Strategic Sourcing and Collaborative Planning in Internet-Enabled Supply Chain Networks Producing Multigeneration Products

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***Abstract*—The design and planning of supply chain networks supporting production and distribution of multiple product generations overlapping with each other is of critical importance in the high-tech industry. In this paper, we address the strategic supply chain network design problem in rapidly changing industry segments, where the selection of partners such as component suppliers, contract manufacturers and logistics providers is done, based on the capabilities of the partners for supporting the strategic needs of the current and near future generations of a finished product. We develop a mixed integer-programming model for integrated planning and scheduling across the supply chain and show how such a model may be used for making decisions related to introduction and rollovers of finished products and components from one generation to another. We assume that all stakeholders in the supply chain collaborate and 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. Managerial insights are obtained by performing a series of simulated experiments on the model developed. For example, we show that an expensive supplier possessing the ability to develop and supply components required across a number of generations, might be preferred against a cheaper supplier supplying components suitable for a specific generation of the product. In addition, we show how the supply chain network configuration changes over the lifecycle of the product, wherein cheaper overseas suppliers slowly replace responsive and expensive local suppliers as the product matures. We also develop a framework to quantify and compare the costs and benefits of pursuing alternative product introduction plans and deadlines. Such a framework might be employed to determine the optimal product introduction schedule. We show here that in some cases it might not be profitable to launch a product in the market after a certain period of time.**

***Note to Practitioners*—This paper solves decision problems in supply chain management raised by the increasing prevalence of Internet-based collaborative manufacturing, short product life cycles and the proliferation of product families. Existing approaches and models, in supply chain management, that are commonly available to practitioners do not handle either of these areas adequately. Traditionally, the focus of supply chain planning tools has been on the selection of optimal locations for establishment of distribution facilities, and on the determination of optimal stocking levels at these locations. We steer away from this direction to build models that instead optimally select, and coordinate with, partners, in Internet-based virtual supply chain networks that have flourished in recent years. In addition, the model presented in this paper also incorporates a hitherto unseen functionality to configure the supply chain based on the rollout plans for new product introductions and the disposal schedule for older products. In terms of application, this model would be extremely useful to supply chain managers, particularly in discrete manufacturing industries such as consumer electronics and automotive, to analyze the costs and benefits involved in pursuing alternative product introduction plans and deadlines. Such a framework might be employed to determine the optimal product introduction schedule. We show here that in some cases it might not be profitable to launch a product in the market after a certain period of time. This model can also provide a means for the development team to understand the operational and financial impact of alternative product designs, having different bill of materials, on the manufacturing and distribution ramp-up plan.**

***Index Terms*—Collaboration, collaborative scheduling, integrated supply chain management, Internet-enabled supply chains, managing product families, product introduction, product rollovers, supply chain planning, supply chain scheduling.**

I. INTRODUCTION

BUSINESSES today operate in a very tough environment that is constantly in flux. Customers have become increasingly demanding looking for better and innovative goods and services that are specifically customized to meet their unique needs. There is also an implicit requirement on the accuracy, timeliness, convenience, responsiveness, quality and reliability of the service offered to them. And all of this is desired at ever-lower prices. Simultaneously, the rapid pace of innovation has resulted in shorter product and technology cycles, leading to uncertainties in supply and demand. These trends are clearly evident in the PC and mobile phone industries, where new models are introduced every three to nine months under intense competitive pressure on cost, functionality and service. As a result, the ability to quickly and efficiently develop, produce and sell a new product has become a key competitive advantage, in capturing market share and value in many industries such as hi-tech and automotive manufacturing. To cope with these challenges, companies are adopting a number of innovative new strategies such as outsourcing and collaboration.

A. Supply Chain Design as Partner Selection

Outsourcing is the contracting out to partners a part of the business process, such as manufacturing, support and maintenance, accounting, or logistics. In the manufacturing context, a trend away from vertically integrated models is distinctly evident, with many manufacturers previously undertaking the

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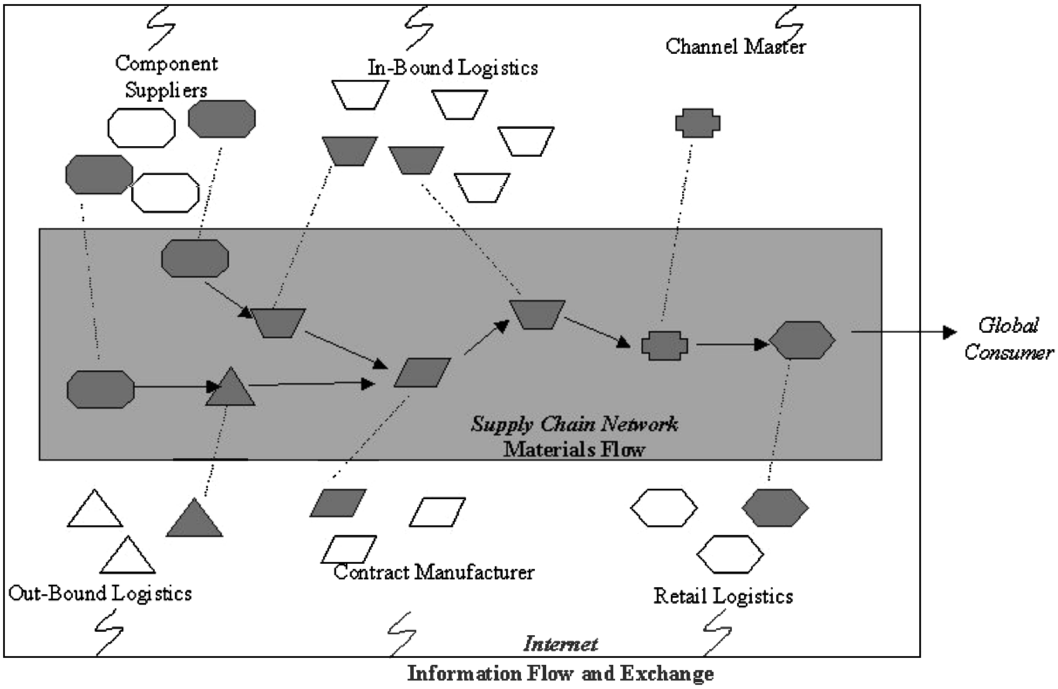


Fig. 1. Partner selection in supply chain networks.

internal production of the entire product, now outsourcing the production of a number of subassemblies (SAs) to their partners. Outsourcing allows a company to focus on its core competencies, eliminate its investments in noncore activities, leverage upon the specialized expertise of its partners, and to build strategic flexibility. By engaging specialists for outsourced operations companies can quickly move from design to market by leveraging upon the superior capabilities of its partners to rapidly ramp up production and distribution of its products. For example, leading contract manufacturers such as Solectron, are now involved in all phases of the product life cycle and provide very short time-to-market capabilities. It has been reported that within a period of six months, Solectron helped Nortel plan for product introduction, designed and tested the system and launched the product [1]. It is thus very important to select the best of breed component manufacturers, contract manufacturers, and logistics providers, who can help quickly launch products and rapidly respond to changes in market demands.

