Upstream vs. Downstream Flexibility in a Production-Distribution Supply Chain

Amitabh S. Raturi

Jayanth Subramani

ML # 130, University of Cincinnati,

Cincinnati, OH 45221-0130.

Abstract

The capability to improve market responsiveness to meet future uncertain demand is a critical imperative for many firms today. Flexibility in the supply chain to accommodate such changes in demand is a function of the alternative routes a product may take as it travels from the plant where it is made to the distribution center to the regional warehouse and finally to the retailer. From a supply chain perspective, this output flexibility means the capability of the network to provide a mix of products at the retail level. This paper tries to provide an insight into supply chain flexibility by comparing upstream and downstream flexibility from a two-echelon multi-product scenario. The two echelons modeled here are the plant and the distribution center.

Upstream flexibility in the supply chain is defined as the capability of the supply chain to fill distribution centers from plants. Thus if all plants can supply all distribution centers all the items in the product portfolio, the supply chain has complete upstream flexibility. Similarly, downstream flexibility is defined as the capability of the supply chain to ship products from the distribution center to the market (regional warehouses or the retailer). A supply chain has complete downstream flexibility if all distribution centers have capability to ship to all products to all markets.

The paper is develops a non-linear integer program to model the supply chain system. We then evaluate the consequences of upstream and downstream flexibility in the supply chain by simulating alternative demand patterns and solving for the optimal product movement in the supply chain under alternative design conditions. We find that upstream flexibility has better payoffs (much higher service level) when demand of products is negatively correlated. We also find that moving towards full flexibility has marginally decreasing payoffs. Thus if the cost of developing these routes in the supply chain is significant, it may be optimal to design the supply chain for limited or partial flexibility.

1. Introduction

A supply chain is a network of facilities and distribution options that performs the functions of procurement of materials, transformation of these materials into intermediate and finished products, and the distribution of these finished products to customers (Ganesan and Harrison, 1995). A simple schematic of a two-product two-echelon supply chain is shown in Figure 1. Echelons in the supply chain refer to the number of stages at which the product is inventoried before it arrives in the hands of the customer. The arrows in the figure indicate product movement.

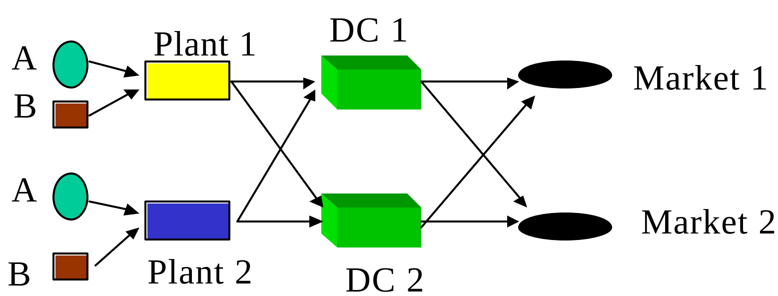


Figure 1:
A Two product Two Echelon Supply Chain

Any firm (or coalition of firms) has at least four choices with regard to the product movement in this supply chain. These are as follows:

I. It may choose to make product A at one plant (Plant 1), and serve both markets using one distribution center (DC1).
II. It may choose to make product A at both plants but route it to the two markets using only one distribution center (DC1)
III. It may choose to make product A at only one plant (Plant 1) and route it through both distribution centers (DC1 and DC2)
IV. It may choose to make product A at both plants (Plant 1 and Plant 2) and route it through both distribution centers (DC1 and DC2). This is the scenario shown in Figure 1.

These choices have important consequences for the market performance (for example, service level) and costs (for example, shipping and routing costs) related to any product category. For example, design I might be least costly in terms of shipping and manufacturing cost as substantial economies of scale are generate in both manufacturing and transporting the product to markets. However, it may not perform that well from a customer service perspective as it has the least capability to be flexible to changes in demand. Since product is made a dedicated facility and routed through a dedicated warehouse, any upswing in demand will have to be absorbed by the inventory at one distribution center or capacity at one plant. Alternatively, Designs II, III and IV provide other options such as using the inventory at another distribution center or the capacity at another plant. Jordan and Graves (1995) capture this concept succinctly for a multi-plant network. In developing several principles on the benefits of flexibility, they conclude that 1) limited flexibility (i.e., each plant builds only a few products), configured in the right way, yields most of the benefits of total flexibility (i.e., each plant builds all product); and 2) limited flexibility has the greatest benefits when configured to chain products and plants together to the greatest extent possible.

In this paper we extend the above arguments by developing the concepts of upstream and downstream flexibility in a supply chain. Upstream flexibility in the supply chain is defined as the capability of the supply chain to fill distribution centers from plants. Thus if all plants can supply all distribution centers all the items in the product portfolio, the supply chain has complete upstream flexibility. Similarly, downstream flexibility is defined as the capability of the supply chain to ship products from the distribution center to the market (regional warehouses or the retailer). A supply chain has complete downstream flexibility if all distribution centers have capability to ship to all products to all markets.

Based on the four design options before, we can then conclude that design I is the case when the supply chain has no flexibility. Design II on the other hand offers upstream flexibility in the supply chain as a change in the demand for A and B can be accommodated by plant 1 or plant 2. Consider the simple scenario where both plants make both products and the demand for A increases, and demand for B decreases by 10 units. Also ignore the inventory levels at the distribution centers and lead time to deliver the products through the supply chain. Then design II is capable of shipping the entire product to the market, whereas in design I we would have excess inventory of product B and would have had to backorder or stockout for product A.

Similarly, design III reflects the situation where the supply chain has downstream flexibility. In the situation where both products are routed through both distribution centers, inventory at either DC may be used to meet the variations in demand in the market. This gives greater flexibility than design I, and the incremental cost is maintaining inventory and shipping routes to both distribution centers.

Finally, design IV reflects the full flexibility situation as changes in demand in the market can be accommodated either through DCs or through alterations in the production schedule at the plants. Table 1 summarizes these four options and evaluates the hypothesized consequences of alternative design choices.

