hours, while customers of normal service are responded to within 72 hours. Different service offerings result in different service network designs.

Service network design issues are, however, not relevant for pure information-based services like travel, hotel booking and banking services, which do not require physical cash. Unlike software and music, pizza and service parts cannot be delivered through the Internet. So any service system that requires the delivery of some form of physical product will definitely face service network design issues discussed in this section.

## Incorporating Uncertainty in Network Design

Facility design decisions are strategic in nature and a firm will have to live with facility location and capacity decisions for several years. Most of the data used in the network design model are likely to change over a period of time. Projections of cost, price and demand over a longer horizon usually have a lot of uncertainties associated with those numbers. For example, in international network design, foreign exchange rates affect relative cost structures significantly and predicting the same is extremely difficult, if not impossible. Firms like Birla Cement or Asian Paints do not face this problem because they design multi-plant networks within a country. Though cost of living, inflation and other factors are likely to vary in different regions even within a country, the extent of variations is likely to be of much lower in magnitude because migration within a country is much easier compared to migration across countries. So, in general, design decisions about multi-plant networks within a country are easier compared to global networks. There are several ways in which firms handle these issues. Firms try and use scenario building through which they try and generate large numbers of likely future scenarios and select an option that performs reasonably well across the projected scenarios. So the focus shifts to selecting a robust solution rather than on picking a solution that is optimal for one scenario.

Over a period of time, Toyota has introduced greater flexibility in its plants worldwide. That is, a plant should be able to produce models that are required in the domestic market but must also be able to produce models for a few export markets. On the whole, the network will have excess capacity, so based on the exchange rates movement, volume will be allocated to the respective plants in the network. For example, Toyota might look at its Indian and Thai plants as the supply source for the South Asian market and keep excess capacity at both places. If baht is cheaper, it can allocate more volume to the Thailand facility, and if rupee is cheaper, it can allocate a higher share of the export market to India. This excess capacity in network provides the luxury of options to the Toyota network. This is known as real option because it provides a firm flexibility similar to financial options in financial markets. But unlike financial options, real options are difficult to trade. Firms that have excessively focused on their global manufacturing facilities have realized that any significant change in Yuan rate can change the cost structures in a significant way. There is a lot of pressure on China to devalue Yuan. Currently, LG uses its China facility as an export base and exports 70 per cent of its production from China. Given the uncertainty on the Yuan front, LG has decided to build excess capacity in India so that there is another hub available as an option for export.

The idea of excess capacity in global networks may go against the current logic of a lean supply chain design. In the lean philosophy, firms are not encouraged to keep this excess capacity, which has associated costs. Because of the pressures faced by global firms, it is quite tempting to avoid any excess capacity that may not have short-term payoffs. However, by doing so, the process firms will lose their flexibility.

## Summary

- The decision to allocate volumes and markets to plants is an important tactical decision for a global firm. The decision to locate these plants is an important strategic network design decision and has significant implications on the supply chain performance.
- Firms can use linear programming models to decide on optimal networks design and operations.
- A company's organization structure, performance measurement schemes and business strategy are key factors that affect the way network operations planning issues and design problems are modelled and solved.
- Network designing requires a large amount of data, and converting transactions data into meaningful data that can be used in the model is not a trivial task.
- Deciding optimal locations for services where the facility will be visited by customers involves considerations very different from decisions related to plant networks for product businesses.
- A firm has to live with a facility decision for a long time to come, so it should generate several scenarios based on the world view of likely developments in the future before taking a final decision.
- Global firms disperse their manufacturing plants to different locations and keep excess capacity in network as a hedge against uncertainties in markets and prices of finished products and raw material.

## Discussion Questions

1. How is managing a multi-plant international network different from managing a domestic multi-plant network?
2. A global company has put up a captive facility in India to manage a couple of internal backend processes. The CEO of the local unit is worried about the long-term competitiveness of the Indian unit. Labour cost has been increasing at the rate of 15 per cent in the last few years, and the CEO is worried that in the near future these processes may get shifted to Eastern Europe or some other part of the world. What should the CEO do so that the local unit can survive in the long run?
3. Reliance is trying design a network for its retail operations from the scratch. Suggest a suitable approach.
4. The central government has given several tax concessions for plants located in Baddi, and hence a large number of pharmaceutical and consumer non-durable firms have located their plants there. Why do you think auto component companies and garment companies have not moved to Baddi?
5. While Hyundai India Limited has only one manufacturing plant in India, Asian Paints has 18 processing centres. Why do firms in different industries work with different numbers of plants for serving the same market? List the pros and cons of having a large number of facilities?
6. Why should global firms question their network design decisions every few years?
7. Over a period of time Amazon.com has built new warehouses located at geographically different parts of the United States of America. Why should an e-retailer need multiple warehouses located at different parts of the country?

