DEMAND-SUPPLY INTERACTION AND INVENTORY BUILDUP STRATEGIES FOR SHORT LIFE CYCLE PRODUCTS

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ABSTRACT

Revenues and profits from short life-cycle products will depend upon careful formulation and execution of production plans in response to demands in the marketplace. This research contributes to the development of the production and inventory buildup strategies for short life-cycle products under different demand-supply scenarios. A modified Bass diffusion model is used to characterize the product demand pattern with consideration of demand-sales interaction. We develop cost models based on production costs, inventory carrying costs, backlog costs, and cost of lost sales for a number of different production scenarios. The optimal production rate can be obtained by minimizing the total cost. We also investigate the benefit of an initial buildup of inventory before the product's sales period starts.

1. INTRODUCTION

In today's highly competitive, global marketplace, supply chains must respond quickly to changes in customer requirements (Chopra and Meindl 2010). The impact of a product's life cycle on supply chain design and performance is of significant interest due to the uncertainty and risk involved (Kurawarwala and Matsuo 1996). Short life-cycle products, e.g., personal computers and other consumer electronics, are generally characterized by constant innovation. Revenues and profits generated from new products would hinge on the careful formulation and implementation of production plans in response to demand in the marketplace. To achieve cost minimization/profit maximization, production planning requires accurate demand forecasting, detailed analysis of demand signals, and careful consideration of the dynamics of demand-sales interactions.

Short life-cycles are typically encountered in two kinds of products: innovative products such as electronic goods and fashion goods which have a seasonal demand. Short life-cycle products have distinct characteristics such as capricious demand patterns, high rate of obsolescence, risky capacity decisions, and high levels of uncertainty at all levels of operations. Judging a customer's desire to own or buy is often highly unpredictable. Adding to the forecasting uncertainties are the rapid market diffusion in an Internet-connected world and severe competition which brings in newer technologies ands speed up the rate of obsolescence. The growth stage in the short life-cycle poses many interesting questions. Due to "panic" growth, management invariably faces the issue of production capacity expansion. In a case study of the *Tamagotchi*™ 'virtual pet' toy, Higuchi and Troutt (2004) discussed how an electronic toy company went from boom to bust in a total period of 24 months due to an imprudent expansion decision.

The current study delves into the mechanics of a short life-cycle product's diffusion patterns and their implications on supply chain design. We seek to develop generalized cost models to better explain the demand-supply interaction that occurs in short life-cycle products and its impact on production capacity planning. Integrated demand-supply interaction and production graphs are utilized to visualize the times and volumes of inventory, backlogs, and other components that generate costs during product's entire life cycle. The optimal production capacity planning responding to a particular demand pattern can be found after we build the cost models to analyze each demand-sales interaction circumstance.

The remainder of the paper is organized as follows. In Section 2, a demand-sales model based upon the well-known Bass diffusion model (Bass 1969) is introduced and its interaction with production rate will be discussed. The cost minimization/profit maximization models based on inventory, backlog, lost sales, and production quantities for the different production scenarios over the product's life cycle will be derived in Section 3, followed by a discussion of the strategy of inventory build-up at the beginning of product's life cycle in Section 4. Finally, we conclude and remark on our findings in Section 5.

2. BASS DIFFUSION MODEL

The Bass diffusion model (Bass 1969) posits that the instantaneous rate of adoption of a new product by the population of potential adopters at any time period is subject to two means of communications: mass-media (external) and word-of-mouth (internal). The external communication influences 'innovators', while the internal communication describes the interaction between innovators and 'imitators'.

Let *p*, the "coefficient of innovation," and *q*, the "coefficient of imitation," represent the extent of external and internal communication levels, respectively. Let *m* be the size of the target population and let *D*(*t*) be the cumulative number of adopters of a new product by time t. Under the assumption that *D*(*t*) is a continuous function with *D*(0) = 0, then

$$\frac{dD(t)}{dt} = \left[p + q\frac{D(t)}{m} \right] \left[m - D(t) \right], \ t \geq 0 \cdot \tag{1}$$

That is, the growth rate of *D*(*t*) at time *t* is equal to the product of $m - D(t)$, the size of the remaining population, and $\left[p + q\frac{D(t)}{m} \right]$, the instantaneous adoption rate of an individual in the remaining population. Initial purchases of the product are made by both 'innovators' and 'imitators'. Innovators are not influenced in the timing of their initial purchase by the number of people who have already bought the product, while imitators are influenced by the number of previous buyers. Imitators 'learn', in some sense, from those who have already bought. The solution to the differential equation (1) is given by

$$D(t) = \left[1 - e^{-(p+q)t} \right] / \left[1 + (q/p)e^{-(p+q)t} \right]. \tag{2}$$