With the increased reliance on outsourcing, the supply design problem no longer relates to optimal location of facilities, but rather to the optimal selection of partners as shown in Fig. 1. Specifically, with regards to global original equipment manufacturesr (OEMs), channel masters, and private marketplace managers, the supply chain design problem translates into the systematic selection of logistics providers, contract manufacturers, and assembly plants such that the total cost of delivery to the customer is minimized, while taking into consideration the resource availability of partners and capabilities of partners to support multiple product generations. Furthermore, given the increasing contribution of suppliers at each stage of the product lifecycle, strategic sourcing is an important aspect of partner selection. Strategic sourcing concerns the ability to methodically identify, qualify, evaluate, and select suppliers based on the strategic impact of that supplier on the overall supply chain and the entire product lifecycle, instead of simply awarding each supply order to the supplier with the lowest bid. With shortened product lifecycles, the strategic sourcing decision is particularly key in the product development stage, when planning supplies for product rollovers and managing multiple generations of products.

B. Collaboration

Another cornerstone of a highly competitive and efficient supply chain network is collaboration, through the sharing of proprietary real-time operational data such as production schedules, operational costs, and inventory levels. The Internet, and, in particular, the emergence of web-based electronic marketplaces, have fuelled this trend by providing an inexpensive, secure and pervasive medium for information transfer between businesses. Collaborative supply chain networks are emerging in industries as diverse as automobiles, grocery retailing, and apparel manufacturing [2]. Hewlett-Packard (HP), a large PC manufacturer, recently established a private collaborative marketplace to share information amongst all the participants in its supply chain. HP posts it demand on the system for it partners to see and the partners in turn post their production plans and schedules for HP to see and plan upon. HP plays the coordinating role in the center of this system, that of a dominating channel master, keeping the supply and demand in balance [2]. Such collaborative arrangements are the foundation of extended enterprises.

Channel masters, contract manufacturers, third and fourth party logistics service providers, electronic marketplaces, and other supply chain stakeholders are using the platform of the Internet and the information obtained through collaborative arrangements to improve their operations and provide better service levels to their customers. Furthermore, the relative ease of forming partnerships and collaborating through the Internet has allowed the formation of fluid and dynamic supply chain networks based upon virtual integration between partners, further requiring systematic tools for strategic partner selection and management of such dynamic networks.

The complexity of the strategic supply chain design process requires that it be supported with powerful analytical tools and models. Currently used spreadsheet models are highly inadequate for detailed and complex analysis requiring number crunching and large-scale optimization involved in today's supplier selection process. We address this need in this paper.

C. Current Literature

There is limited research in the business literature dealing with some of the qualitative aspects of strategic sourcing and outsourcing. However, there is a significant amount of literature existing on component vendor selection from the manufacturers' perspective, which is closely related to the area of strategic sourcing, in the operations research and management science literature. In the area of strategic sourcing, Narasimhan and Das [3] present an empirical investigation of the impact of strategic sourcing on manufacturing flexibility and performance. Venkatesan [4] discusses some of the key issues to be considered in the outsourcing decision for manufacturing activities. In the related area of vendor selection, Weber and Current [5] discuss a multicriteria analysis for vendor selection. They develop a model for minimizing total cost, late deliveries and supply rejection given the infrastructure constraints and constraints imposed by the company's policy. Chaudhry *et al.* [6] consider the problem of vendor selection where buyers need to choose order quantities with vendors in a multisourcing network. Narasimhan and Stoynoff [7] present a model for optimizing aggregate procurement allocation keeping in mind contract requirements, supplier capacities and economic manufacturing quantity related constraints. The interested reader might find [8] useful for a comprehensive classification of publications on supplier selection criteria. In addition, there is some literature in the field of virtual enterprises that is relevant to our work. Tian *et al.* [9] present a substantial review of publications relating to infrastructure and system design for Internet-based manufacturing. Huang and Wu [10] discuss a qualitative decision model for partnership development within virtual enterprises.

However, with regards to our specific problem of supply chain planning for optimally managing product lifecycles, there is very little previous research. The issue of product development and market introductions has been studied from various angles in the marketing, operations management and engineering design literature. Krishnan and Ulrich [11] present a comprehensive review of the literature in this field in their review paper. Their review highlights the fact that there has been a lot of work done on decision making with regards to product design and the choice of technologies and suppliers for manufacturing of a new product. Under their classification, our problem is related to the to the study of supply chain design and specifically comes under the topic of production ramp-up and launch. They present a review of papers in both areas. The supply chain design problem addressed by all the papers relates to the selection of suppliers for specific components during the product design stage, with the objective of reducing the material cost the developed product, the time-to-market or other such product development metrics. Recently, Graves and Willems [12], addressed the question of identifying the minimal cost supply chain configuration for a new product introduction, by managing the tradeoff between cost-to-market and the time-to-market. Related work by Willems [13] also looked at part selection during the design of multigeneration products. However, the management and coordination of the supply chain during the introduction of the product, especially in case of multigeneration products, has so far been ignored. Billington *et al.* [14] make an attempt to study some of the issues in this area through a qualitative framework that helps companies manage product rollovers by choosing an appropriate rollover strategy. They consider the benefits and the risks between a solo-product roll and a dual-product rollover based on various market and internal operational factors. Possibly, the only quantitative model in planning for production ram-up is given in Terwiesch and Bohn [15], which tries to model the process improvement and learning and the resultant gradual increase in production yield during the introduction of a new product.

D. Our Contribution

Our thesis is that the key issue in supply chain design facing companies today is no longer the location of manufacturing and distribution facilities for their vertically integrated operations, but rather the strategic selection of partners for each stage of their outsourced value chain. Furthermore, this selection needs to take into account the synchronization of schedules for suppliers, manufacturers, and logistics providers in order to streamline processes throughout the supply chain. Given shrinking product lifecycles, a good sourcing plan will take into consideration the geographically distributed demand of the market over multiple generations within product families, and the capabilities of the suppliers to support the needs of each generation of product over its entire lifecycle. We base our analysis in the context of Internet-enabled supply chain networks and virtual organizations, where a high-level of trust and collaboration exists between all the supply chain stakeholders.

In this paper, we attempt to address a totally new question relating to the scheduling, planning and coordination in supply chains during product introductions, production ramp-ups and product rollovers, possibly between multiple generations of a product. Our motivation in this paper is to develop a strategic sourcing decision-support tool for decision makers that provides critical functionality with regards to the determination of suppliers, the allocation of contracts and volume amongst them, and improved coordination between the selected supply chain stakeholders during product rollovers and introductions. Hence, we provide an integrated planning framework that apart from strategic partner selection also considers the issue of tactical synchronization and coordination in supply chain networks supported and managed through the Internet. Among other things, we employ our model to determine optimal market entry schedules and to study the evolution of the supply chain configuration over the product lifecycle.

II. 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. Each generation of a product corresponds to a model that shares certain components and SAs with other models in product family, but is different from other models in the characteristics and specifications of some other components and SAs.

We assume that there are a number of pre-qualified component suppliers, SA manufacturers (SAMs), contract manufacturers and logistics service providers in the supply chain controlled by a powerful channel master (typically, an OEM). These supply chain participants may be pre-qualified to be a part of the supply chain system controlled by the channel master on the basis of their cultural, strategic and operational fit with the channel master's own goals. In addition, they may be geographically distributed in different parts of the globe. Their participation in the supply chain requires each of them to share information on their production schedules, capacities, costs, quality, etc., with the channel master through a collaborative private marketplace. In practice, the channel master locks in production capacity with its upstream suppliers and contract manufacturers well in advance and can track the availability of this capacity [14]. The logistics providers also share information on their costs and capacities for transporting various goods between the supply chain participants.