## Exercises

1) Take the example of Indian Paints. If the company is expecting that demand in each of the six markets will grow by 50 per cent in the next 2 years, should the firm close down any facilities? How much should each plant produce?
2) If Indian Paints decides to produce an extra 500 units in the second quarter to take care of the peak demand in the third quarter, what should the production and distribution plan be? Assume that 500 units will be shipped to all six regions in proportion of their normal demand and stocked in warehouses located close to the market.
3) Magic Mattress, a mattress manufacturing company in Bangalore, is trying to finalize its distribution network for northern India. The company has a manufacturing facility and a central inventory depot in Bangalore

attached to it. In the northern region, the firm presently markets its product through six demand points—Delhi, Kanpur, Jalandhar, Jaipur, Faridabad and Dehra Dun. Each of these demand points belongs to different states and union territories. If the firm serves retailers within the region from distribution centres (DCs) located in the same region (state/union territories) then it does not have to pay central sales tax (CST). CST is an inter-state sales tax and is levied on goods that are sourced from outside the region. If the firm locates DCs in all six regions it can avoid paying CST completely. The fixed cost per period of installing (apportioned) and operating a DC is Rs 2,500 per week. Transportation cost is Rs 0.2 per kilometre per unit, and the unit cost of a mattress is Rs 1,000. The firm has decided to locate at least one DC in the northern region so that the lead time for the retailer is less than 48 hours. The firm will try to serve a market in any region from a DC located closest to the market.

***Demand point specific data.***

| | Delhi | Kanpur | Jalandhar | Jaipur | Faridabad | Dehra Dun |
|---|---|---|---|---|---|---|
| Distance from central warehouse | 2,050 | 1,855 | 2,415 | 2,000 | 2,020 | 2,240 |
| Weekly demand | 40 | 16 | 16 | 16 | 8 | 4 |

***Distances matrix (in km).***

| Warehouse/ market | Delhi | Kanpur | Jalandhar | Jaipur | Faridabad | Dehra Dun |
|---|---|---|---|---|---|---|
| Delhi | 0 | 480 | 375 | 260 | 30 | 235 |
| Kanpur | 480 | 0 | 855 | 520 | 450 | 575 |
| Jalandhar | 375 | 855 | 0 | 635 | 405 | 365 |
| Jaipur | 260 | 520 | 635 | 0 | 290 | 495 |
| Faridabad | 30 | 450 | 405 | 290 | 0 | 260 |
| Dehra Dun | 235 | 575 | 365 | 495 | 260 | 0 |

The firm wants to decide the optimal location of its DCs so as to minimize the total cost. The total cost will include transport cost, fixed facility cost and CST-related cost.

(a) Where should the company locate its warehouses? Current CST rate is 4 per cent.

(b) The Indian government is planning to reduce CST over a period of time. How will your decision change if CST is brought down to 2 per cent.

4) Applichem (this exercise is based on "Applichem (A)", a case published by Harvard Business School), a manufacturer of release-ease, a speciality chemical, markets its product in six countries and has six plants in each of the six countries. Relevant data on plant capacity, production cost, market demand data, exchange rate and duty structure are as shown in the table below:

| | Mexico | Canada | Venezuela | Germany | USA | Japan |
|---|---|---|---|---|---|---|
| Unit production cost* | 9,167 | 119.3 | 498.8 | 183 | 103 | 35,955 |
| Capacity | 22 | 3.7 | 4.5 | 47 | 18.5 | 5.0 |
| Demand | 3 | 2.6 | 16 | 20 | 26.4 | 11.9 |
| Duty** | 60% | 0% | 50% | 9.5% | 4.5% | 6% |
| Exchange rate (currency/ $US 1) | 96.5 Pesos/ $US 1 | 1.23 Canadian dollar/ $US 1 | 4.3 Bolivareas/ $US 1 | 2.38 Deutsche Mark/ $US 1 | 1.0 | 235.0 Yen/ $US 1 |
| Currency used | Pesos | Canadian dollar | Bolivareas | Deutsche Mark | US dollar | Yen |

* Cost per unit in local currency.