This function has been found to provide an excellent empirical fit for the timing of initial purchase for a wide range of consumer durables (Niu 2004). The derivative of cumulative demand is then given by

$$d(t) = mp(p+q)^2 e^{-(p+q)t} / \left[p + qe^{-(p+q)t} \right]^2, \tag{3}$$

which gives instantaneous demand at time *t*. Figure 1 is a sample graph of both instantaneous demand and cumulative demand, as specified by equations (2) and (3) respectively, with parameter values *m* = 3000, *p* = 0.03, and *q* = 0.4.

The original Bass model does not consider the production capacity issue, an important aspect in supply chain design (Ho, Sergei, and Terwiesch 2002). In a supply chain, there always exists a maximal production rate as defined by the capacity of the plant, which can adversely affect the product diffusion rate (Jain, Mahajan, and Muller 1991). An important modification to the Bass model was developed by Kumar and Swaminathan (2003), where they propose that, in light of the rapid growth of demand, it is possible that a large number of consumers may attempt to buy the product but will be unsuccessful due to supply constraints. It is unreasonable to assume that these customers would continue to spread word about the product. The word-of-mouth effect then is better represented as being proportional to the cumulative sales *S*(*t*) up to time *t*, instead of the cumulative demand *D*(*t*). Then the Bass model can be modified to

$$\frac{dD(t)}{dt} = [p + q\frac{S(t)}{m}][m - D(t)] \cdot \tag{4}$$

Figure 2 illustrates the modification in the cumulative demand curve.

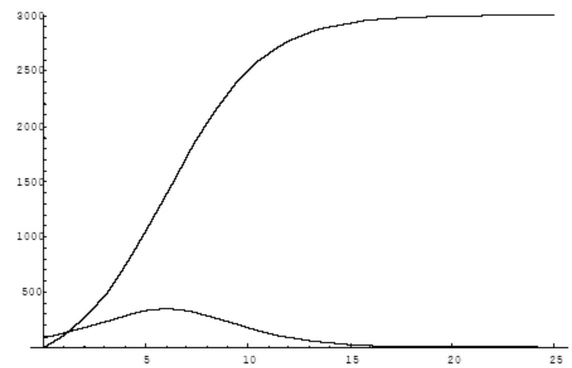

Figure 1: Instantaneous and Cumulative Demand Curves with *m* = 3000, *p* = 0.03, and *q* = 0.4

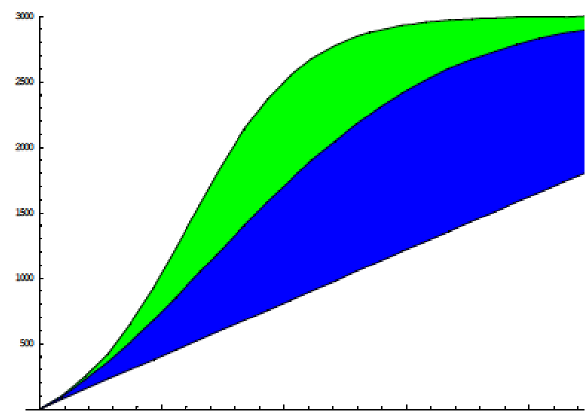

Figure 2: Change of Demand Curve due to Supply Constraint

The key feature of this modified Bass model is that the future demand depends not only on past demand but also on past realized sales (Kumar and Swaminathan 2003). The quantity of sales at a given time is determined by the demand as well as the production volume.

To evaluate the interaction between sales and demand, Ho, Savin, and Terwiesch (2002) looked into the Bass model with supply constraints and found that a myopic sales plan is always optimal given an objective of profit maximization rather than minimization of lost sales. Angelus and Porteus (2002) developed a model to better understand the interaction between capacity and production management. They derived an optimal simultaneous capacity and production plan for a short life-cycle, make-to-stock good under stochastic demand.

There are four basic scenarios where the production plan is matched against the demand profile:

- *Scenario 1*. Production plan is barely satisfying the demand generated from the beginning of the product's life cycle.
- *Scenario 2*. Production rate is satisfying some demand (till a period of time when the demand overtakes the production) with inventory but total demand cannot be met by total production quantity.
- *Scenario 3*. Production completely satisfies the total market capacity and is terminated when the total production quantity reaches the total demand quantity.
- *Scenario 4*. Production rate is so high that it reaches market capacity much ahead of actual complete market consumption, that it carries inventory to satisfy the demand.