We also assume the possibility of various demand scenarios (high, medium, and low demand) that the supply chain network needs to meet. These demand scenarios over the entire life cycle exist for the various models in the product family for different geographical market areas. In practice, if demand is not known managers are typically able to estimate the demand by extrapolating their insights on demands for similar products. It is also assumed that the values of the various cost elements are known over their entire lifecycle. These costs can also be estimated through well-documented estimation approaches [16]. The supply and production quantities for all components and SAs, used in the production of the various models, over their entire lifecycles is also known.

The demand for the models in various geographical markets can be fulfilled by different sets of manufacturers and suppliers, with the support of the logistics service providers, at different costs and in different lead times. With access to complete visibility into its supply chain, afforded by its private marketplace, the channel master needs to plan how best to manage rollovers between models in a product family and introduce a new generation of a product into the market, using a team of suppliers, contract manufacturers, and logistics service providers, to meet the market demand and maximize profit over the entire product lifecycle. Hence, a collaborative approach in supply chain management during product introduction is required to efficiently capture the market opportunity.

Our assumption of centralized planning, which is commonly observed in some environments [1], [2], contrasts sharply with traditional supply chains based on decentralized planning. In traditional environments, there is no collaboration and information sharing between supply chain participants and each locally optimizes its own objective. Such a supply chain is, however, ridden with uncertainty, which results in companies maintaining unnecessary safety stocks at each possible location in the supply chain. Decentralized planning can be modeled by decomposing the problem into a series of smaller subproblems, one for each tier. In such a framework, the solutions at one tier in the supply chain serve as input to the next. However, the overall solution obtained will be suboptimal when compared to our models for overall network optimization.

A. Illustrative Scenario

To facilitate the understanding of our problem, we present an illustrative scenario for our model. Consider the case of a large PC manufacturer introducing new models of desktop PCs and laptops every 5–6 months. Each model corresponds to a generation within a generic product family. Each model of desktop PCs and laptops goes through the product lifecycle. When it is introduced into the market the model contains the latest features and commands a premium amongst the few pioneering buyers. With time the demand for the model goes up and it enters the mass market with simultaneous decrease in price. Subsequently, other models of desktop PCs and laptops, with newer features are introduced into the market and the demand for the older model drops until it is taken out of the market. The drop in demand for the older models coincides with the increasing demand for the newer models, and hence, there is a rollover from one generation of the product to another. However, it very often happens that a significant part of desktop PCs and laptops, from both the newer and older generations, are made of the same components. For example a newer PC model might be running on a 1-GHz processor as compared to an older PC model running on a 667-MHz processor, but the hard disks, disk drives, monitors, and other components in both models might in fact be exactly the same. Additionally, the duration and the apex of the product lifecycles for various product generations may vary across various geographical and customer market segments, requiring detailed planning with consideration for issues in product rollovers across both market segments and product generations. This problem is further complicated if you consider the lifecycle effects of the components themselves, wherein newer models of hard disks, disk drives, and monitors gradually replace older models.

B. Notation

For development of a mathematical model for the above scenario, the following notations were used. Even though the decision variables and decision problems at each tier of the supply chain are similar, we list them out completely to ease readability and understanding.

Identifiers:

r	Component type identifier.
R	Number of component types.
v	Component supplier identifier.
V	Number of component suppliers.
i	SA type identifier.
I	Number of SA types.
j	SAM identifier.
J	Number of SAMs.
k	Contract manufacturer identifier.

TABLE I
KEY FEATURES OF MILP MODEL FOR INTEGRATED SUPPLY CHAIN PLANNING

Supply Chain Information Shared	Decisions to be Made
1. Bill of materials for a complex product structure with multiple components, sub-assemblies, brands.	1. Selection of suppliers.
2. Market demand for each generation within a product family.	2. Allocation of procurement quantities amongst multiple suppliers.
3. Product cost over its lifecycle.	3. Determination of production and procurement schedules for product introduction and rollover.
4. Market Service Level.	4. Selection of logistics service providers.
5. Cost of a lost sale.	5. Allocation of shipment quantities between various logistics providers.
6. Production capacity and supply information for each generation of components and sub-assemblies.	6. Determination of mode of transportation for logistics.
7. Cost of components and sub-assemblies over their lifecycles.	7. Determination of logistics schedules.
8. Available-to-Promise Manufacturing Capacity for each Supplier.	8. Determination of inventory holding in each time period at each location.
9. Transportation Schedules and Capacities.	
10. Transportation Lead-time.	
11. Transportation costs.	
12. Inventory holding costs at multiple levels.	

K	Number of contract manufacturers.
m	Market area identifier.
M	Number of market areas.
l	Model identifier.
L	Number of models.
d	Transportation mode (sea/air) identifier.
D	Number of transportation modes.
t	Time period identifier.
T	Total time horizon of the model.

Parameters:

$P\mathrm{Cap}$	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.
$T\mathrm{Cap}$	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.
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.
RC	Cost of forming a relationship with a selected component supplier, SAM, or contract manufacturer. This cost would among other things include the cost of setting up processes, systems, EDI links and/or a collaborative exchange for facilitating coordination with the selected partner.
BD	Market demand. This can be obtained through some product lifecycle forecasting models or estimation based on demand for similar models.
BSL	Service level (The percentage of the market demand that is desired to definitely be satisfied).
P	Per-unit revenue of finished model.
LSC	Per-unit cost of a lost sale. While the other costs are directly accrued and strictly intuitive, the cost of lost sale is an opportunity cost that needs to be estimated.
R_{ri}	Units of component type a required in the production of one unit of SA b.
M_{il}	Units of SA 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	Selection of a partner. Takes on binary values $\{0, 1\}$. Takes on the value 1 if selected and 0 if not selected.
BS	Quantity sold of the model.

Some of the key features of the model presented in this paper are presented in Table I.

It is important to note that even though the engagement of partners is long term within the supply chain network of the channel master, the involvement of specific partners in the context of each product is short term. In fact, the selection of partners is dynamic in the sense that the supply chain configuration will be different for different products and generations, based on the market demand and the capabilities and capacities of the partners.

C. *MIP Model*

We now develop a mixed integer-programming model for planning product rollovers in a manufacturing network. The objective of the model is to maximize the profit earned by the manufacturing network over the entire lifecycle of its various output models, subject to various capacity, production and logistics schedules and flow balancing constraints.

1) Objective Function: The profit was calculated, as given in (1) at the bottom of the page, as the sum of the revenue made from sales over the entire lifecycle of the various models to the different markets, less the costs incurred in the operation of the supply chain network. The first term in the equation represents the revenue followed by fixed costs for establishing relationships with various supply chain partners, the variable costs for production and transportation respectively, inventory holding costs and the cost of lost sales.

There are various capacity constraints and product launch schedules for the component suppliers, SA suppliers, contract manufacturers and the logistics service providers servicing the various markets that make the solution nontrivial.

2) Component Supplier Constraints: The component suppliers cannot produce more than their maximum production capacity in a given period of time. Hence

$$Q_{rvt} \leq P\mathrm{Cap}_{rvt}, \quad \text{for all } r \in R; \quad v \in V; \quad t \in T. \tag{2}$$

The maximum capacity available for a particular component will gradually increase and decrease as it moves through its lifecycle and requisite capacity is built up and phased out.