**Percentage duty in each country was imposed on the value of the release-ease imported.

Transportation cost matrix from the plant to markets is as shown below:

***Transport costs ($/unit)***

| From/to | Mexico | Canada | Venezuela | Germany | USA | Japan |
|---|---|---|---|---|---|---|
| Mexico | 0.0 | 11.4 | 7.0 | 11.0 | 11.0 | 14.0 |
| Canada | 11.0 | 0.0 | 9.0 | 11.5 | 6.0 | 13.0 |
| Venezuela | 7.0 | 10.0 | 0.0 | 13.0 | 10.4 | 14.3 |
| Germany | 10.0 | 11.5 | 12.5 | 0.0 | 11.2 | 13.3 |
| USA | 10.0 | 6.0 | 11.0 | 10.0 | 0.0 | 12.5 |
| Japan | 14.0 | 13.0 | 12.5 | 14.2 | 13.0 | 0.0 |

What is the optimal production and the market allocation plan?

(Hint: Convert all costs in US$)

How will the decision change if there is a change in exchange rate; the new exchange rate structure is as follows:

| | Mexico | Canada | Venezuela | Germany | USA | Japan |
|---|---|---|---|---|---|---|
| Exchange rate (currency/$US 1) | 22.7 | 1.09 | 4.3 | 2.10 | 1.0 | 240.0 |

(a) How will the decision change if as a part of GATT agreement Mexico and Venezuela bring down the import duty on imported release to 10 per cent?

## Notes

1. See www.imagesretail.com/cover_story2_apr06.htm and www.thehindubusinessline.com/catalyst/2006/11/09/stories/2006110900010100.htm.
2. See www.unilever.com and Geoffrey Jones and Peter Miskell, "European Integration and Corporate Restructuring: The Strategy of Unilever, c. 1957-c. 1990," *European History Reviews* (2005, Vol LVIII): 113–119.
3. B. Fleischmann, S. Ferber, and P. Henrich, "Strategic Planning of BMW's Global Production Network," *Interfaces* (2006).
4. See www.asianpaints.com and interview of Ashwin Dani, VC & MD, Asian Paints, at www.cio.in/topview/viewArticle/ARTICLEID=1237.
5. Kasra Ferdows, "Making the Most of Foreign Factories," *Harvard Business Review* (March–April 1997): 73–88.
6. Romi Malhotra in interview with Mckinsey, see www.mckinsey.com/clientservice/bto/pointofview/pdf/MoIT8_Dell_F.pdf.
7. Based on personal discussion with Dr N. K. Venkatramana, Director for Neurological Disorders, Manipal Hospital.

## Further Reading


B. C. Arnzten, G. B. Brown, T. P. Harrison, and L. L. Trafton, "Global Supply Chain Management at Digital Equipment Corporation," *Interfaces* (1995, Vol 25): 69–93.

R. H. Ballou, *Business Logistics Management* (Upper Saddle River, NJ: Prentice Hall, 1999).

J. D Camm, T. E. Chorman, F. A. Dill, J. R. Evans, D. J. Sweeney, and G. W. Wegryn, "Blending OR/MS, Judgement, and GIS: Reconstructing P&G's Supply Chain," *Interfaces* (1997, Vol 27): 128–142.

Kasra Ferdows, "Making the Most of Foreign Factories," *Harvard Business Review* (March–April 1997): 73–88.

B. Kogut, "Designing Global Strategies: Profiting from Operational Flexibility," *Sloan Management Review* (1985, Vol 27): 27–38.

D. Lessard and J. Lightstone, "Volatile Exchange Rates Put an Operation at Risk," *Harvard Business Review* (1986, Vol 64): 107–114.

C. Markides and N. Berg, "Manufacturing Offshore Is Bad Business," *Harvard Business Review* (1998, Vol 66): 113–120.


## Appendix A: Solving Network Design and Operations Problem Using Excel Solver

Network operations planning and design problems can be formulated as linear programming problems and solved using Excel Solver. In this appendix, we describe the use of Excel Solver for formulating and solving network planning and design problems.