Based on the above scenarios, we develop various cost functions in order to establish the optimal production plan for a given set of parameters which govern the demand profile.

3. PRODUCTION CAPACITY OPTIMIZATION

It is assumed that a product's life cycle begins at the time when sales occur and it ends when the sales reach close to the total market size. The production may start much earlier than the beginning of product's life cycle to build up inventory for the anticipated rapid-growing sales. Combining the Bass demand curve (or its modification) and production curve we formulate cost functions over the entire product lifetime and seek to minimize the total cost. The various costs that are considered here include inventory carrying costs, backlog costs, production costs and cost of lost sales. In addition, we associate a discount factor to make the model more realistic. The discount factor is used to analyze the present value of money over the period of the product's life cycle.

3.1. Deterministic Demand-Production Model Development

We start from the simplest demand-production scenario where the demand is driven by a Bass diffusion model and the production rate is kept constant. There are several assumptions we make to best explain the conditions within which the cost models are built:

1. *Loss of sales occurs only at the end of the life cycle.* It is assumed that the demand fulfillment is executed using a first-in, first-out (FIFO) policy and loss of sales are attributed to those customers who are in the queue to be satisfied but, due to the end of production and non-availability of the product, the manufacturer would have to refuse the product from those customers.
2. *Demand-sales interaction does not occur at any instant of the product lifetime.* Here, the demand curve is unaffected by the production rate; this assumption will be removed later.
3. *No inventory buildup.* It is assumed that the sales and production would start simultaneously at the beginning of product's life cycle. This implies that there will be no inventory at the beginning of the product's sales process. Again, we will consider the inventory buildup strategy later.
4. *Company employs a make-to-stock production policy.* With a constant production rate, the residual inventory at any time will be held to satisfy the anticipated future demand.
5. *Monopolistic market state.* As clearly mentioned in Bass (1969), we consider that the product is in a monopolistic market condition where the manufacturer has no competitor or competing product in the same category. In a competitive market environment, the parameters which govern the adoption rates are many more than the ones explained here in this paper and they are also susceptible to qualitative measures which govern the success of the product (e.g., value, design, form, fit, function, etc.).

The modified Bass model which we use in this paper has three parameters which govern the shape of the demand pattern. The cumulative demand is as specified in (4). Production rates govern the extent of sales-demand interaction. Holding the given set of parameters m, p, and q constant in the demand function, higher production would typically entail more inventory which may fully satisfy market demand. On the contrary, however, if we have a production plan which cannot fulfill total demand of the market, then after a partial fulfillment of the demand, the sales would typically follow the output of the production.

In Figure 3 both demand and production curves are plotted. The demand curve asymptotically approaches m, and is arbitrarily cut off at 99.9% of this total market potential, in effect signaling the end of the product's life cycle. For a given demand function (based upon values of m, p, and q) there are three special production lines:

- Line y_1 - This line passes through the origin and its slope is given by

$$b_1 = mp. \qquad (5)$$

- Line y_2 – The production line intersects the demand curve at the end of the product's life cycle. The production here totally satisfies the demand of the market with no inventory and no backlogs at the end of the life cycle. The slope of y_2 is given by

$$b_2 = 0.999m/T \,. \tag{6}$$

- Line y_3 – This line is tangent to the cumulative demand curve. The slope of the line is

$$b_3 = mp(p+q)^2 e^{-(p+q)t} \Big/ \left[p + qe^{-(p+q)t}\right]^2 . \tag{7}$$

There are four regions, R_1, R_2, R_3, and R_4, separated by these special lines:

- Region R_1 – Production plan never satisfies the demand generated from the beginning of the product's life cycle (*Case 1*).
- Region R_2 – Production rate is satisfying some demand with inventory (until a period of time when the demand overtakes the production) but total demand cannot be met by total production quantity (*Case 2*).
- Region R_3 – Production completely satisfies the total market capacity and production is terminated when the total production quantity reaches the total demand quantity (*Case 3*).
- Region R_4 – Production rate is so high that it reaches market capacity much ahead of actual complete market consumption, that it carries inventory to satisfy the demand (*Case 4*).