Table 1: Tradeoffs in Supply Chain Design

Design Choice	Service level (such as fill rate in the market)	Inventory costs	Manufacturing cost	Shipping and Route maintenance cost
I: No flexibility	Low	Low	Low	Low
II: Upstream flexibility	Medium	Medium	High	Low
III: Downstream flexibility	Medium	Medium	Lo	High
IV: Full flexibility	High	High	High	High

The rest of the paper is organized as follows. We first review the literature pertinent to the design of the supply chain for flexibility. In section 3, we develop a non-linear integer program that captures the tradeoffs in the design choices as indicated in Table 1. The model allows us to develop the benchmarks for alternative designs under varying conditions of demand. In section 4, we show several computations that reflect the optimal choice under varying scenarios and make conclusions from these results. We conclude the paper with key results and suggestions for future research.

2. Literature Review

Manufacturing flexibility has been interpreted as process flexibility, the ability of being able to produce and deliver products to the market in different ways (Ramesesh and Jayakumar, 1991). In recent years, much has been stressed on supply chain in a manufacturing environment, the necessity to fine-tune the chains with principles such as variability and postponement (for example, Bhatnagar and Chandra, 1997 and Pyke and Cohen, 1994). In the light of these studies and the effect of flexibility in manufacturing environments, it might be valuable to study operational or routing flexibility in a supply chain that will indirectly give process flexibility to the entire chain. Though there has been work done on production and distribution systems in a supply chain, the effect on flexibility on the echelons of the supply chain and its positional advantage has not been studied to great depths.

Flexibility is a key strategy for market responsiveness in situations where firms face uncertain product demand For example, Slack (1990) considered what flexibility means in a production context and examined how it can be measured. Slack argued that flexibility has three dimensions: (1) range of states the system can adopt; (2) cost of moving from one state to another; and (3) time required to move from one state to another. Slack also argues that perhaps there is no single measure of flexibility because it is ultimately a measure of the systems potential to perform rather than its actual performance.

Ramasesh and Jayakumar (1991) measured the aggregate flexibility of a manufacturing system by investigating the joint effect of flexibilities on a variety of dimensions when measurement for a medium-term time horizon is appropriate. They propose a value-based approach in which flexibility is measured by the ability of a manufacturing system to generate revenues consistently across all conceivable states. They suggest an index, (the ratio of the mean to the standard deviation of the distribution of optimal revenues) as the flexibility measure. Our interpretation of flexibility in this paper is similar. A design choice is more flexible if it can achieve higher average performance under varying conditions of demand.

Jordan and Graves (1995) reach some farsighted conclusions on the issue of how much flexibility is appropriate. They show that the incremental value of flexibility is generally diminishing. By interpreting flexibility in terms of the capability of the system to provide for market demand and simultaneously optimizing resource utilization, they establish a unique and insightful definition of process flexibility in a manufacturing network -- it is the inverse of the joint probability of having stockouts and underutilized capacity. Our interpretation of flexibility in the supply chain is similar. A supply chain design is flexible if it can simultaneously optimize on resource utilization as well as accommodate variations in market conditions. Unlike Jordan and Graves, however, we explicitly model the cost of obtaining this flexibility.

Much research has focussed on models for production distribution systems. Cohen and Lee (1988) evaluate strategies in multi-location supply chain systems and tradeoffs in flexibility with cost and service for stochastic demand. An analytical model is used to arrive at operating policies to minimize inventory and cost. However, they do not discuss the effect of service and flexibility at the different echelons of the supply chain. Multi-product scenarios are evaluated in Pyke and Cohen (1994) with an optimization algorithm. Under certain assumptions, they are able to predict a three-way tradeoff among replenishment size, finished goods inventory and retailer inventory with respect to cost and service. They come closest to our work since one interpretation of finished goods inventory may be upstream flexibility and retailer inventory may be viewed as downstream flexibility.

Routing flexibility has been conventionally defined as the ability of the part being produced through different ways or with different process plans (Sethi and Sethi, 1994). Our paper departs somewhat from this definition, though it retains the essence of this definition. Supply chain routing flexibility is defined here as the flexibility of being able to reach the customer through different routes from the production facility. The effect of this routing flexibility is to be evaluated at two echelons in the supply chain- between the production facility and the distribution center (upstream flexibility) and between the distribution center and the customer or market (downstream flexibility). DeGroote (1994) characterizes flexibility as a hedge against diversity and argues that flexibility is a measure of capability of the technology or system and not a measure of the diversity in the environment. This contradicts the measurement of flexibility through variables such as variation in sales volume (Fiegenbaum and Karnani 1995). In this paper, the flexibility in a system to ship a product from alternate distribution centers or from alternate plants provides the hedge against the demand uncertainty for the product. Using Sethi and Sethi's terminology, we are concerned primarily about volume flexibility in the supply chain.

3. Supply Chains with Upstream & Downstream Flexibility

Our main objective in this paper is to evaluate the impact of routing flexibility in a supply chain. Thus our decision variables had to be defined in a nested fashion: we want to find out specifically:

- Quantity of any product made at any plant,
- Quantity of any product made at any plant and transported to any DC, and,
- Quantity of any product made at any plant and transported to any DC and shipped to any market.

Let I be the index for products, j the index for plants, k the index for DCs and l the index for markets. Then our decision variables are r_{ijkl} , that is, the amount of product I shipped through the specific supply channel (j,k) to market l. Then, if all distribution centers were shipping to all markets, we can define the product movement through any DC as:

$$q_{ijk} = \sum_l r_{ijkl}$$

where q_{ijk} = quantity of product I shipped from plant j to distribution center k. However, since a DC may not supply a market, the design choice would reflect the actual movement and if Z_{ijkl} were defined as the 0-1 variable indicating the existence of this link, then[1],

$$q_{ijk} = \sum_l r_{ijkl}*Z_{ijkl}.$$

[1] Note that this laborious definition of links is necessary to evaluate downstream flexibility.

Similarly, if Y_{ijk} is the 0-1 variable representing the existence of a link between plant j and distribution center k, then,

$Q_{ij} = \sum_k q_{ijk} * Y_{ijk}$

Also, since a product may or may not be produced at a plant, we use X_{ij} as a 0-1 variable to represent if product I is made at plant j, and the total quantity of product I made at plant j is just $X_{ij}Q_{ij}$.