We illustrate the use of Excel Solver through the example of Indian Paints. We will work with cost minimization for both network operations planning and design formulations. The whole exercise involves three steps:

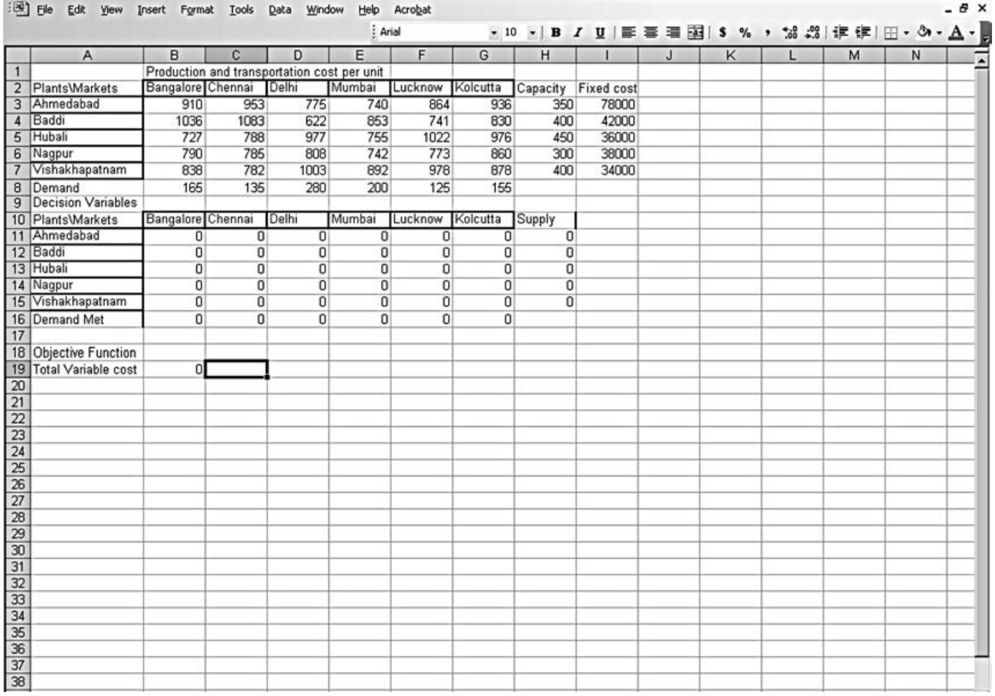
Step 1: Preparing base data in Excel

Step 2: Formulating the model in Solver

Step 3: Solving the problem and carrying out sensitivity analysis of the solution using Solver

### *Step 1: Preparing Base Data*

As can be seen in Figure A6.1, cells B3:G7 contain production and transportation cost data ($Cost_{ij}$) for supply of product from plant to market, cells H3:H7 and I3:I7 contain capacity



| | A | B | C | D | E | F | G | H | I |
|---|---|---|---|---|---|---|---|---|---|
| 1 | | Production and transportation cost per unit | | | | | | | |
| 2 | Plants\Markets | Bangalore | Chennai | Delhi | Mumbai | Lucknow | Kolcutta | Capacity | Fixed cost |
| 3 | Ahmedabad | 910 | 953 | 775 | 740 | 864 | 936 | 350 | 78000 |
| 4 | Baddi | 1036 | 1083 | 622 | 853 | 741 | 830 | 400 | 42000 |
| 5 | Hubali | 727 | 788 | 977 | 755 | 1022 | 976 | 450 | 36000 |
| 6 | Nagpur | 790 | 785 | 808 | 742 | 773 | 860 | 300 | 38000 |
| 7 | Vishakhapatnam | 838 | 782 | 1003 | 892 | 978 | 878 | 400 | 34000 |
| 8 | Demand | 165 | 135 | 280 | 200 | 125 | 155 | | |
| 9 | Decision Variables | | | | | | | | |
| 10 | Plants\Markets | Bangalore | Chennai | Delhi | Mumbai | Lucknow | Kolcutta | Supply | |
| 11 | Ahmedabad | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 12 | Baddi | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 13 | Hubali | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 14 | Nagpur | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 15 | Vishakhapatnam | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 16 | Demand Met | 0 | 0 | 0 | 0 | 0 | 0 | | |
| 17 | | | | | | | | | |
| 18 | Objective Function | | | | | | | | |
| 19 | Total Variable cost | 0 | | | | | | | |

**Figure A6.1**

Spreadsheet for the data.

($Cap_i$) and fixed cost ($Fcost_i$) data for each of the five plants, and B8:G8 contains demand ($Dem_j$) data for each of the market.

Objective function and the respective left-hand sides of demand (Equation 6.1) and supply (Equation 6.2) are prepared using the formula shown in Table A6.1.