The components produced are held at the component suppliers' end until they are shipped off to the SAMs. The production of new components adds to the inventory held by the component suppliers at the end of each time period, while the products sold and shipped to the SA suppliers in each time period reduces the component suppliers' inventories

$$I_{rv(t-1)} + Q_{rvt} = \sum_{j=1}^{J}\sum_{d=1}^{D} S_{rvjdt} + I_{rvt}, \quad \text{for all } r \in R; \quad v \in V; \quad t \in T. \tag{3}$$

However, the quantity that can be transported in a single period is constrained by the maximum capacity of the transportation infrastructure. Furthermore, the quantity procured from the supplier will be zero if the channel master does not select it. Conversely, if the quantity procured from the supplier is zero there is no need to select the supplier and establish a relationship

$$S_{rvjdt} \leq T\mathrm{Cap}_{rvjdt} F_v \quad \& \quad S_{rvjdt} \geq F_v, \quad \text{for all } r \in R; \quad v \in V; \quad j \in J; \quad d \in D; \quad t \in T. \tag{4}$$

3) SAM Constraints: The shipped components reach the SAMs after a certain amount of time, which relates to the transportation lead-time. The supply chain model we assume is such that the material is collected by the transportation system from the output buffer of one stage and delivered to the input buffer of the subsequent stage after a designated time interval equivalent to the transportation lead time. Hence, transportation lead-time between the component suppliers and SAMs is modeled by equating the outbound shipment from the component supplier to the inbound shipment at the SAM, in a subsequent time period

$$S'_{rvjdt} = S_{rvjd(t-TL_{vjd})}, \quad \text{for all } r \in R, \quad v \in V, \quad j \in J, \quad d \in D; \quad t \in T. \tag{5}$$

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

$$I_{rj(t-1)} \geq \sum_{i=1}^{I} R_{ir} Q_{ijt}, \quad \text{for all } r \in R; \quad j \in J; \quad t \in T. \tag{6}$$

$$\begin{aligned}
\mathrm{MaxPROFIT} = {} & \sum_{l=1}^{L}\sum_{m=1}^{M}\sum_{t=1}^{T} P_{lmt} BS_{lmt} \\
& - \left[\sum_{v=1}^{V} RC_v F_v + \sum_{j=1}^{J} RC_j F_j + \sum_{k=1}^{K} RC_k F_k\right] \\
& - \left[\begin{array}{l} \sum_{r=1}^{R}\sum_{v=1}^{V}\sum_{t=1}^{T}(PC_{rvt}Q_{rvt}) \\ \quad + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}(PC_{ijt}Q_{ijt}) \\ \quad + \sum_{l=1}^{L}\sum_{k=1}^{K}\sum_{t=1}^{T}(PC_{lkt}Q_{lkt}) \end{array}\right] - \left[\begin{array}{l} \sum_{r=1}^{R}\sum_{v=1}^{V}\sum_{j=1}^{J}\sum_{d=1}^{D}\sum_{t=1}^{T}(TC_{rvjdt}S_{rvjdt}) \\ \quad + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{d=1}^{D}\sum_{t=1}^{T}(TC_{ijkdt}S_{ijkdt}) \\ \quad + \sum_{l=1}^{L}\sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{d=1}^{D}\sum_{t=1}^{T}(TC_{lkmdt}S_{lkmdt}) \end{array}\right] \\
& - \left[\sum_{i=1}^{T}\left(\begin{array}{l} \sum_{r=1}^{R}\sum_{v=1}^{V} WC_{rvt}I_{rvt} + \sum_{r=1}^{R}\sum_{j=1}^{J} WC_{rjt}I_{rjt} \\ \quad + \sum_{i=1}^{I}\sum_{j=1}^{J} WC_{ijt}I_{ijt} + \sum_{i=1}^{I}\sum_{k=1}^{K} WC_{ikt}I_{ikt} \\ \quad + \sum_{l=1}^{L}\sum_{k=1}^{K} WC_{lkt}I_{lkt} + \sum_{l=1}^{L}\sum_{m=1}^{M} WC_{lmt}I_{lmt} \end{array}\right)\right] \\
& - \left[\sum_{l=1}^{L}\sum_{m=1}^{M}\sum_{t=1}^{T}(BD_{lmt} - BS_{lmt})LSC_{lmt}\right]
\end{aligned} \tag{1}$$

However, once the production process begins, the inventory drops. The inventory status for component types with the SAM can be determined as

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

The capacity constraints and the inventory constraints that apply to the component suppliers apply to the SAMs as well.

The maximum production of SAs is constrained by the production capacity of the SAMs. The maximum production capacity of the SAs will gradually increase and subsequently decrease as the SA matures in its lifecycle

$$Q_{ijt} \le P\mathrm{Cap}_{ijt}, \quad \text{for all } i \in I; \quad j \in J; \quad t \in T. \tag{8}$$

The inventory of SAs at the SAM's end increases at the end of each period by the quantity produced and decreases by the amount of SA shipped out to the contract manufacturer, in that time period

$$I_{ij(t-1)} + Q_{ijt} = \sum_{k=1}^{K}\sum_{d=1}^{D} S_{ijkdt} + I_{ijt}, \quad \text{for all } i \in I; \quad j \in J; \quad t \in T. \tag{9}$$

The quantity of assembly parts that can be shipped is constrained by the capacity of the transportation infrastructure. Also, shipments from an SAM will be zero if it has no relationship with the contract manufacturer. Hence

$$S_{ijkdt} \le T\mathrm{Cap}_{ijkdt}F_j \quad \& \quad S_{ijkdt} \ge F_j, \quad \text{for all } i \in I; \quad j \in J; \quad k \in K; \quad d \in D \quad ; t \in T. \tag{10}$$

4) Contract Manufacturer Constraints: The shipped assembly parts reach the contract manufacturer after a certain amount of time

$$S'_{ijkdt} = S_{ijkd(t-TL_{jkd})}, \quad \text{for all } i \in I; \quad j \in J; \quad k \in K; \quad d \in D; \quad t \in T. \tag{11}$$

The shipped assembly parts will be stored at the contract manufacturer. The contract manufacturer will employ these assembly-parts to produce a number of models corresponding to various generations within a product family. The production of these models will use up the inventory of the SAs in the process. However, only in the case of sufficient availability of all the needed SAs will production of the models take place

$$I_{ik(t-1)} \ge \sum_{l=1}^{L} M_{li}Q_{lkt}, \quad \text{for all } i \in I; \quad k \in K; \quad t \in T. \tag{12}$$

As regards the inventory levels of SAs at the contract manufacturer, incoming stocks will add to the inventory and SA stocks will be used up in the production of the various models types. The inventory status for SAs at the contract manufacturer can be determined as

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

The manufacturer cannot produce the different model types, in a quantity more than its maximum production capacity. Hence

$$Q_{lkt} \le P\mathrm{Cap}_{lkt}, \quad \text{for all } l \in L; \quad k \in K; \quad t \in T. \tag{14}$$

The manufactured units of the models are stored at the manufacturer awaiting delivery to the buyer. The inventory level of the models obeys the following flow constraint:

$$I_{lk(t-1)} + Q_{lkt} = \sum_{m=1}^{M}\sum_{d=1}^{D} S_{lkmdt} + I_{lkt}, \quad \text{for all } l \in L; \quad k \in K; \quad t \in T. \tag{15}$$