Finally, if

c_{ij} is the cost of producing item i at plant j,

s_{ijk} is the cost of shipping product i made at plant j to to distribution center k,

S_{ikl} is the cost of shipping product i from distribution center k to market l, and,

π_{il} is the penalty cost of not meeting the stochastic demand, ξ_{il}, in market l

then the total supply chain cost may be represented as,

$$TC= \sum_i\sum_j [c_{ij}Q_{ij} *X_{ij}+ \sum_k \{s_{ijk} q_{ijk}* Y_{ijk} + \sum_l S_{ikl} r_{ijkl}* Z_{ijkl}\}] + \sum_i\sum_l\pi_{il} (\xi_{il} - \sum_j\sum_k r_{ijkl}* Z_{ijkl})$$

The constraints to this formulation include

(1) the limited capacity at the plant, that is, $\sum_i Q_{ij} *X_{ij} \leq C_j$

where C_j is the capacity of plant j.

(2) the limited capacity at the distribution center, or, $\sum_i\sum_j q_{ijk}* Y_{ijk} \leq D_k$

where D_k is the capacity of distribution center k.

(3) demand constraints that restrain selling more than the demand realization, that is,

$\sum_j \sum_k r_{ijkl}* Z_{ijkl} \leq \xi_{il}$

(4) upper and lower bounds on manufactured quantity as well as the shipping quantities, both from plant to DC and DC to market, such as,

$L_j \leq \sum_i Q_{ij} * X_{ij} \leq U_j$ for mimimum and maximum production at the plant

$L_{jk} \leq \sum_i q_{ijk} * Y_{ijk} \leq U_{jk}$ for minimum and maximum shipment between plants and DCs

$L_{jkl} \leq \sum_i r_{ijkl} * Z_{ijkl} \leq U_{jkl}$ for minimum and maximum shipment between DCs and markets

(5) the implied constraints on the decision variables (for example, a distribution center may not ship a product it does not receive)

$MX_{ij} \geq \sum_k Y_{ijk}$

$MY_{ijk} \geq \sum_k Z_{ijkl}$

where M is a large number.

The objective function is the cost for the entire chain including production shipping and penalty costs for stockouts. Thus the model was a simultaneous cost minimization and service maximization model. The service level for demand met for the two products for each scenario can also be calculated since by varying the penalty cost for not meeting the demand we can generate scenarios with high or low overall service level. The model is a non-linear integer program solved with the help of Excel Solver.

4. Computational results

To gain insight into the nature of consequences generated by upstream and downstream flexibility, we consider a simple scenario. The model considered here is a two-echelon supply chain where two products are produced at two plants produced, stored in two distribution centers and being shipped to two markets (see Figure 1). Products A and B are the two products able to be produced in either plant 1 or plant 2. Flexibility in routing is brought about by incorporating shipping flexibility fin the supply chain upstream and downstream. The arrows indicate the possible routes that the products could take.

To solve the complex formulation, we chose to maintain certain decision variables manually and use the following assumptions:

- Cost of production of the two products were the same
- Cost of shipping the products A or B and shipping cost upstream or downstream were the same (this avoids biasing the result based on cost)
- Capacity of the plants were 100 units each and capacity at the DCs were 200 each (irrespective of whether product A or B), and
- Penalty cost of not meeting demand at both the markets and for both the products were the same.

The model is evaluated based on all possible routes of product A. Product B has only two configurations, either full flexibility or no flexibility (see Figure 2 below). The second sets of arrows indicate the possible routes for product B. The various steps for comparing were executed by varying the decision variables for the routing so as to simulate the configuration. The demands for the two products were obtained from Crystal Ball and were stochastic in nature. The Excel solver was used to specify the quantities stored and shipped for each route thereby arriving at different service levels and penalty costs for various configurations. The results were grouped into Excel spreadsheets for the purpose of analysis and obtaining graphs. Suitable graphs were obtained which gave insight into flexibility aspects and where it made sense to increase the flexibility and where it did not.