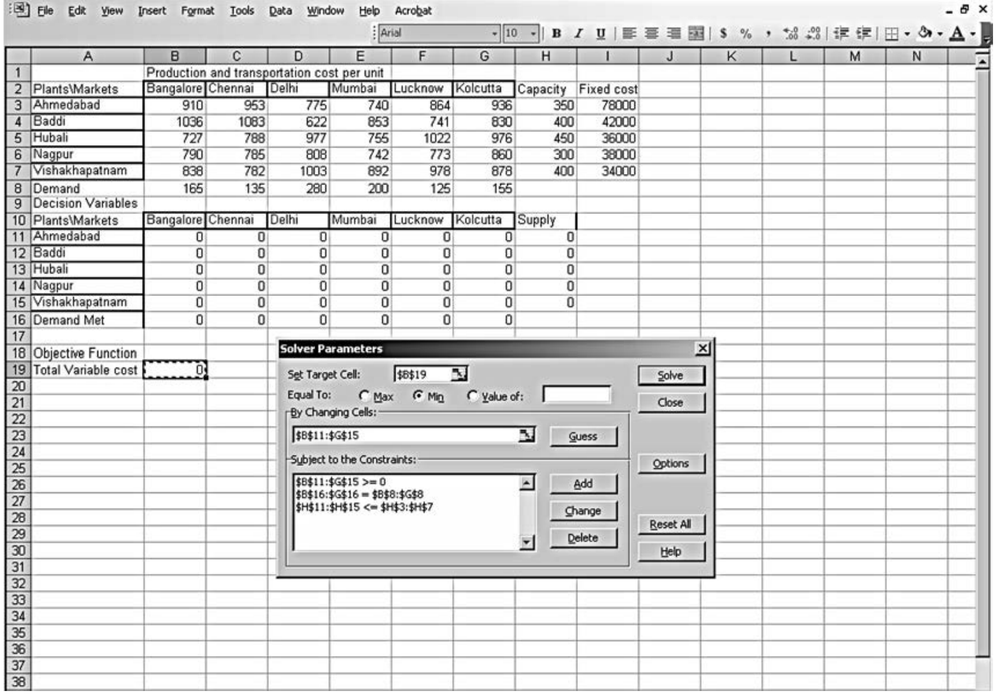
Decision variable supplies from plant to market ($Quant_{ij}$) are represented by Cells B11: G15. Objective function is represented by cell B19. The left- and right-hand sides of Equation 6.1 are represented by cells B16:G16 and B8:G8. Similarly, the cells H11:H15 and H3:H7 represent the left- and right-hand sides of Equation 6.2. The left-hand side of Equation 6.3 is represented by cells B11:G15. Now we are ready to set up the Solver in Excel.

## *Step 2: Formulating Model in Solver*

Choosing Solver from the tool menu displays the Solver parameter box, as can be seen in Figure A6.2. This parameter box allows us to set up the model in the Solver. The objective function cell (B19) is treated as the target cell in Solver, and as we are working on a minimization problem, we choose the minimization option. Decision variables (B11:G15) are entered in the box indicated "Guess".

***Table A6.1: Relevant spread formulae.***

| Cell | Cell formula | Equation | Copied to | Remark |
|---|---|---|---|---|
| B19 | = SUMPRODUCT(B3:G7,B11:G15) | Objective function | | |
| B16 | = SUM(B11:B15) | Demand constraint (Equation 6.1) | C16:G16 | Six demand constraints |
| H11 | = SUM(B11:G11) | Supply constraint (Equation 6.2) | H12:H15 | Five supply constraints |



| | A | B | C | D | E | F | G | H | I |
|---|---|---|---|---|---|---|---|---|---|
| 1 | | Production and transportation cost per unit | | | | | | | |
| 2 | Plants\Markets | Bangalore | Chennai | Delhi | Mumbai | Lucknow | Kolcutta | Capacity | Fixed cost |
| 3 | Ahmedabad | 910 | 953 | 775 | 740 | 864 | 936 | 350 | 78000 |
| 4 | Baddi | 1036 | 1083 | 622 | 853 | 741 | 830 | 400 | 42000 |
| 5 | Hubali | 727 | 788 | 977 | 755 | 1022 | 976 | 450 | 36000 |
| 6 | Nagpur | 790 | 785 | 808 | 742 | 773 | 860 | 300 | 38000 |
| 7 | Vishakhapatnam | 838 | 782 | 1003 | 892 | 978 | 878 | 400 | 34000 |
| 8 | Demand | 165 | 135 | 280 | 200 | 125 | 155 | | |
| 9 | Decision Variables | | | | | | | | |
| 10 | Plants\Markets | Bangalore | Chennai | Delhi | Mumbai | Lucknow | Kolcutta | Supply | |
| 11 | Ahmedabad | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 12 | Baddi | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 13 | Hubali | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 14 | Nagpur | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 15 | Vishakhapatnam | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 16 | Demand Met | 0 | 0 | 0 | 0 | 0 | 0 | | |
| 17 | | | | | | | | | |
| 18 | Objective Function | | | | | | | | |
| 19 | Total Variable cost | 0 | | | | | | | |



**Figure A6.2**

Solver parameter box.