The transportation capacity constraint for the movement of the models from the contract manufacturer to the buyer's location will be governed by the below transportation capacity constraint, with consideration for whether the contract manufacturer is selected by the channel master or not

$$S_{lkmdt} \le T\mathrm{Cap}_{lkmdt}F_k \quad \& \quad S_{lkmdt} \ge F_k, \quad \text{for all } l \in L; \quad k \in K; \quad m \in M; \quad d \in D; \quad t \in T. \tag{16}$$

5) Market Constraints: The models reach the various geographical market areas after a certain transportation lead time

$$S'_{lkmdt} = S_{lkmd(t-TL_{kmd})}, \quad \text{for all } l \in L; \quad k \in K; \quad m \in M; \quad d \in D; \quad t \in T. \tag{17}$$

The shipment of the models is stored at some central location in the market, possibly a regional distribution center, and is sold to the market based on the demand

$$I_{lm(t-1)} + \sum_{k=1}^{K}\sum_{d=1}^{D} S'_{lkmdt} = I_{lmt} + BS_{lmt}, \quad \text{for all } l \in L; \quad m \in M; \quad t \in T. \tag{18}$$

Finally, quantity sold to the market in each time period cannot be more than the demand or less than the desired service level. The demand grows and falls in tune with the lifecycle of the model

$$BSL_{lm}BD_{lmt} \le BS_{lmt} \le BD_{lmt}, \quad \text{for all } l \in L; \quad m; \in M; \quad t \in T. \tag{19}$$

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. However, the solution generated by the model may change with time as more updated information is available on the demand and cost elements along the lifecycle. However, for practical purposes each time the model is run with updated information, the solution for the initial few time periods needs to be frozen to that obtained from the earlier solution.

With the above mathematical model any of the available optimization toolkits might be used in order to generate the optimal schedules for the supply chain.

D. Model Solution in ILOG OPL Studio

The above MILP model for new product introduction was developed in OPL Studio from ILOG and solved for a small-scale academic scenario with two model introductions in two market areas, three contract manufacturers, five SAMs supplying two assembly parts to the supply hub, and three component suppliers selling three types of components. Some of the assembly parts are common to both the models. It is possible that not all Component Suppliers manufacture all components or all SAMs supply all SA types. The facilities are all connected to each other through a logistics network. The time horizon for the model was taken as 24 periods, which is typically in terms of weeks in the hi-tech industry. The number of variables that were encountered was 10736 (including 8 binary variables) and the constraints numbered 12004. In practice, the scale of the model is much larger.

The rate at which the model grows is closely related to size of the underlying network of the supply chain model and is governed by the following relationships:

$$\begin{aligned}&\text{Number of Nodes}\\&\quad = RVT + RJT + IJT + IKT + LKT + LMT\\&\quad = (RV + RJ + IJ + IK + LK + LM)T \qquad (20)\\&\text{Number of Arcs}\\&\quad = RVT + RVJDT + RJIT + IJKDT\\&\qquad + ILKT + LKMDT\\&\quad = (RV + RVJD + RJI + IJKD\\&\qquad + ILK + LKMD)T. \qquad (21)\end{aligned}$$

The number of float and binary variables encountered in the model is dependent on the number of nodes and arcs in the network, as given

$$\begin{aligned}&\text{Number of Float Variables}\\&\quad = (RV + RJ + IJ + IK + LK + LM)T\\&\qquad + (RV + 2RVJD + IJ + 2IJKD\\&\qquad + LK + 2LKMD)T \qquad (22)\\&\text{Number of Binary Variables}\\&\quad = \text{Number of Partners} = V + J + L \qquad (23)\\&\text{Number of Constraints}\\&\quad = (RV + IJ + LK)T + 2(RJ + IK)T + 3LMT\\&\qquad + (RV + 3RVJD + IJ + 3IJKD\\&\qquad + LK + 3LKMD)\,T. \qquad (24)\end{aligned}$$

It is noticed that the size of the model strongly 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.

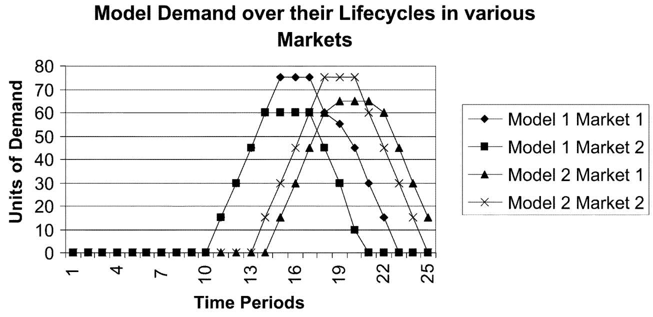
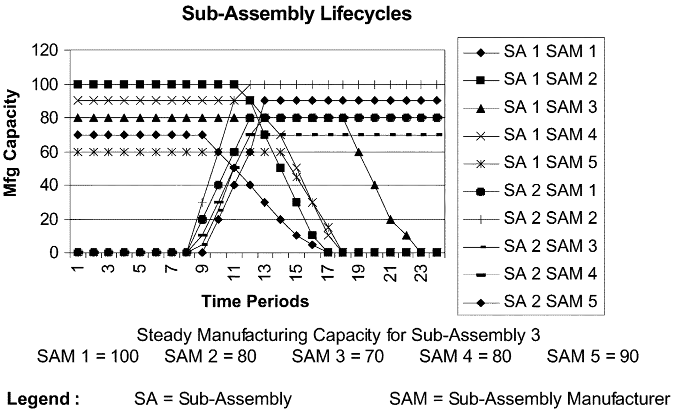


Fig. 2. Product demands over their lifecycles.



Steady Manufacturing Capacity for Sub-Assembly 3
SAM 1 = 100 SAM 2 = 80 SAM 3 = 70 SAM 4 = 80 SAM 5 = 90

Legend : SA = Sub-Assembly SAM = Sub-Assembly Manufacturer

Fig. 3. Subassembly lifecycles.

An analysis of some of the results from the optimization exercise is presented in the following sections.

III. EXPERIMENTAL RESULTS

A. Experiment 1: Strategic Sourcing for Multigenerational Products

In order to generate optimal plans for the management of multiple generations of products, the model that was developed in earlier sections was solved for known product lifecycle demand curves and a given supply chain network environment. The choice of supply chain partners and the scheduling of activities in the supply chain were observed.