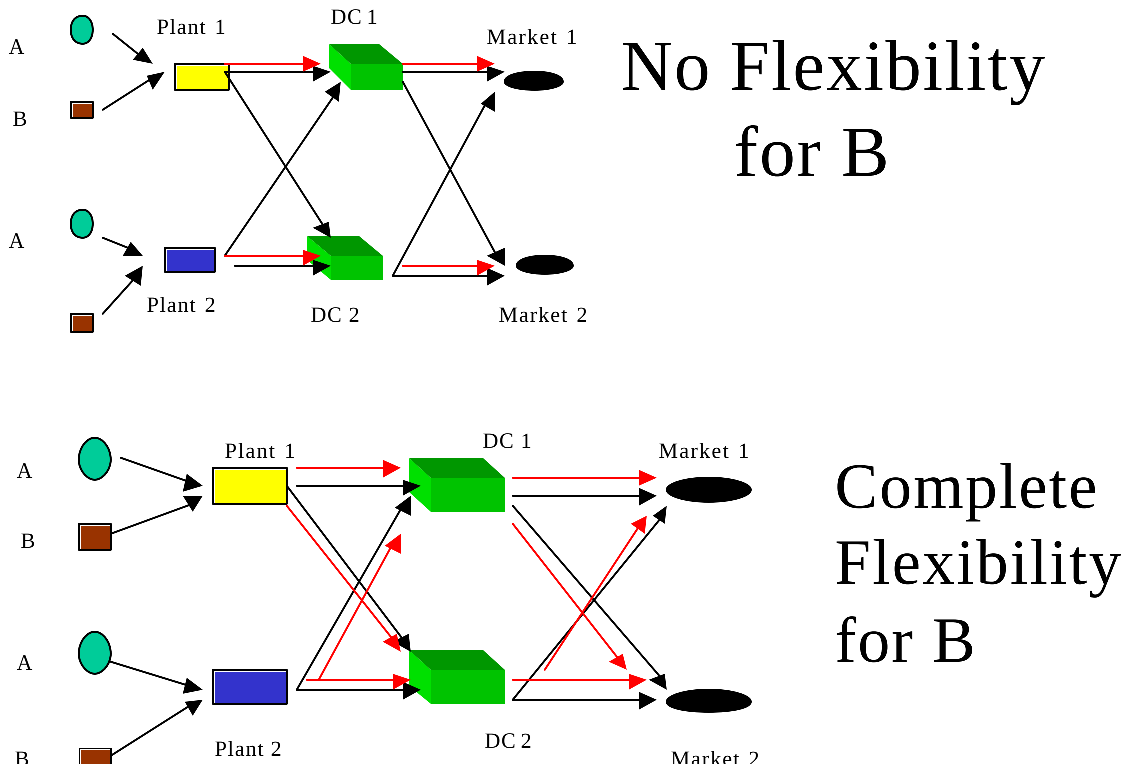


Figure 2: Configurations evaluated

Note that the two additional arrows for product B in the bottom figure from plant to DC indicate upstream flexibility, while the two additional arrows from DC to markets represent downstream flexib ility. We used the following three steps to evaluate the impact of flexibility, both upstream and downstream, in this scenario.

- We first compare the effect of full and no flexibility of product B on the service levels of product A in markets 1 and 2 under alternative configurations for A. These results establish the validity of the model by verifying that as links
- We then compare the service levels of product B under the conditions of full and no flexibility under a fixed configuration of product A.

- Finally, we compare upstream and downstream flexibility by looking at the service levels of product A and product B with certain correlation in the markets between the two products.

The following three sub-sections show how these steps impact the results. We discuss our results briefly within each section.

A. Full flexibility versus no flexibility in B

To further with the evaluation of upstream vs. downstream flexibility, it was imperative to be able to design a proper experiment with limited number of runs that would not affect the results. As a start, the effect of complete or full flexibility on product A was the first test. The decision variables X, Y and Z were suitably varied to simulate the 15 possible alternate routes for product A (see Figure 3 below).

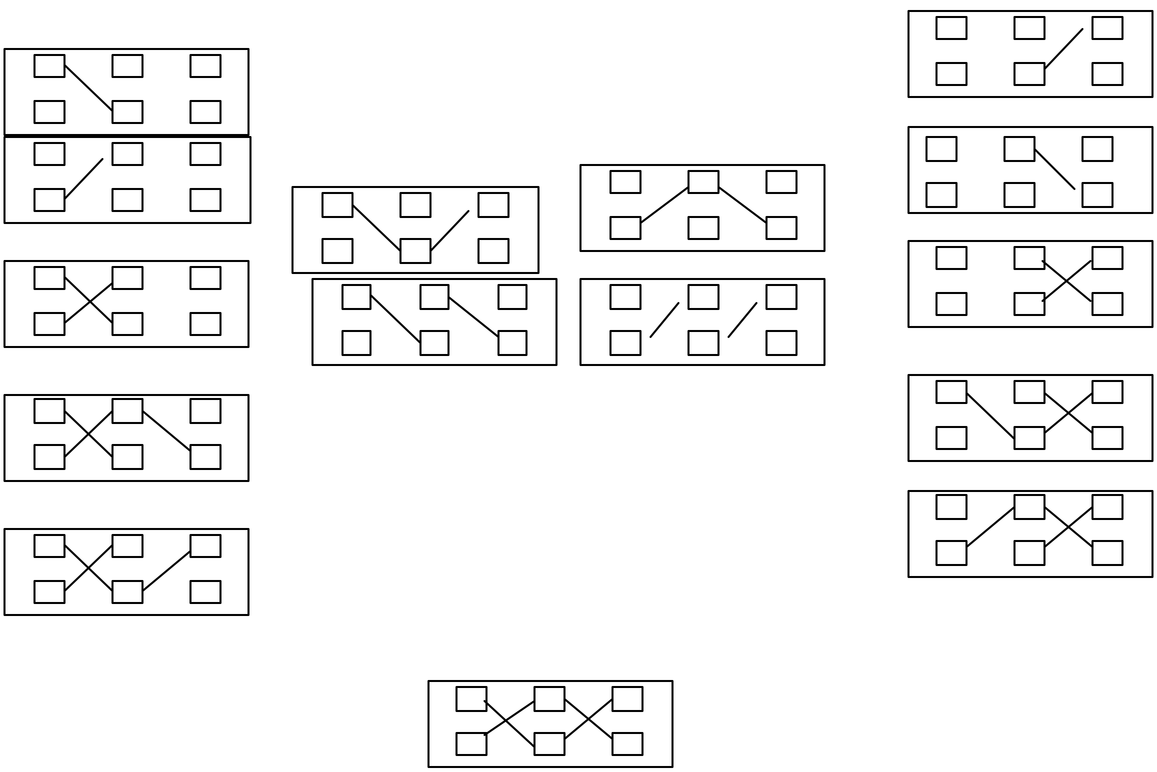
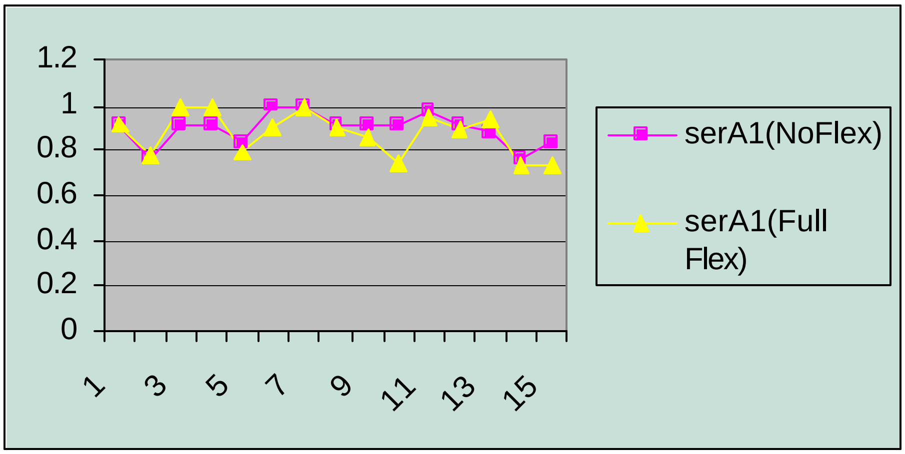


Figure 3 Alternative Scenarios Considered

In Crystal Ball, an Excel add-on, a stochastic demand was chosen as follows: Product A at markets 1 and 2 were 107 and 121 with demand for product B at the two markets being 103 and 76 respectively. The two cases of no and full flexibility on product B are shown in Figure 4 below.