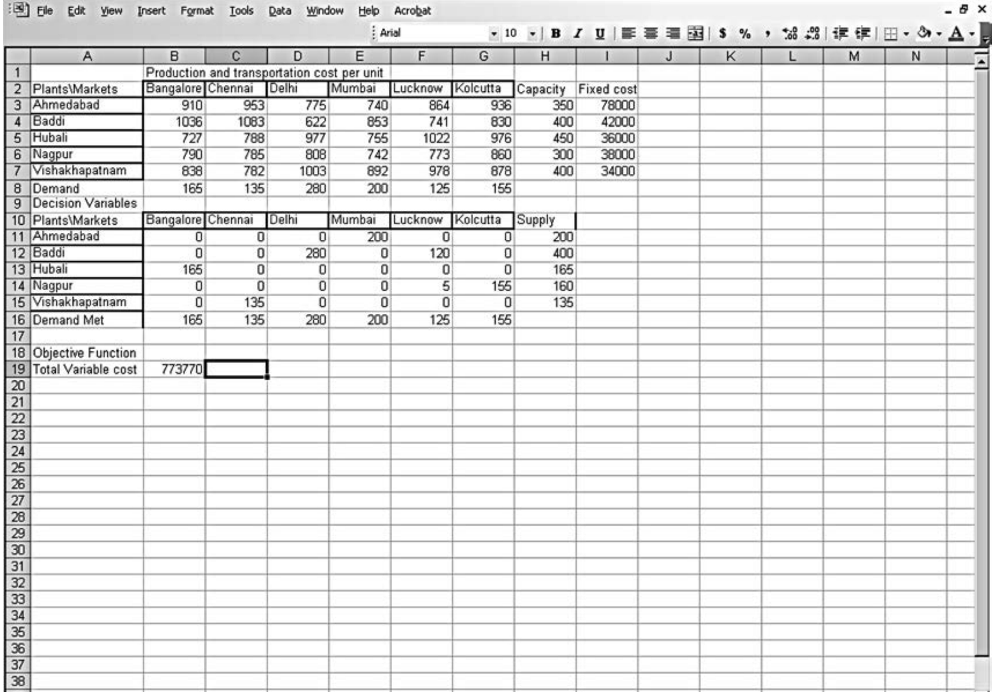
As can be seen in Figure A6.2, Equations 6.3, 6.1 and 6.2 are entered in that order in the constraint box.

## *Step 3: Solving Problem and Carrying Out Sensitivity Analysis of the Solution Using Solver*

Clicking solve within the Solver parameter box will result in an optimal solution as shown in Figure A6.3. The details of the solution are reported in Table 6.3.

While clicking solve on Solver parameter box, one can choose to obtain data on sensitivity analysis as one of the outputs of Solver. The sensitivity analysis output contains two outputs: (a) sensitivity analysis on constraints (see Figure A6.4(a)) and (b) sensitivity analysis on parameters of objective function (see Figure A6.4(b) for a partial extract of the output).

For each demand and supply constraint, the shadow price is also reported in the above table. The shadow price of the constraint equation measures the marginal value of this resource. If we look at supply constraints, the shadow price is –32 for Baddi and zero for all other plants. So, if the capacity of the Baddi plant is increased by one unit, the objective function (total variable cost) will increase by –32. For all other plants change in capacity will have no impact on objective function. This is quite intuitive because all other plants are operating at less than full capacity in the final solution, so a change in the capacity value will have no impact on network planning decisions. The shadow price of –32 for Baddi will be valid from the capacity range of 280 (400 – 120) to 405 (400 + 5). Beyond this range of capacity, one will have to run Solver again to understand the impact of change in the capacity on the objective function. Similarly, if demand from Delhi increases by one unit, the objective function will increase by 654, while any increase in unit demand at Kolkata will increase cost by 860. This information will help the marketing department in making appropriate plans for different markets.



