SUPPLY CHAIN PLANNING OVER PRODUCT LIFECYCLES

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ABSTRACT

Supply chain configurations should change over the lifecycle of the product. During the early stages expensive suppliers with greater reliability and flexibility are desirable in order to meet uncertain market requirements, whereas in later stages with steady and declining demand, low cost suppliers should be chosen. Given the extremely short and overlapping product lifecycles in the Hi-Tech industry, it becomes necessary to use formal planning models to manage such dynamic supply chain configurations. In this paper, we develop a mixed integer-programming model for integrated planning across the supply chain and show how such a model may be used for decision-making across the product lifecycle. We assume that all stakeholders in the supply chain share information on their capacities, schedules and cost structures. Based on this information the model addresses the issue of partner selection and planning for optimal profit. The model was solved using optimization tools from ILOG.

1. INTRODUCTION

The primary role of supply chain networks is to deliver products to the market, whenever and wherever it is needed. However, the constantly changing market demand, which evolves with the lifecycle of the product, necessitates a change in the configuration of the supply chain configuration.

In the early stages of product design and introduction, sourcing is a critical process and consequentially the focus of supply chain management should be on inbound logistics. Subsequently, during the growth phase out-bound logistics and distribution become extremely important. Also, in this early stage of the product lifecycle there might be ongoing engineering and redesign, based upon feedback from pioneering customers. As a result, the supply chain needs to be composed of suppliers and service providers who are responsive and close to the manufacturer. However, as the product stabilizes and matures, low product cost becomes a critical competitive factor. This drives the selection of cheaper overseas suppliers within the network. Also, at this late stage in the product's lifecycle the ability to service and maintain products already in the market becomes crucial and the importance of service logistics comes to the fore. Finally, at the end of the products lifecycle, products need to be collected from the customers and safely disposed off or refurbished for further use. This is where reverse logistics becomes the dominant logistics requirement as shown in Figure 1.

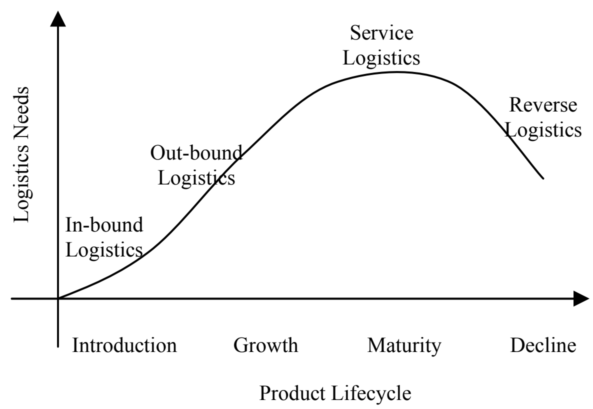

Figure 1: Changing Logistics Needs over the Product Lifecycle

In addition, increasing customer expectations has increased manifold the competition in almost all industries. Consequentially companies are trying to differentiate themselves by constantly innovating and introducing new products that appeal to the needs of the customers (for example, in the PC industry, new product models appear every 6 to 9 months). In such a scenario, a well-planned logistics strategy for the entire product lifecycle can provide a critical competitive advantage. In particular, the supply chain network needs to be highly flexible in order to support the rapidly varying logistics needs of the product over its lifecycle. Furthermore, given the fact that newer products compete significantly with older models, there are additional logistics challenges in handling multiple generations of products.

To successfully manage these issues it is imperative for businesses to develop systematic tools and methodologies for planning, based on the market demand and the production and distribution capabilities of the supply chains. Furthermore, given the highly distributed nature of manufacturing today, collaboration is a very essential aspect of supply chain planning. Hence, integrated planning on global information and close collaboration between supply chain partners are the two key critical success factors for successfully managing the logistics needs of multiple generations of products over their lifecycles. In this regard, the ubiquitous nature of the Internet provides the ideal tool to not only collect and share operational information across the supply chain but also to manage and coordinate the activities of all the supply chain participants. In particular, Internet-based public exchanges and private marketplaces have played an important role in redefining the nature and scope of supply chain interactions and decision-making.