The following demand curves for the two models in two market areas were assumed as given in Fig. 2. The model 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 models are being sold in the market. It is to be noted that no assumption is made on the shape of the lifecycle curves, which may in practice include seasonal trends and other distortions. Also, the products are assumed to share certain components, which have their own lifecycles as given in Fig. 3. SAs 1 and 2 represent two different generations of SAs. Again there is no assumption on the shape of the lifecycle curves. As the demand for the newer SA 2 increases the production quantity available for it increases and simultaneously demand for SA 1 falls resulting in assignment of lesser capacity

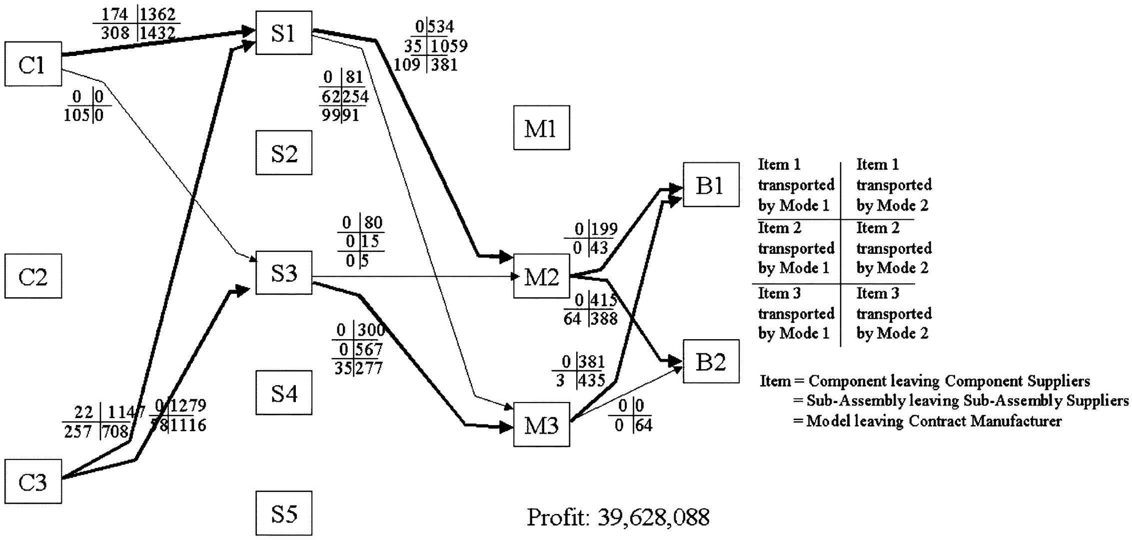


Fig. 4. Supply chain configuration when SAM 1 manufactures all three components (flows are totalled over the entire time horizon).

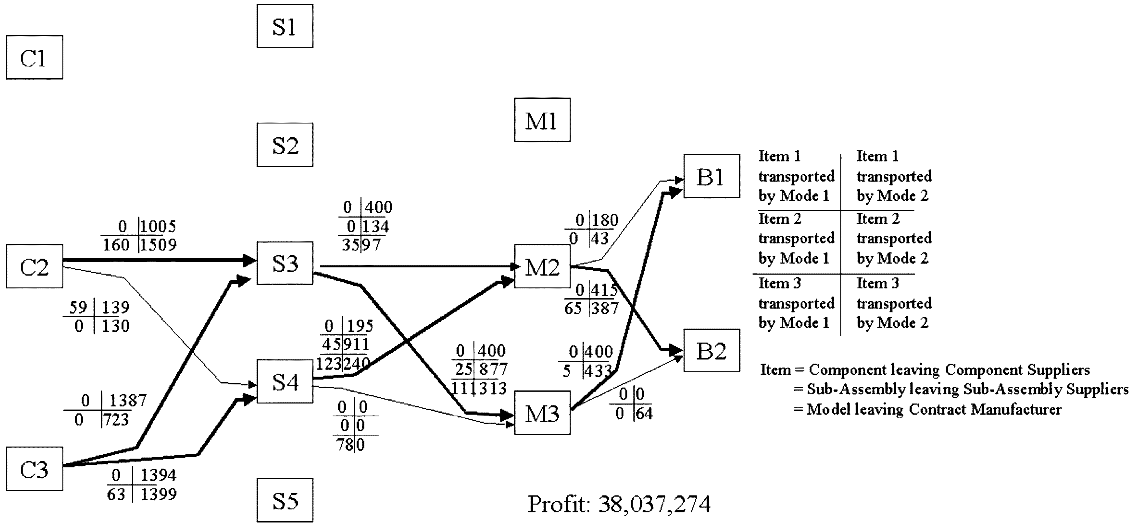


Fig. 5. Supply chain configuration when SAM 1 manufactures only SA 1 (flows are totaled over the entire time horizon).

for its production. SA 3 on the other hand is assumed to be a basic constituent and has a constant steady demand. Model 1 utilizes SA 1 and SA 3 and Model 2 employs SA 2 and SA 3. Hence, some of these components are substitutable and may have overlapping lifecycles. The procurement of these components needs to be done keeping in mind their supply and the demand over the lifecycles both the models.

Experiments were performed to observe the strategic selection of partners. Two scenarios were considered—first, where SAM 1 manufactures all three SA types (SA 1, SA 2, and SA 3) and second where SAM 1 manufactures only SA 1. For the given supply chain network, the following supply chain configurations, with integrated planning for managing rollover between two generations of products were obtained, as given in Figs. 4 and 5.

From Figs. 4 and 5, it is noted that the supply chain configurations for both cases are different, underlining the need to consider all the relevant information about the supply and demand at the planning stage. In the first scenario, SAM 1 is selected because it is the cheapest and it fulfills a large part of the demand. However, under scenario two even though SAM 1 is definitely the cheapest source of SA 1, which is needed for the production of model 1, it is not selected. This is because it is strategically not cost-effective to form a relationship with SAM 1, when considering the needs over the entire lifecycles of both models 1 and 2. Instead, it is deemed better to form a relationship with a more expensive supplier, in this case SAM 4, because it can more efficiently support the needs for both generations of the model. Hence, our model selects a supplier based on the strategic needs of the supply chain over multiple generations of the product.

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 product models. This is especially true for components that are common to both models. In terms of procurement the costs may be very low. However, one issue that needs to be considered is that the lowest cost supplier and transportation provider might not have adequate capacity to meet the needs of both the model generations together. This will necessi-

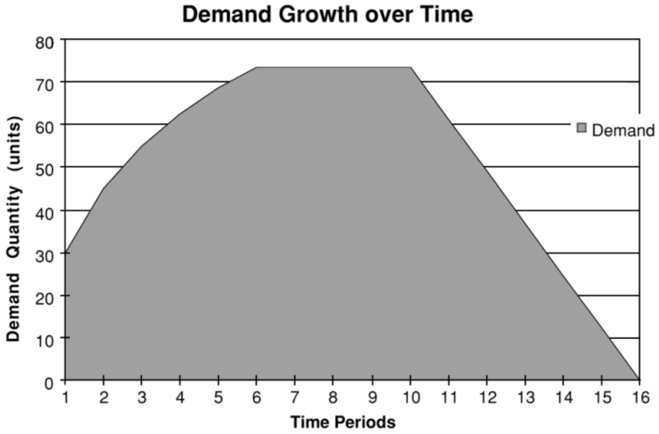


Fig. 6. Demand for the product over its lifecycle.

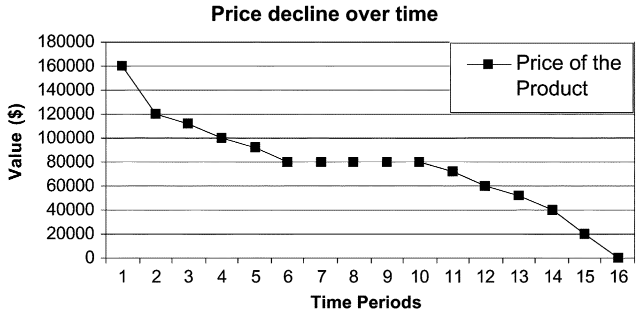


Fig. 7. Price of the product over its lifecycle.

tate 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 introductions the tradeoff 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 generations of products, significant savings can be expected from joint planning and procurement for multiple generations of products.