| | A | B | C | D | E | F | G | H | I |
|---|---|---|---|---|---|---|---|---|---|
| 1 | | Production and transportation cost per unit | | | | | | | |
| 2 | Plants\Markets | Bangalore | Chennai | Delhi | Mumbai | Lucknow | Kolcutta | Capacity | Fixed cost |
| 3 | Ahmedabad | 910 | 953 | 775 | 740 | 864 | 936 | 350 | 78000 |
| 4 | Baddi | 1036 | 1083 | 622 | 853 | 741 | 830 | 400 | 42000 |
| 5 | Hubali | 727 | 788 | 977 | 755 | 1022 | 976 | 450 | 36000 |
| 6 | Nagpur | 790 | 785 | 808 | 742 | 773 | 860 | 300 | 38000 |
| 7 | Vishakhapatnam | 838 | 782 | 1003 | 892 | 978 | 878 | 400 | 34000 |
| 8 | Demand | 165 | 135 | 280 | 200 | 125 | 155 | | |
| 9 | Decision Variables | | | | | | | | |
| 10 | Plants\Markets | Bangalore | Chennai | Delhi | Mumbai | Lucknow | Kolcutta | Supply | |
| 11 | Ahmedabad | 0 | 0 | 0 | 200 | 0 | 0 | 200 | |
| 12 | Baddi | 0 | 0 | 280 | 0 | 120 | 0 | 400 | |
| 13 | Hubali | 165 | 0 | 0 | 0 | 0 | 0 | 165 | |
| 14 | Nagpur | 0 | 0 | 0 | 0 | 5 | 155 | 160 | |
| 15 | Vishakhapatnam | 0 | 135 | 0 | 0 | 0 | 0 | 135 | |
| 16 | Demand Met | 165 | 135 | 280 | 200 | 125 | 155 | | |
| 17 | | | | | | | | | |
| 18 | Objective Function | | | | | | | | |
| 19 | Total Variable cost | 773770 | | | | | | | |

**Figure A6.3**

Optimal Solver solution.

| Cell | Name | Final Value | Shadow Price | Constraint R.H. Side | Allowable Increase | Allowable Decrease |
|---|---|---|---|---|---|---|
| $B$16 | Demand Met Bangalore | 165 | 727 | 165 | 285 | 165 |
| $C$16 | Demand Met Chennai | 135 | 782 | 135 | 265 | 135 |
| $D$16 | Demand Met Delhi | 280 | 654 | 280 | 120 | 5 |
| $E$16 | Demand Met Mumbai | 200 | 740 | 200 | 150 | 200 |
| $F$16 | Demand Met Lucknow | 125 | 773 | 125 | 140 | 5 |
| $G$16 | Demand Met Kolkata | 155 | 860 | 155 | 140 | 155 |
| $H$11 | Ahmedabad Supply | 200 | 0 | 350 | 1E+30 | 150 |
| $H$12 | Baddi Supply | 400 | -32 | 400 | 5 | 120 |
| $H$13 | Hubli Supply | 165 | 0 | 450 | 1E+30 | 285 |
| $H$14 | Nagpur Supply | 160 | 0 | 300 | 1E+30 | 140 |
| $H$15 | Vishakapatnam Supply | 135 | 0 | 400 | 1E+30 | 265 |

**Figure A6.4(a)**

Sensitivity analysis on constraints.

| Cell | Name | Final Value | Reduced Cost | Objective Coefficient | Allowable Increase | Allowable Decrease |
|---|---|---|---|---|---|---|
| $B$11 | Ahmedabad Bangalore | 0 | 183 | 910 | 1E+30 | 183 |
| $C$11 | Ahmedabad Chennai | 0 | 171 | 953 | 1E+30 | 171 |
| $D$11 | Ahmedabad Delhi | 0 | 121 | 775 | 1E+30 | 121 |
| $E$11 | Ahmedabad Mumbai | 200 | 0 | 740 | 2 | 1E+30 |
| $F$11 | Ahmedabad Lucknow | 0 | 91 | 864 | 1E+30 | 91 |
| $G$11 | Ahmedabad Kolkata | 0 | 76 | 936 | 1E+30 | 76 |
| $B$12 | Baddi Bangalore | 0 | 341 | 1036 | 1E+30 | 341 |
| $C$12 | Baddi Chennai | 0 | 333 | 1083 | 1E+30 | 333 |
| $D$12 | Baddi Delhi | 280 | 0 | 622 | 121 | 1E+30 |
| $E$12 | Baddi Mumbai | 0 | 145 | 853 | 1E+30 | 145 |
| $F$12 | Baddi Lucknow | 120 | 0 | 741 | 2 | 121 |
| $G$12 | Baddi Kolkata | 0 | 2 | 830 | 1E+30 | 2 |

**Figure A6.4(b)**

Sensitivity analysis on parameters of objective function.