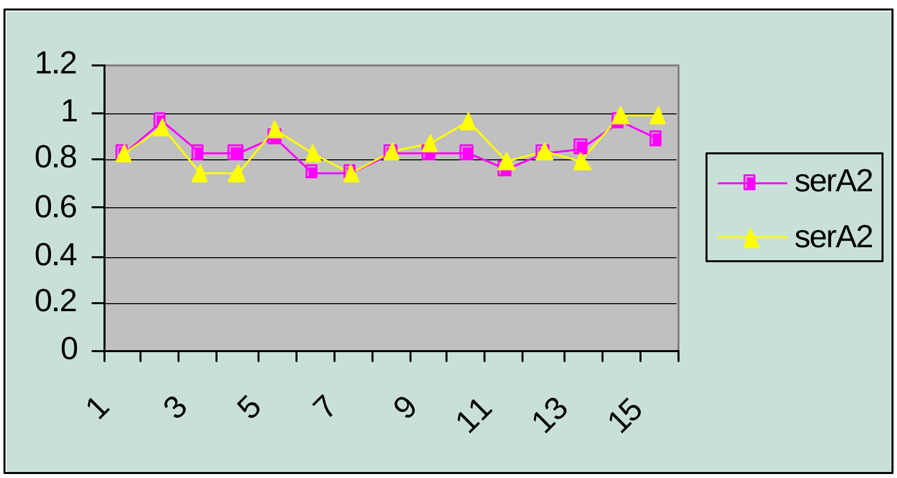


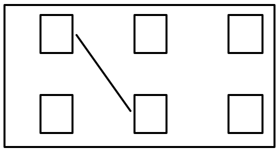
Fig 4:

Comparing 15 configurations for A and No/Full Flexibility for B

It is thus seen from the second chart that the full flexibility has no effect on product A in market 2 for this particular demand. But from chart 1, it is seen that since there is no buffer inmarket1, actually having full flexibility for B hampers market 1 as the model tries to optimize for service B thereby reducing service level of product A in market 1.

Part II

The conclusion that flexibility in B not affecting service levels of product A is not completely justified unless more than 1 type of demand is tested.

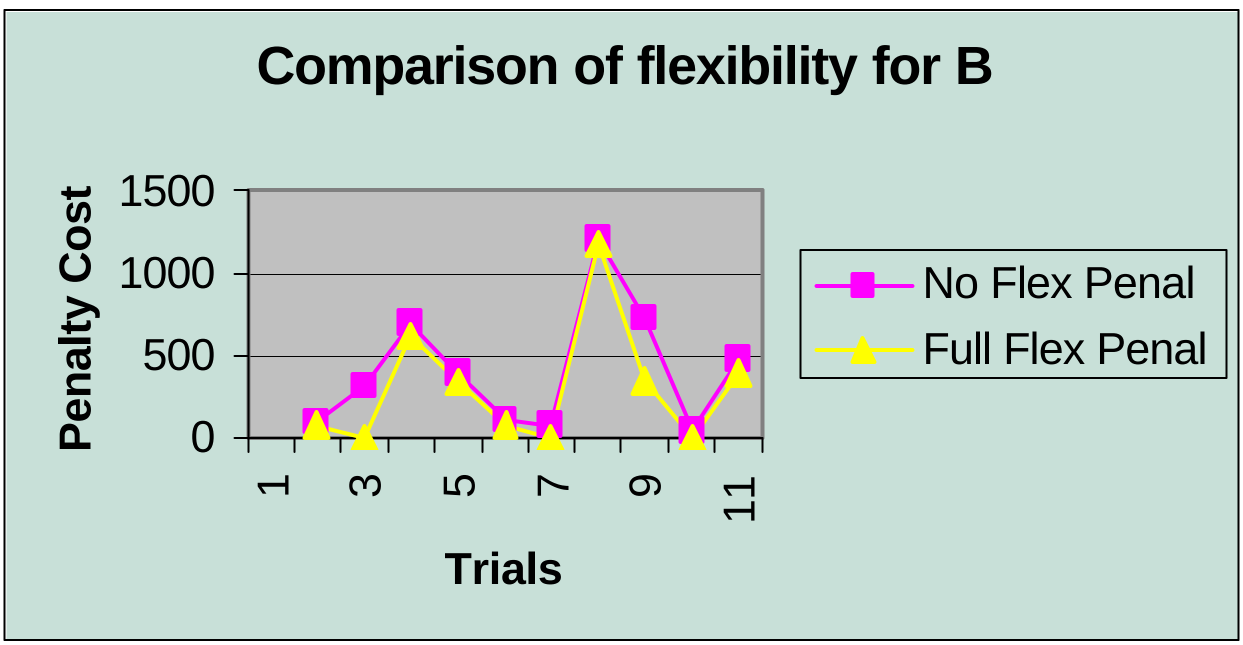


Fixed Configuration:

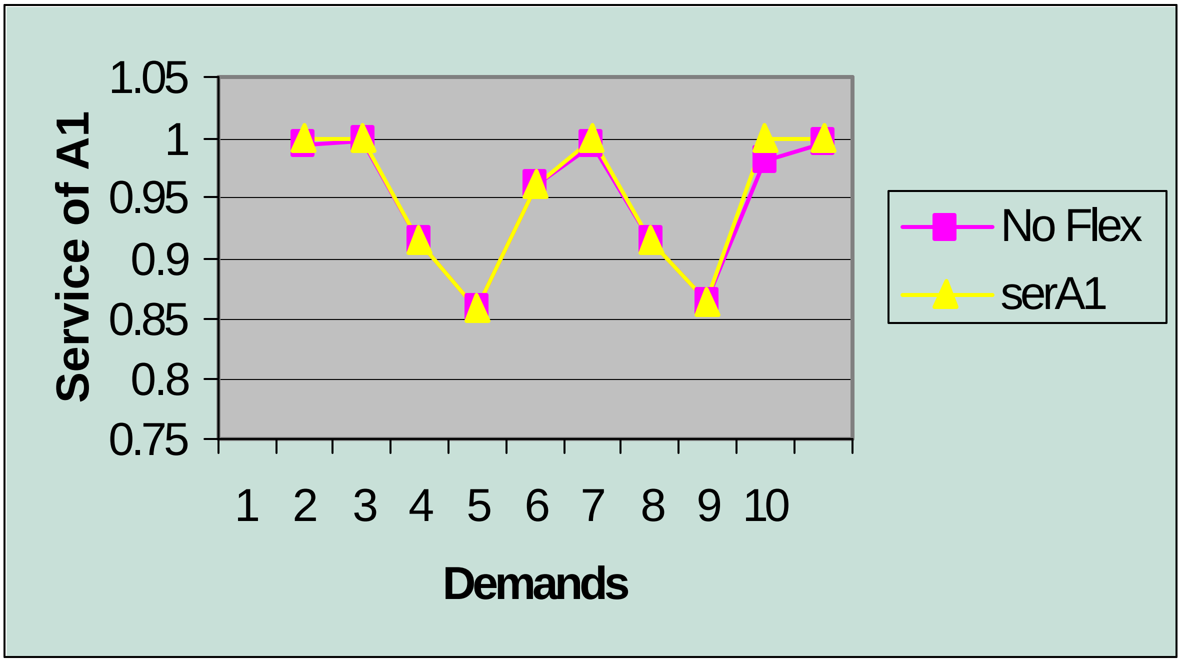
Product A is allowed to be shipped from plant 1 to DC1 and DC2 and from DC1 straight to market 1 and from DC 2 straight to market 2 (with no cross shipment)

Types of tests:

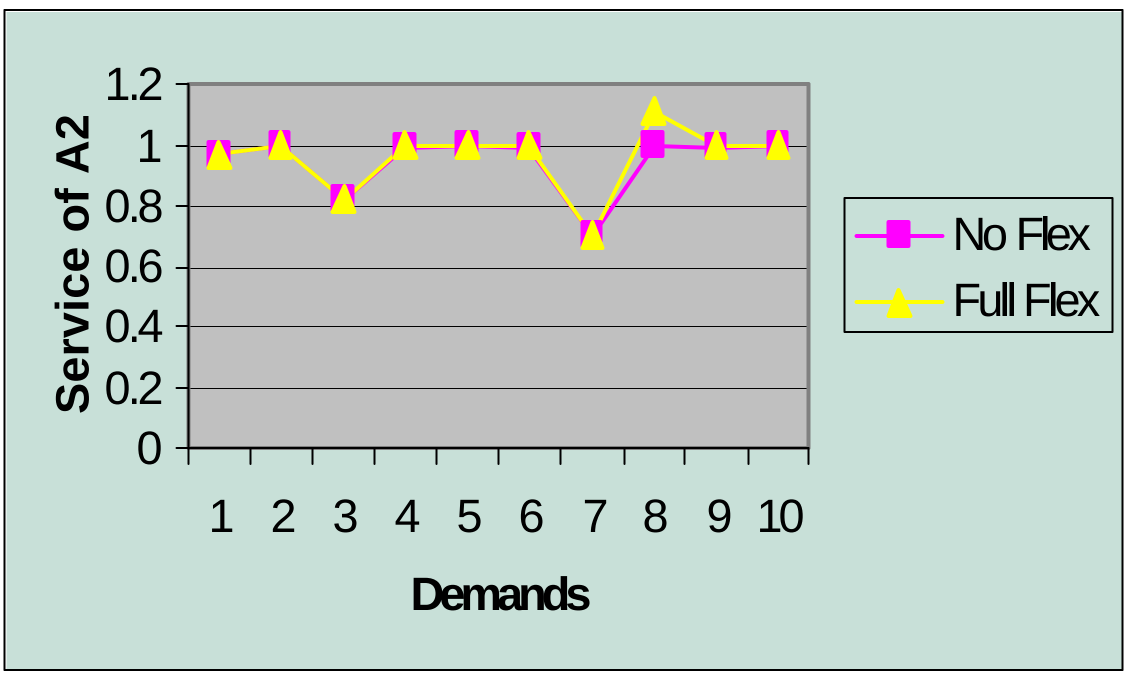
- The penalty cost of not meeting demand for product A in market 1 for no and full flexibility of product B for the above fixed configuration of A (Appendix A-Fig 2).



- For 10 different demands the service level of product A in market1 and market 2 is plotted.



- For 10 different demands the service level of product B in market1 and market 2 is plotted



From the above tests and charts, it is evident that the previous conclusion of flexibility of product B will not really affect the evaluation of upstream vs. downstream flexibility of product A. It is also seen that the scenarios with just 1 flexible link are worse than those with higher links (which is expected) but links upstream are better than the link downstream as the downstream has no input at the DC level. (Penalty cost for scenario 3 and 4 in fig 2 are the worst).

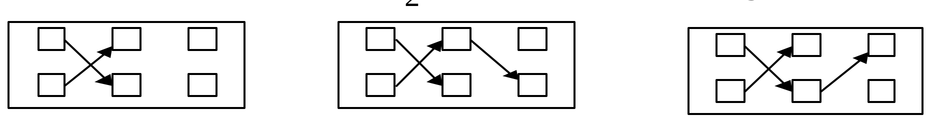
Also from the chart on the service level of product B in market 1 and 2 with 10 different demands, it is evident that the flexibility by adding links for product B is not required in most cases of stochastic demand. Thus for purposes for further modeling and analysis, there is only scenario considered. Having seen that there is no effect on upstream vs. downstream flexibility for product A by the flexibility scenarios of product B, only full flexibility scenario for product B is considered.