In this paper, we focus our efforts on integrated production and logistics planning for new product introductions and product rollovers in supply chains managed through private marketplaces, especially within the discrete manufacturing industry. A private marketplace is usually driven by a channel master with enough bargaining power to force its supply chain partners to participate in the marketplace. A description of a collaborative private marketplace implemented by Hewlett Packard is provided by Hammer [1]. In a collaborative private marketplace all the supply chain partners openly share information on their capacities, inventories, schedules, costs and lead-times in the marketplace. Sharing of such detailed operational information requires a high-level of trust between the various supply chain participants and a sense of a collective common destiny in the pursuit of common market objectives. The mission of the channel master then is to optimally plan in collaboration with its partners new product introductions and rollovers for maximum profit, subject to the production and logistics capacity constraints of its supply chain partners.

1.1 Literature Survey

The issue of new product development has been widely studied in the marketing, operations management and engineering design literature. Krishnan and Ulrich [1] present a comprehensive review of the literature in this field in their review paper. Under their classification our problem in general arises under the study of supply chain design and specifically under the topic of production ramp-up and launch. They present a review of number of papers in both areas. However, the literature in the arena of planning for new product introduction and launch is mostly in the area of marketing with very little quantitative analysis with respect to production planning. Terwiesch and Bohn [2] try to quantitatively model the process improvement and learning and the resultant gradual increase in production yield during the introduction of a new product. In this respect our paper is an initial attempt to explore the application of some supply chain planning models towards meeting logistics needs over the entire product lifecycle.

2. Problem Formulation

We consider the problem of manufacturing and logistics planning for managing product introductions and rollovers across multiple generations of products in a web-based collaborative environment. We assume that there are a number of component suppliers, sub-assembly manufacturers, contract manufacturers and logistics service providers in the supply chain owned by a powerful channel master. These supply chain participants may be geographically distributed in different parts of the globe. Each of them shares information on their production schedules, capacity, cost, quality, etc through the private marketplace. The logistics providers also share information on their costs and capacities for transporting various goods between the supply chain participants. We also assume that the demands over the entire life cycles of the various products in the various geographical market areas are known, through some forecasting model.

These demands can be fulfilled by different sets of manufacturers and suppliers at different costs and in different lead times with the support of the logistics service providers. With access to complete visibility into its supply chain, afforded by its private marketplace, the channel master needs to plan how best to plan its logistics over the entire product lifecycle, and in the process manage rollovers between products and introduce a new generation of a product into the market. Towards achieving this goal he needs to select an optimal team of suppliers, contract manufacturers and logistics service providers that meets the market demand and maximizes profit over the entire product lifecycle. Hence, a collaborative approach in product development and supply chain management is required to efficiently capture the market opportunity.

2.1 Notation

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

<u>Identifiers</u>

r : Component type identifier.
R : Number of component types.
v : Component supplier identifier.
V : Number of component suppliers.
i : Sub-assembly type identifier.
I : Number of sub-assembly types.
j : Sub-assembly supplier identifier.

J : Number of sub-assembly suppliers.
k : Contract Manufacturer Identifier.
K : Number of Contract Manufacturers.
m : Market Area Identifier.
M : Number of Market Areas.
l : Brand Identifier.
L : Number of Brands.
l : Shipping Package Identifier.
L : Number of Shipping Package.
d : Transportation Mode (Sea/Air) Identifier
D : Number of Transportation Modes
t : Time Period identifier.
T : Total time horizon of the model.