B. Experiment 2: Planning Over Product Lifecycle

In order to verify the shift in manufacturing from local facilities to overseas facilities, over the lifecycle of a product, 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, the demand for only one of the end products considered in the above experiment was estimated over its lifecycle as given in Fig. 6. Also, it was considered that the price of the product early on in its lifecycle would be higher due to its innovativeness and with time the price would drop due to competition as given in Fig. 7.

In terms of the supply chain parameters, it was assumed that local partners were 10 times more expensive than overseas partners, but were also 6 times faster in fulfilling the demand. The shift in partner supplies over the product lifecycle is depicted in Fig. 8.

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 demand. 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. In practice, local vendors nearer to the market also provide superior support in case of design defects inherent in any new product. They are able to handle frequent change requests better and faster. However, once the product design is stabilized it can be mass-produced in cheaper overseas facilities.

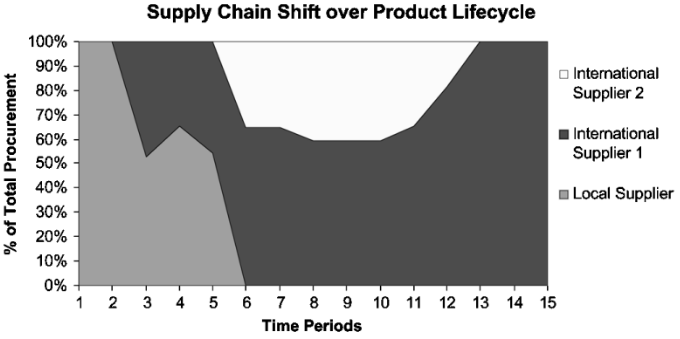


Fig. 8. Shift from local supplier to overseas supplier over the product lifecycle.

C. Experiment 3: Planning With Demand Uncertainty

In dealing with the development and introduction of new products, very often it is very difficult to exactly predict the market demand. In such a scenario, it becomes important to plan for various demand scenarios. Hence, the deterministic model presented in this paper was extended into a stochastic model based on three demand scenarios (high, normal, low) with equal probabilities of occurrence of all three scenarios. The demand given in Fig. 6 was assumed to be representative of high demand, with normal demand two-thirds, and low demand one-third of that.

To model the effect of demand uncertainty, we introduced a superscript $[s \, \varepsilon \, S]$ for all operational variables such as transportation flow that were expected to be different under the various scenarios. However, the selection of partners is done in advance of the scenarios unfolding and consequentially the partner selection was not scenario dependent. In addition all the constraints were enforced separately for each scenario. For example, (8) now becomes

$$Q^s_{ijt} \leq P\text{Cap}^s_{ijt}, \quad \text{for all } i \in I; \quad j \in J; \quad t \in T; \quad s \in S \tag{25}$$

and (13) becomes

$$I^s_{ik(t-1)} + \sum_{j=1}^{J} \sum_{d=1}^{D} S'^s_{ijkdt} = \sum_{l=1}^{L} M_{li} Q^s_{lkt} + I^s_{lkt}, \\ \text{for all } i \in I; \quad k \in K; \quad t \in T; \quad s \in S. \tag{26}$$

The rest of the constraints in the model can accordingly be modified in a similar manner. With regards to the objective, the aim is to maximize the expected profit overall scenarios. Given our case with three scenarios the objective function is obtained as given in (27) at the bottom of the next page.

For the demand scenarios considered, the following optimal supply chain configuration as given in Fig. 9 was obtained with the shown material flows for each scenario.

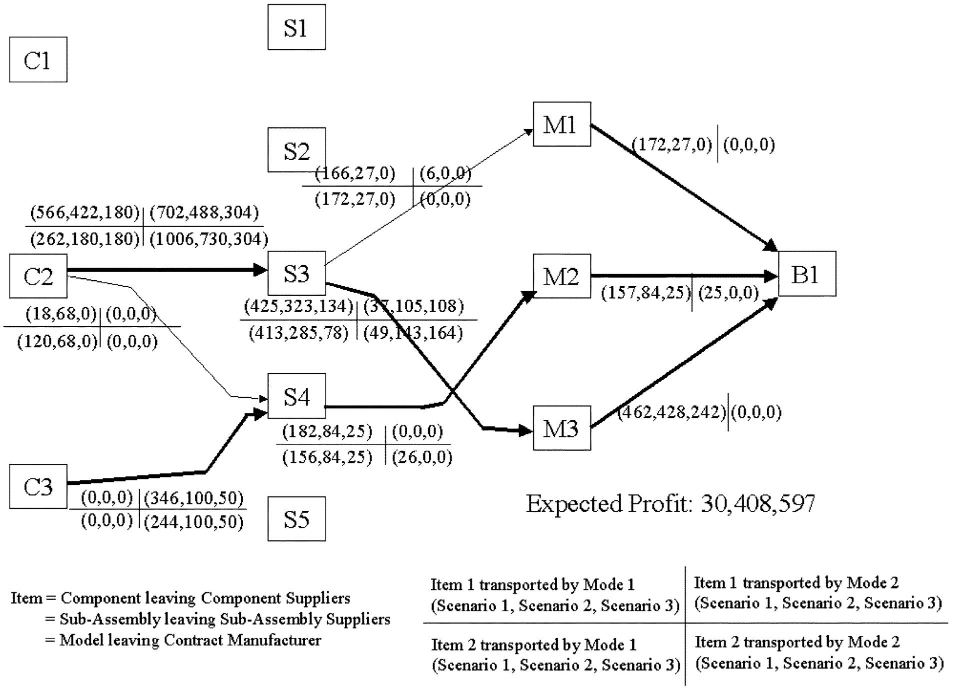


Fig. 9. Supply chain configuration for various demand scenarios.

D. Experiment 4: Decision Framework for Comparison of Alternative Production Introduction Schedules

Based on empirical studies it has been reported by McKinsey & Co., that a six-month delay in product introduction results in a one-third reduction in the lifetime profit of the product [17]. We shall display the use of our model to quantify such an observation.

For the sake of our analysis, we consider a product introduction, with a demand over its lifecycle as given in Fig. 10. We assume that the product prototype has been tested and the main decision facing the channel master is the timing of market entry and extent of subsequent ramp-up. Hence, we attempt to primarily address the decision problem relating to the mass deployment of the product subsequent to the research and development phase and accordingly we do not consider the initial costs for the development of the product and the manufacturing processes. These can however be easily added as an additional fixed cost to the cost of the mass deployment to give us the total cost of getting the product to market.