Part III

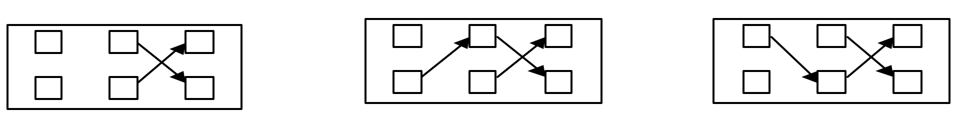
To evaluate upstream and downstream flexibility, a clear definition of the upstream scenarios and downstream scenarios are made in the figure below. There are 3 for the first case and three for the other. The small boxes in the figures represent the supply chain echelons. We illustrate three of the many scenarios possible here in each case. For upstream flexibility, both plants may ship to both DCs. The 6 scenarios in charts from this point refer to these 6 scenarios.

U p s t r e a m F l e x i b i l i t y

1 2 3



D o w n s t r e a m F l e x i b i l i t y

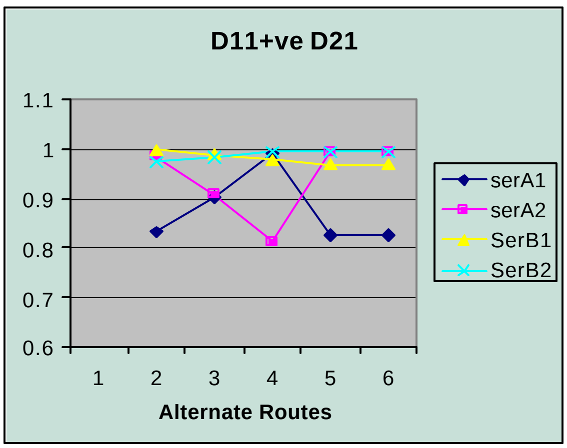


To evaluate the flexibility (upstream vs. downstream), there were three steps considered

- Service level of product A in **market 1** for the 6 scenarios and correlation.
- Service level of product A in **market 2** for the 6 scenarios and correlation.
- Comparison service levels of product A in markets 1 and 2 and product B in market 1 for 4 demand scenarios.

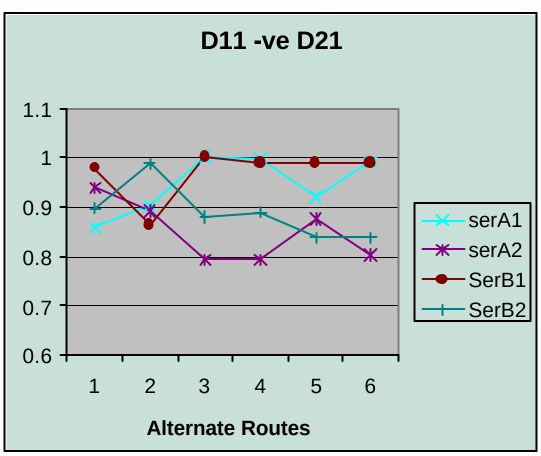
Correlation: There are 4 different possibilities- product A having positive correlation with product B in markets 1 and 2 and product A having the similar negative correlation. This is obtained by demands generated IDD and stochastic by Crystal Ball with the necessary correlation with a normal correlation co-efficient of 0.35.

Service Level of product A with positive correlation with product B in market 1



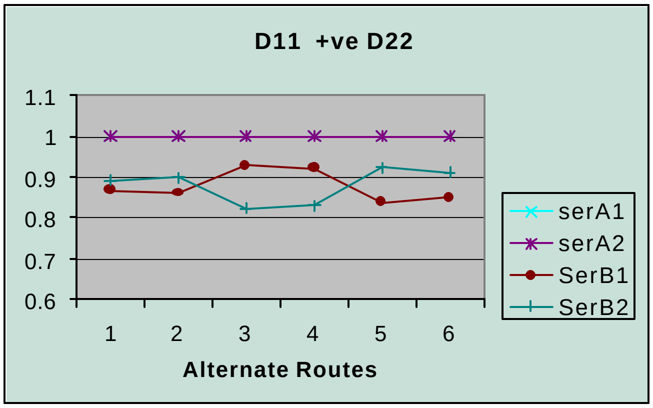
From this chart, though the correlation does not have much significance, it is seen that Routes 1 and 6 are at extremes for the service levels. The objective is to select routes for which almost all service levels is at maximum. From this standpoint, routes 2 and 3 are the best as service levels A2 and A1 are at minimum for the other routes namely 5 and 6. Here we see that upstream flexibility is better for this kind of correlation.

Service Level of product A with negative correlation with product B in market 1

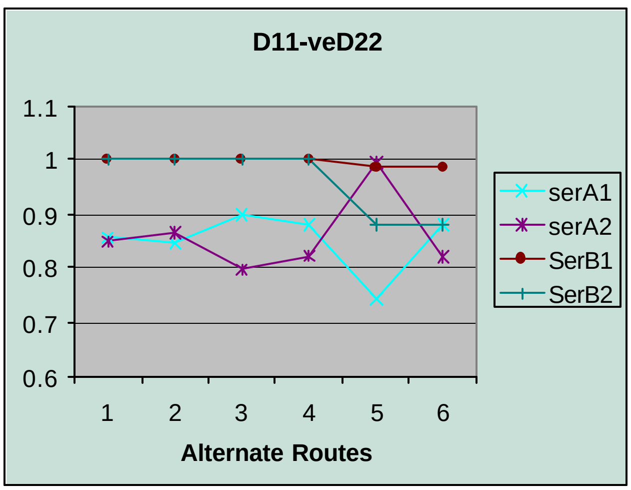


The negative correlation indicates the possibility of meeting more demand at market 1 with the decrease for demand in product B. Thus it is obvious that service level of product A in market 1 is relatively high. If we look at the other curves, it is seen that route 2 looks the best (this is the one which adds more flexibility to market 2 which is essential as the correlation exists in market 1). Routes 1 and 5 are pretty efficient in themselves but routes 4 and 6 are not very supportive of downstream flexibility.