Parameters

PCap : Maximum production capacity. It can be assumed that the maximum capacity is the total available capacity with the producer, which already takes into consideration other commitments that the producer may have made on his capacity. Also future plans for adding or purging of capacity must be taken into consideration.
PC : Unit cost price of production if the channel master undertakes production or the unit cost of procured manufacturing capacity from an outsourced provider. These costs may vary with the lifecycle of the item produced or procured and need to be forecasted.
PFC : Fixed cost of production set-up or ordering.
TCap : Maximum transportation capacity. Consideration should be given to the future plans of the logistics service providers to add or remove capacity on the various routes within the network.
TC : Unit transportation cost for shipment. These costs may vary depending on the long-term supply and demand in the logistics market and can be forecasted.
TFC : Fixed cost for procuring shipment capacity.
WC : Unit inventory holding cost. These costs may vary with time as the item held matures in its lifecycle and can be forecasted as well.
TL : Transportation lead-time for shipment.
BD : Market demand. This can be obtained through some product lifecycle forecasting models.
BSL : Service level (The percentage of the market demand that is desired to definitely be satisfied).
P : Per unit cost of finished model.
LSC : Per unit cost of a lost sale.
R_{ab} : Units of component type *a* required in the production of one unit of sub-assembly *b*.
M_{ab} : Units of sub-assembly type *a* required in the production of one unit of model *b*.

Variables

Q : Quantity produced.
I : Inventory held.
S : Quantity shipped.
S' : Quantity received.
F : Fixed cost of production or transportation applies. 1 if fixed cost is incurred, 0 if not incurred.
BS : Quantity sold of the model.

2.2 MIP Model

We now develop a mixed integer-programming model for a dynamic manufacturing network for new product introduction. The objective of the model is to maximize the profit earned by the manufacturing network subject to various capacity, production and logistics schedules and flow balancing constraints.

Objective Function

$$
\begin{aligned}
MaxPROFIT = & \sum_{l=1}^{L}\sum_{m=1}^{M}\sum_{t=1}^{T} P_{lm} BS_{lmt} \\
& - \left[\begin{array}{l} \sum_{r=1}^{R}\sum_{v=1}^{V}\sum_{t=1}^{T}\left(PFC_{rv}F_{rvt} + PC_{rv}Q_{rvt}\right) \\ + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}\left(PFC_{ij}F_{ijt} + PC_{ij}Q_{ijt}\right) \\ + \sum_{l=1}^{L}\sum_{k=1}^{K}\sum_{t=1}^{T}\left(PFC_{lk}F_{lkt} + PC_{lk}Q_{lkt}\right) \end{array}\right] \\
& - \left[\begin{array}{l} \sum_{r=1}^{R}\sum_{v=1}^{V}\sum_{j=1}^{J}\sum_{d=1}^{D}\sum_{t=1}^{T}\left(TFC_{rvjd}F_{rvjdt} + TC_{rvjd}S_{rvjdt}\right) \\ + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{d=1}^{D}\sum_{t=1}^{T}\left(TFC_{ijkd}F_{ijkdt} + TC_{ijkd}S_{ijkdt}\right) \\ + \sum_{l=1}^{L}\sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{d=1}^{D}\sum_{t=1}^{T}\left(TFC_{lkmd}F_{lkmdt} + TC_{lkmd}S_{lkmdt}\right) \end{array}\right] \\
& - \left[\sum_{i=1}^{T}\left(\begin{array}{l} \sum_{r=1}^{R}\sum_{v=1}^{V} WC_{rv}I_{rvt} + \sum_{r=1}^{R}\sum_{j=1}^{J} WC_{rj}I_{rjt} \\ + \sum_{i=1}^{I}\sum_{j=1}^{J} WC_{ij}I_{ijt} + \sum_{i=1}^{I}\sum_{k=1}^{K} WC_{ik}I_{ikt} \\ + \sum_{l=1}^{L}\sum_{k=1}^{K} WC_{lk}I_{lkt} + \sum_{l=1}^{L}\sum_{m=1}^{M} WC_{lm}I_{lmt} \end{array}\right)\right] \\
& - \left[\sum_{l=1}^{L}\sum_{m=1}^{M}\sum_{t=1}^{T}\left(BD_{lmt} - BS_{lmt}\right)LSC_{lmt}\right]
\end{aligned}
$$

… (1)