For our analysis, we assume that at each time period a new company enters the market and the market growth within that period is shared equally between all companies in the market. This occurs until the market for the product matures, from which point onwards each company maintains its market share. Thus, the company that enters the market earlier has an advantage that it can garner a larger part of the market over the entire lifecycle of the product. The company under study might wish to deploy its supply chain network to either be the first, second, third, fourth, fifth or sixth entrant into the market. Based on when the company decides to enter the market, the number of existing companies in the market and the demand that it can hope to capture will be different. In order to compare the profits from market entry at different time periods with a given supply chain network, we compare the profits that the company can accrue under scenarios where it is the first entrant, the second entrant, the third and so on.

$$
\begin{aligned}
&\text{MaxPROFIT}\\
&=\sum_{s=1}^{S}\frac{1}{3}\left[\begin{array}{l}
\sum_{l=1}^{L}\sum_{m=1}^{M}\sum_{t=1}^{T}P_{lmt}BS_{lmt}^{s}-\left[\sum_{v=1}^{V}RC_vF_v^s+\sum_{j=1}^{J}RC_jF_j^s+\sum_{k=1}^{K}RC_kF_k^s\right]\\
-\left[\begin{array}{c}\sum_{r=1}^{R}\sum_{v=1}^{V}\sum_{t=1}^{T}\left(PC_{rvt}Q_{rvt}^{s}\right)\\ +\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}\left(PC_{ijt}Q_{ijt}^{s}\right)\\ +\sum_{l=1}^{L}\sum_{k=1}^{K}\sum_{t=1}^{T}\left(PC_{lkt}Q_{lkt}^{s}\right)\end{array}\right]-\left[\begin{array}{c}\sum_{r=1}^{R}\sum_{v=1}^{V}\sum_{j=1}^{J}\sum_{d=1}^{D}\sum_{t=1}^{T}\left(TC_{rvjdt}S_{rvjdt}^{s}\right)\\ +\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{d=1}^{D}\sum_{t=1}^{T}\left(TC_{ijkdt}S_{ijkdt}^{s}\right)\\ +\sum_{l=1}^{L}\sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{d=1}^{D}\sum_{t=1}^{T}\left(TC_{lkmdt}S_{lkmdt}^{s}\right)\end{array}\right]\\
-\left[\sum_{i=1}^{T}\left(\begin{array}{c}\sum_{r=1}^{R}\sum_{v=1}^{V}WC_{rvt}I_{rvt}^{s}+\sum_{r=1}^{R}\sum_{j=1}^{J}WC_{rjt}I_{rjt}^{s}\\ +\sum_{i=1}^{I}\sum_{j=1}^{J}WC_{ijt}I_{ijt}^{s}+\sum_{i=1}^{I}\sum_{k=1}^{K}WC_{ikt}I_{ikt}^{s}\\ +\sum_{l=1}^{L}\sum_{k=1}^{K}WC_{lkt}I_{lkt}^{s}+\sum_{l=1}^{L}\sum_{m=1}^{M}WC_{lmt}I_{lmt}^{s}\end{array}\right)\right]\\
-\left[\sum_{l=1}^{L}\sum_{m=1}^{M}\sum_{t=1}^{T}\left(BD_{lmt}^{s}-BS_{lmt}^{s}\right)LSC_{lmt}\right]
\end{array}\right]
\end{aligned}
\tag{27}
$$

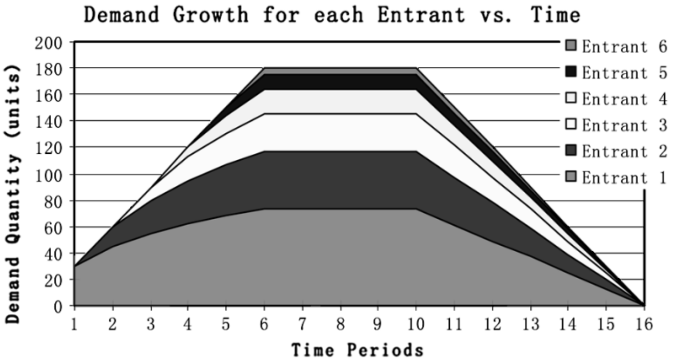


Fig. 10. Demand growth and market share in each time period for Entrants.

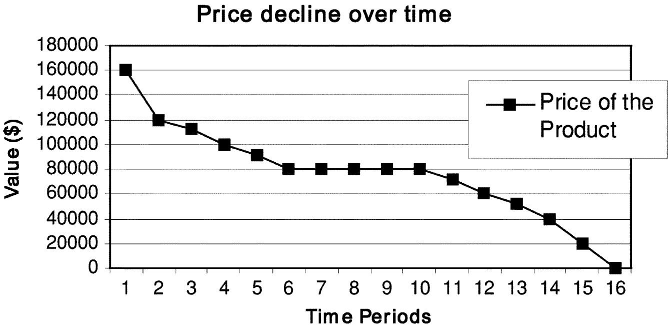


Fig. 11. Price decline over time.

Another advantage that early entrants can capitalize on is that they can charge consumers a premium for their goods in the early stages of the product lifecycle. For the purpose of our study we assumed the price-time relation for the product as given in Fig. 11, where the product is sold at a premium early on and its price drops as it matures. In practice, executives can employ historical data and forecasting tools to predict such price declines over with time for various products.

The typical tradeoff decision in the timing of product introductions is that faster product introductions require more money and resources in the product development and production ramp-up process. One of the reasons from the manufacturing perspective for increased cost might be the need to engage expensive suppliers and service providers who charge a premium in return for rapid response. On the other hand, an early market entry might offer a large market share with its resulting volume benefits and steady streams of profit.

To quantitatively obtain the cost of a delayed market entry we solved our optimization model for each entrant, with the given supply chain network and its respective share of the market demand. The profits accrued for scenarios where the company is the first entrant, second entrant, third entrant and so on is presented in Fig. 12.

The results obtained, reinforce the findings of various studies including the McKinsey study that profits drop significantly when the product introduction is delayed. In fact, in some cases it might not be profitable at all to introduce a product after a certain period of time, since the market share and sales of the product might not be able to recoup the fixed costs of operating the supply chain network. In the example we have considered above, it would not be wise to target for a product introduction after the time period 4. Hence, our model might be employed to analytically weigh the costs and benefits of various market entry schedules.

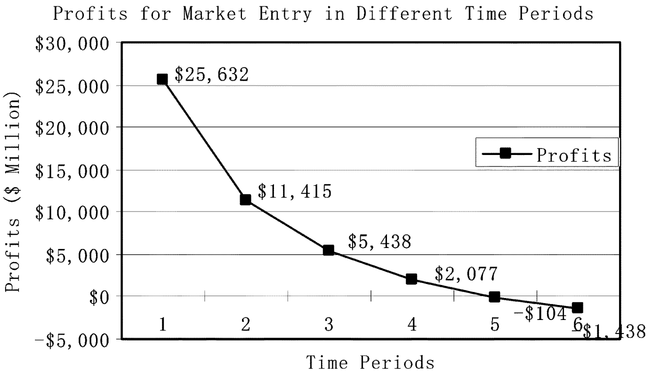


Fig. 12. Expected profit from market entry at various time periods.

IV. CONCLUSION

In this paper, we have formulated and solved an integrated strategic planning model for new product introductions and product rollovers of multiple generations of products, in a web-based collaborative environment. Our formulation here, which is a mixed integer linear programming model, provides a good and simple planning tool to strategically select suppliers and schedule production and shipment activities across the supply chain in line with the market demands over the products' entire life cycles. We show that an expensive supplier possessing the ability to develop and supply components required across a number of generations will be preferred against a cheaper supplier supplying components suitable only for a specific generation of the model. We also develop a framework to quantify the costs and benefits of delayed product introduction into the market. For the given supply chain network and market growth forecasts it was shown that profits over the products lifecycle reduced by more than 50% with a product introduction delay of 1 period. We also notice that for market entries scheduled after time period 4 will result in loss over the product's lifecycle. Hence, such a framework might be employed to determine the optimal product introduction schedule. An approach to incorporate demand uncertainties into the model is also presented.

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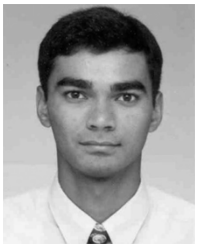

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