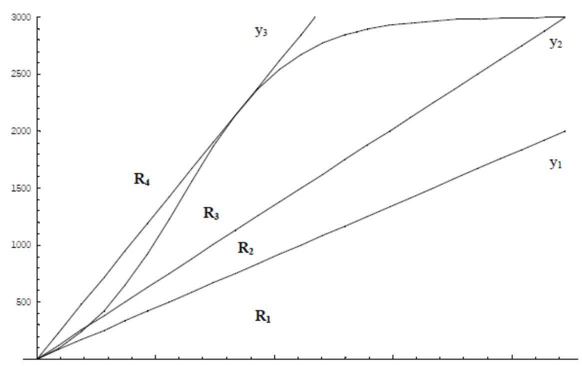

Figure 3: Cumulative Demand Curve Shown with the Different Production Plans

3.1.1. Cost Functions of Region R_1

In this case (Figure 4), the production rate is anywhere between zero and b_1. Total production can never fully satisfy cumulative demand at any point in time. All the unmet demand is backlogged. At the end of the product's life cycle, there would be some demand which would be unmet due to the limited production and be eventually lost. The cut-off time at the threshold limit of 99.9 % of the market capacity is the solution of the equation

$$0.999\left(1 + \frac{q}{p} e^{-(p+q)T}\right) = 1 - e^{-(p+q)T} . \tag{8}$$

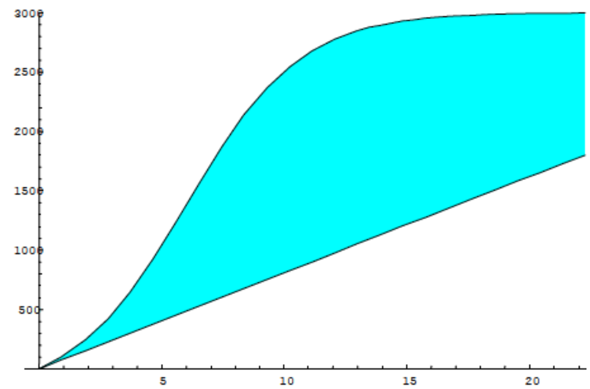

Figure 4: Case 1 – Production Never Meets Total Demand with m = 3000, p = 0.03 and q = 0.4

Both production volume and total sales volume at time t are given by the production curve $y = bt$, where b is the production rate. There is no inventory built up in this scenario. The backlog volume at time t is the difference between demand curve and production curve, i.e., $\left[m\left(1-e^{-(p+q)t}\right)\Big/\left(1+\frac{q}{p}e^{-(p+q)t}\right) - bt\right]$. To convert the cost generated at time t to the value as at the beginning of the product's life cycle, the discount rate can be written as $(1+\gamma)^{-t}$, where γ denotes the rate of return. Since we are dealing with short life-cycle products, γ should be very small and we use the approximation $(1+\gamma)^{-t} \approx (1-\gamma)^t \approx e^{-\gamma t}$.

Thus, the backlog cost can be evaluated by the area between two curves,

$$CL = \int_0^T \omega \left[m\left(1-e^{-(p+q)t}\right)\Big/\left(1+\frac{q}{p}e^{-(p+q)t}\right) - bt \right] e^{-\gamma t} dt \,. \tag{9}$$

where ω is the unit backlog cost.

The volume of lost sales over the product's entire life cycle is the difference between cumulative demand and production curves at the production termination time. Hence, lost sales cost is

$$CS = \chi \left[m\left(1-e^{-(p+q)T}\right)\Big/\left(1+\frac{q}{p}e^{-(p+q)T}\right) - bT \right] (1-\gamma)^T , \tag{10}$$

where χ represents the unit lost sales cost.

We assume the production cost is proportional to the total production volume, with

$$CP = \int_0^T \alpha bte^{-\gamma t}dt \quad (11)$$

where α is the unit production cost.

Therefore, in this case the total cost is the sum of total production cost, cost of lost sales and the total backlog costs, i.e., $TC = CP + CL + CS$.

3.1.2. Cost Functions of Region R_2

In this case, the production rate b is higher than b_1 but less than b_2. Any generic line that has a slope between these two special lines intersects the demand curve at a point t_0, which differentiates the inventory and backlog that the production plan creates. The point t_0 can be determined using

$$t_0 = \log[-(mp + bTq)/(bT - m)p)]/(p+q). \quad (12)$$

A small inventory is developed at the early stage of product's life cycle and the backlog will occur once the production curve falls below the demand curve. The cumulative inventory is represented by the area between production curve and demand curve, when production is larger than demand. The total inventory cost is

$$CI = \int_0^{t_0} h\left\{bt - \left[m\left(1-e^{-(p+q)t}\right)\Big/\left(1+\frac{q}{p}e^{-(p+q)t}\right)\right]\right\}e^{-\gamma t}dt, \quad (13)$$

where h is the unit inventory carrying cost. The total backlog cost is

$$CL = \int_{t_0}^{T} \omega\left[m\left(1-e^{-(p+q)t}\right)/\left(1+\frac{q}{p}e^{-(p+q)t}\right) - bt\right]e^{-\gamma t}dt. \quad (14)$$

The cost of lost sales would be as in (10).