Component Supplier Constraints

$$Q_{rvt} \le PCap_{rvt} F_{rvt} \qquad forall \quad r \in R, v \in V \;\&\; t \in T \qquad \dots (2)$$

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

$$S_{rvjdt} \le TCap_{rvjdt} F_{rvjdt} \qquad forall \quad r \in R, v \in V, j \in J, d \in D \;\&\; t \in T \qquad \dots (4)$$

Sub-Assembly Supplier Constraints

$$S'_{rvjdt} = S_{rvjd(t-TL_{vjd})} \qquad forall \quad r \in R, v \in V, j \in J, d \in D \;\&\; t \in T \qquad \dots (5)$$

$$I_{rj(t-1)} \ge \sum_{i=1}^{I} R_{ir} Q_{ijt} \qquad forall \quad r \in R, j \in J, t \in T \qquad \dots (6)$$

$$I_{rj(t-1)} + \sum_{v=1}^{V} \sum_{d=1}^{D} S'_{rvjdt} = \sum_{i=1}^{I} R_{ir} Q_{ijt} + I_{rjt} \qquad forall \quad r \in R, j \in J \;\&\; t \in T \qquad \dots (7)$$

$$Q_{ijt} \le PCap_{ijt} F_{ijt} \qquad forall \quad i \in I, j \in J \;\&\; t \in T \qquad \dots (8)$$

$$I_{ij(t-1)} + Q_{ijt} = \sum_{k=1}^{K} \sum_{d=1}^{D} S_{ijkdt} + I_{ijt} \qquad forall \quad i \in I, j \in J \;\&\; t \in T \qquad \dots (9)$$

$$S_{ijkdt} \le TCap_{ijkdt} F_{ijkdt} \qquad forall \quad i \in I, j \in J, k \in K, d \in D \;\&\; t \in T \qquad \dots (10)$$

Contract Manufacturer Constraints

$$S'_{ijkdt} = S_{ijkd(t-TL_{jkd})} \qquad forall \quad i \in I, j \in J, k \in K, d \in D \;\&\; t \in T \qquad \dots (11)$$

$$I_{ik(t-1)} \ge \sum_{l=1}^{L} M_{li} Q_{lkt} \qquad forall \quad i \in I, k \in K \;\&\; t \in T \qquad \dots (12)$$

$$I_{ik(t-1)} + \sum_{j=1}^{J} \sum_{d=1}^{D} S'_{ijkdt} = \sum_{l=1}^{L} M_{li} Q_{lkt} + I_{lkt} \qquad forall \quad i \in I, k \in K \;\&\; t \in T \qquad \dots (13)$$

$$Q_{lkt} \le PCap_{lkt} F_{lkt} \qquad forall \quad l \in L, k \in K \;\&\; t \in T \qquad \dots (14)$$

$$I_{lk(t-1)} + Q_{lkt} = \sum_{m=1}^{M} \sum_{d=1}^{D} S_{lkmdt} + I_{lkt} \qquad forall \quad l \in L, k \in K \;\&\; t \in T \qquad \dots (15)$$

$$S_{lkmdt} \le TCap_{lkmdt} F_{lkmdt} \qquad forall \quad l \in L, k \in K, m \in M, d \in D \;\&\; t \in T \qquad \dots (16)$$

Buyer Constraints

$$S'_{lkmdt} = S_{lkmd(t-TL_{kmd})} \qquad forall \quad l \in L, k \in K, m \in M, d \in D \;\&\; t \in T \qquad \dots (17)$$

$$I_{lm(t-1)} + \sum_{k=1}^{K} \sum_{d=1}^{D} S'_{lkmdt} = I_{lmt} + BS_{lmt} \qquad forall \quad l \in L, m \in M \;\&\; t \in T \qquad \dots (18)$$

$$BSL_{lm} BD_{lmt} \le BS_{lmt} \le BD_{lmt} \qquad forall \quad l \in L, m \in M \;\&\; t \in T \qquad \dots (19)$$

Constraints 2,4,8,10,14 and 16 describe the production and transportation capacity limitations. Constraints 3,7,9,13,15 and 18 model the flow balancing constraints for the various inventories in the supply chain. Constraints 5,11 and 17 model the deterministic transshipment lead-time between the various locations for the various transportation modes. Constraints 6 and 12 check for availability of all required parts before production begins. Constraint 19 is the demand-pull on the supply chain.