Using the parameter of objective function, sensitivity is captured by reduced cost. If the relevant decision variable ($Quant_{ij}$) is positive, the reduced cost will be zero. But wherever $Quant_{ij}$ is zero, the reduced cost will tell us by what amount the cost parameter should change so that the corresponding decision variable will get a non-zero value in the optimal solution. For example, Baddi does not supply to Mumbai and the corresponding cell E12 has reduced cost to 145. Hence, only if the cost of production plus transportation from Baddi to Mumbai drops by 145 will Baddi start supplying to Mumbai. Similarly, Delhi gets it supply from Baddi and will keep getting supply from Baddi as long as the per unit cost increase is not more than 121. So it allows one to understand the impact of change in value of objective function parameters on optimal solution.

# Network Design Decision

We work with cost minimization for network design formulations. In network design problems, we need to introduce binary variables. As can be seen in Figure A6.5, apart from $Quant_{ij}$

*Table A6.2: Relevant spreadsheet formulae.*

| Cell | Cell formula | Equation | Copied to | Remark |
|---|---|---|---|---|
| B19 | = SUMPRODUCT (I3:I7,H11:H15) + SUMPRODUCT(B3:G7,B11:G15) | Objective function | | |
| B16 | = SUM(B11:B15) | Left side of Demand constraint (Equation 6.7) | C16:G16 | Six demand constraints |
| I11 | = SUM(B11:G11) | Left side of Supply Constraint (Equation 6.8) | I12:I15 | Five supply constraints |
| J11 | = H3*H11 | Right side of Supply Constraint (Equation 6.8) | J12:J15 | Five supply constraints |

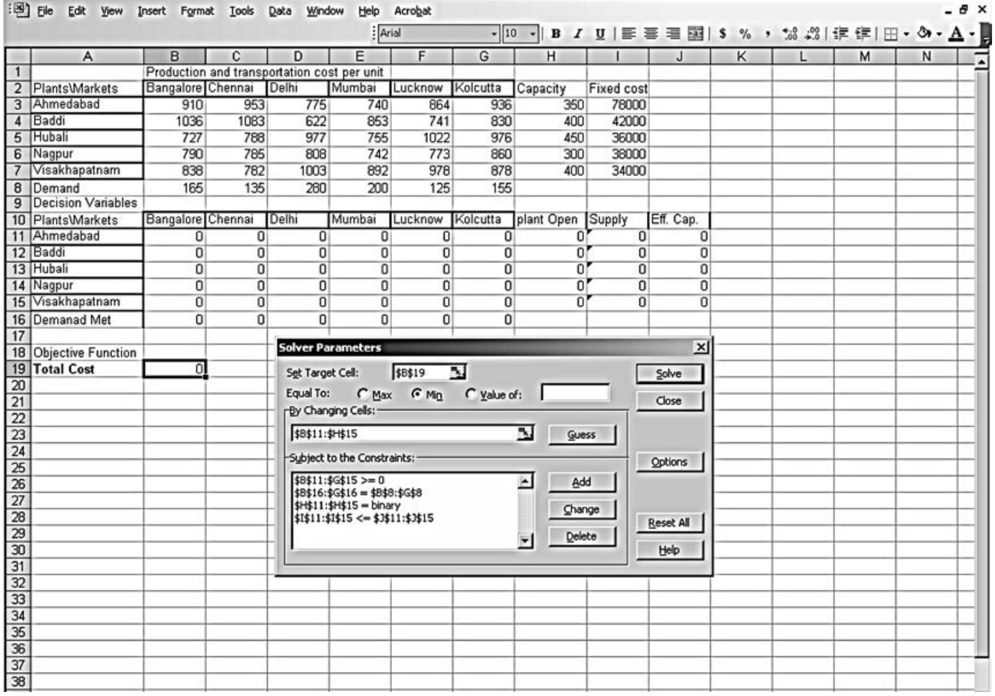



**Figure A6.5**

Solver parameter box for network design problem.

variables, additional variables $Fac\text{-}open_i$ have been introduced in cell H11:H15. The relevant spreadsheet formulae are presented in Table A6.2.

As can be seen in Figure A6.5, in the constraint box Equations 6.9, 6.7, 6.10 and 6.8 are entered in that order. Solver solves binary linear programming problems using the branch and bound solution methodology.