Service Level of product A with positive correlation with product B in market 2

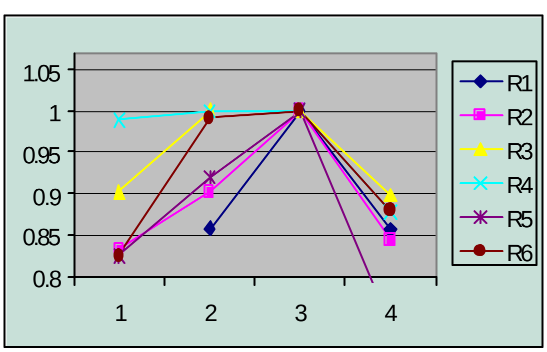


Service Level of product A with positive correlation with product B in market 2

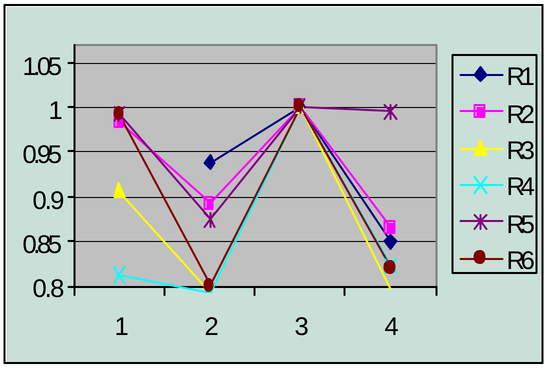


The above two charts have not been taken directly into consideration as they talk about correlation to product B in market 2 and they are not conclusive in themselves. A point though to be noted is that in Fig 6, the best route is route 5 which shows that the key element in that link is from Plant 2 to DC 1 which is again a upstream link component.

Comparison of service levels of product A in markets 1 and markets 2 for four types of demand which are stochastic in nature**.** The chart below gives the service levels of product A in market 1 for the 6 different routes.

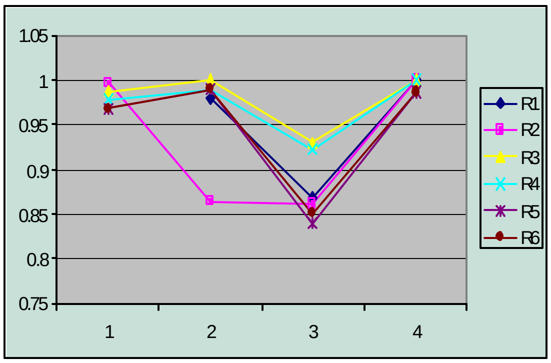


Obviously, the demand 3 has maximum service levels as it is below the overall capacity. But for all the demands, the best route seems to be route 3.



The chart below gives the service levels of product A in market 2 for the 6 different routes. Route 2 has the maximum service level for product A in market 2.

The chart below gives the service levels of product B in market 1 for the 6 different



routes. From the above chart we see that route 3 seems to deliver the maximum service level for product B in market 1. The market 2 has not been completely analyzed as we have concentrated on market 1 and product A as it could be generalized to product B and market 2 as well.

5. Conclusion

This paper compares upstream vs. downstream flexibility and various test have been made to validate the assumption that upstream flexibility is preferable. Only one product in one market is analyzed as it can be generalized to others. With stochastic demand, it can safely interpreted that demand data does not have an adverse affect on the results. Correlated data has also been used to predict dynamic demand situations where markets have certain trends in them.

Some of the inferences which are made are -

- The effect of full flexibility of product B is not really felt for service levels of A in both markets when demand is not strongly correlated.
- Upstream flexibility is preferable when there is negative correlation with the other product in same market to utilize the capacity of the warehouse but this conclusion can be made for other type of correlated data though not with too much proof from the limited data sets. Below are the cumulative service levels for the different routes

indicating higher levels for upstream in the supply chain. Routes 1,2 and 3 have cumulatively a higher service level for products A and B in markets 1 and 2.

- Increasing links to add flexibility has an efficient limit for this scenario which is 3 links and links downstream have no sense without links upstream.

The paper is just a stepping stone into flexibility analysis of this nature on supply chains and can be improved and tuned with a larger data set and validated with real time results.

References:

Bhatnagar, Rohit and Pankaj Chandra, ' Models for multi-plant coordination", European Journal of Operations Research 67 (1993), 141-160.

Cohen, M.A and Lee, H.L. " Strategic Analysis of Integrated Production-Distribution Systems: Models and Methods", Operations Research 36/2 (1988), 216-228

de Groote, Xavier (1994). The Flexibility of Production Processes: A General Gramework, *The Institute of Management Science*, 40(7).

Fiegenbaum, A. and Karnani, A. (1991). Output Flexibility—A competitive Advantage for Small Firms. Strategic Management Journal, Vol. 12, pp. 101-114.

Ganeshan, Ram and Terry P. Harrison (1996), " An Introduction to Supply Chain Management", Working paper, Department of Management Science and Information Systems, 303 Beam Business Building, Penn State University, University Park, PA 16802 U.S.A.

Gerwin, D. (1993). Manufacturing Flexibility: A Strategic Perspective, Management Science, Vol. 39, No. 4, April, pp. 395-410.

Jordan, William C. and Stephen C. Graves, "Principles on the Benefits of Manufacturing Process Flexibility", Management Science 41/4 April 1995, 577-594.

Kekre, S. and Srinivasan, K. Broader Product Line: A Necessity to Achieve Success? Management Science, v36n10, Oct 1990, pp 1216-1230.

Pyke, David F. and Morris A. Cohen, " Multi-product Integrated production-distribution systems", European Journal of Operations Research 74 (1994), 18-49.

Ramesesh, Ranga V. and Maliyakal D. Jayakumar, " Measurement of Manufacturing Flexibility: A Value Based Approach", Journal of Operations Management, 10/4 (October 1991), 446-468.

Sethi. A. K. and S. P. Sethi (1990), Flexibility in Manufacturing: A Survey**.** International Journal of Flexible Manufacturing Systems, 2, pp. 289-328.

Slack, Nigel (1984), Flexibility as a manufacturing objective, IJOPM, 3(3).

Suarez, F. F., Cusumano, and C. H. Fine (1995). An empirical study of flexibility in manufacturing systems, Sloan Management Review, 37 (1), pp. 25-32.

Suarez, F. F., Cusumano, and C. H. Fine (1995). An empirical study of flexibility in printed circuit board assemply, Operations Research, 44(1).

David M. Upton, "Process Range in Manufacturing: An Empirical Study of Flexibility", Management Science 43/8 (August 1997), 1079-1092.