The solution of this model determines the selection of suitable partners who can help the channel master best meet the market opportunity in a cost effective manner, and also provides a schedule for production and assembly activities within the supply chain. With the above mathematical model any of the available optimization toolkits might be used in order to generate the optimal schedules for the supply hub management.

2.3 Model Solution in ILOG OPL Studio

The above MILP model was developed in OPL Studio, available from ILOG, and two experiments were performed on the model. The first experiment was to observe and validate the shift in manufacturing from expensive, but responsive, local partners in the early stages of the lifecycle to cheaper less responsive overseas partners towards the later part. The second experiment was to generate supply chain plans for product introduction and rollovers across 2 Products marketed in 2 different Market Segments.

For the analysis, a sample supply chain network was considered with 3 Contract Manufacturers, 5 Sub-Assembly Manufacturers supplying 2 assembly-parts to the Contract Manufacturer and 3 Component Suppliers selling 2 types of components to the Sub-Assembly Manufacturers. It is not necessary that all Component Suppliers manufacture all components or all Sub-Assembly Manufacturers supply all sub-assembly types. The facilities were all connected to each other through a logistics network. The time horizon for the model was taken as 24 periods. The number of variables that were encountered was 13,050 and the constraints numbered 17,890. An analysis of some of the results from the optimization exercise is presented in the following section. The rate at which the model grows is closely related to size of the underlying network of the supply chain model and depends on the number of time periods considered and increases rapidly as the number of products, facilities and transportation links included in the model rise. However, since the number of binary variables in the model even for practical problems would be limited, overall solution times using a branch and bound solver with a simplex solver for the underlying network will not be too long.

3. COMPUTATIONAL RESULTS

3.1 Planning over Product Lifecycle

In order to verify the shift in manufacturing from local facilities to overseas facilities, over the product lifecycle, the supply chain configuration in the early part of the lifecycle was compared to the configuration in the later part. For the purpose of the analysis, it was assumed that local partners were 10 times more expensive than overseas partners, but were also 6 times faster in fulfilling the demand. Also, it was considered that the price of the product early on its lifecycle would be higher due to its innovativeness. However, with time the price would drop due to competition. The shift in partner supplies over the product lifecycle is depicted in Figure 2 below.

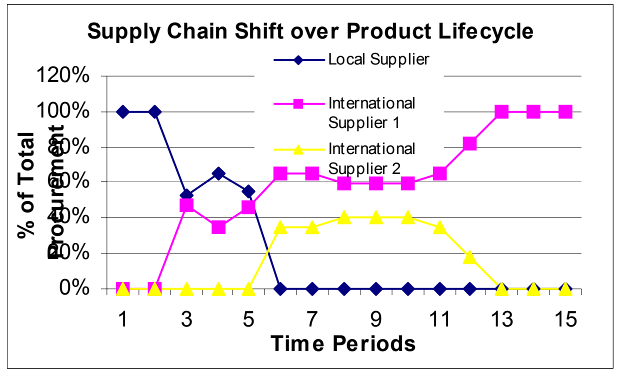

Figure 2: Shift from local supplier to overseas supplier over the product lifecycle.

It was noticed that the local partner was engaged to meet the early demand due to his proximity to the market and his ability to quickly respond to the market. At the same time, supplies are dispatched from overseas partners who get ready to ramp up their production in line with expected future demand, which is entirely fulfilled from the supplies of overseas partners.

3.2 Managing Product Rollovers

The second experiment was to employ the model in the management of product rollovers and product introductions.

The following demand curves for the two products in two market areas were assumed. The product lifecycle durations and the uptake in the two market areas are also different. Hence, as may be noticed there is a rollover period in between when both products are being sold in the market. Also, the products are assumed to share certain components, and procurement of components may be done keeping in mind the demand for both the models.

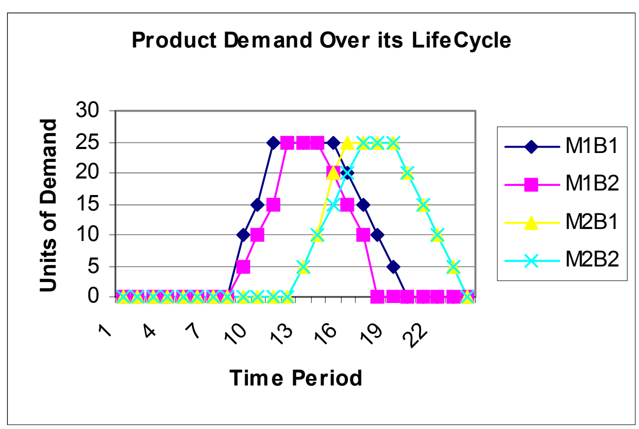

Figure 1. Product Demands over their lifecycles.

For a given supply chain network, the following supply chain configuration with integrated planning for two new product introductions was obtained as given below. The solution with profit of $6,875,650 was obtained in 27 hrs 23 minutes within 3.91% of optimality.

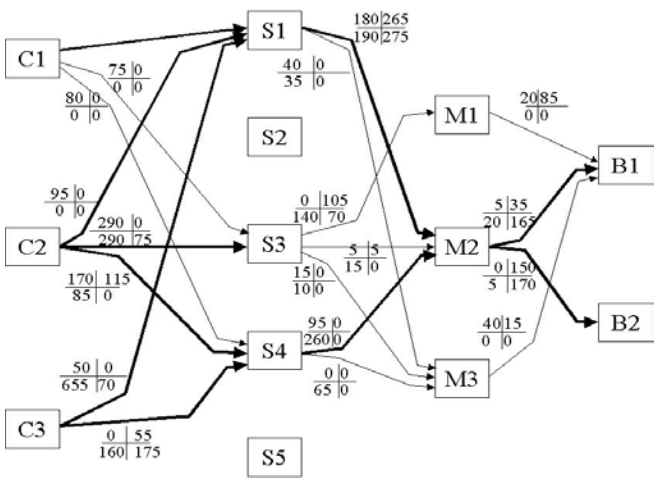

Fig 2 : Supply Chain Configuration with Integrated Planning.

Similarly, the model was solved for the individual introduction of products M1 and M2 separately. The profit for M1 introduction was optimally obtained as $ 3,973,350 and for M2 introduction as $ 3,348,205. The profit expected from individual planning for M1 and M2 is greater by around 6.5% than the profit from integrated planning for both M1 and M2 together.

Planning for individual product introductions can over-estimate or under-estimate the profit expected. When planning for two product introductions simultaneously, there can be a significant benefit in terms of securing lower costs for components and transportation costs, by leveraging upon greater volumes over both products. This is especially true for components that are common to both brands. In terms of procurement the costs may be very low, however the lowest cost supplier and transportation provider might not have adequate capacity to meet the needs of both the product introductions together. This will necessitate a need to deal with more expensive suppliers and transportation providers leading to higher costs and lower profits. Therefore, in integrated planning for new product development the trade-off between the cost efficiencies from joint procurement and the cost of dealing with more expensive suppliers needs to be well managed. In industries where there is excess capacity to be able to meet the needs of multiple product introductions then significant savings can be expected from joint planning and procurement.

4. Conclusion

In this paper we have formulated and solved a integrated supply chain planning model for managing logistics needs over the entire product lifecycle in a web-based collaborative environment. Our formulation here, which is a mixed integer linear programming model, provides a good planning tool to schedule production and shipment activities down the supply chain in line with the demands over the products life cycle. We have assumed the availability of operational information in each stage of the supply chain to all the supply chain partners, which might not be the case in the real world.

5. References

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