3.1.3. Cost Functions of Region R_3

In this case, the production rate b is between b_2 and b_3. The production is able to produce enough to sustain till the end of the product's life cycle with little backlog, and the production stops when the total quantity reaches m. There are no lost sales registered. The production line intersects the demand curve at two points and terminates at a third point before the end of product's life cycle, as illustrated in Figure 5. We denote the three points as t_1, t_2, and t_p. There are three regions I_1, I_2, and I_3 where inventory is carried. Carrying costs of those inventories are determined separately to constitute total inventory cost:

$$CI_1 = h\int_0^{t_1}\left\{bt - \left[m\left(1-e^{-(p+q)t}\right)\Big/\left(1+\frac{q}{p}e^{-(p+q)t}\right)\right]\right\}e^{-\gamma t}dt, \quad (15)$$

$$CI_2 = h\int_{t_2}^{t_p}\left\{bt - \left[m\left(1-e^{-(p+q)t}\right)\Big/\left(1+\frac{q}{p}e^{-(p+q)t}\right)\right]\right\}e^{-\gamma t}dt, \quad (16)$$

$$CI_3 = h\int_{t_p}^{T}\left\{0.999m - \left[m\left(1-e^{-(p+q)t}\right)\Big/\left(1+\frac{q}{p}e^{-(p+q)t}\right)\right]\right\}e^{-\gamma t}dt. \quad (17)$$

The backlog cost is given by

$$CL = \int_{t_2}^{t_3} \omega\left[m\left(1-e^{-(p+q)t}\right)/\left(1+\frac{q}{p}e^{-(p+q)t}\right) - bt\right]e^{-\gamma t}dt. \quad (18)$$

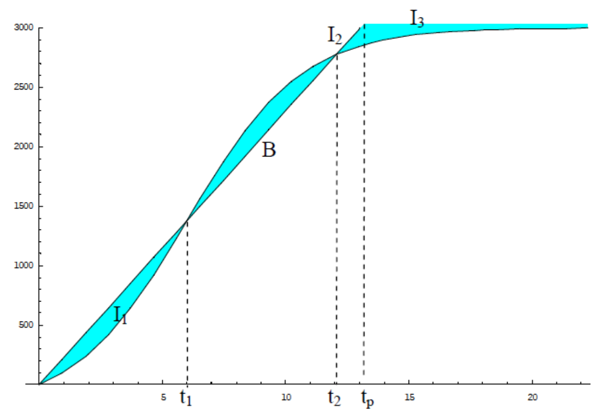

Figure 5: Case 3 – Inventory and Backlog

3.1.4. Cost Functions of Region R_4

In this case, as shown in Figure 6, production is always enough to cover demand until the end of the product's life cycle. There would be no backlog and lost sales costs, but a large inventory cost is associated with this case.

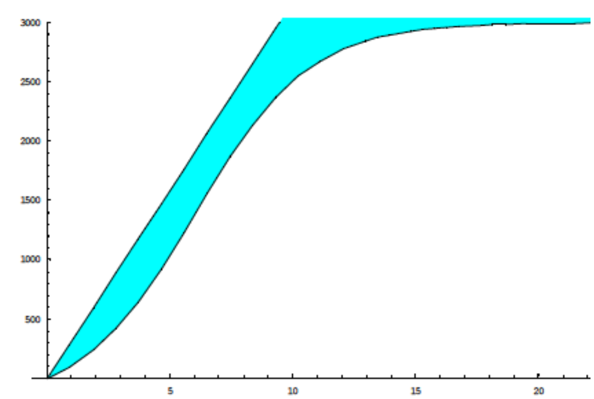

Figure 6: Case 4 – More than Enough Production

The inventory costs associated with this case comes from two regions. It can be determined by

$$CI = h\int_0^{t_p}\left\{bt - \left[m\left(1-e^{-(p+q)t}\right)\Big/\left(1+\frac{q}{p}e^{-(p+q)t}\right)\right]\right\}e^{-\gamma t}dt + h\int_{t_p}^{T}\left\{0.999m - \left[m\left(1-e^{-(p+q)t}\right)\Big/\left(1+\frac{q}{p}e^{-(p+q)t}\right)\right]\right\}e^{-\gamma t}dt. \quad (19)$$

So far, we have developed the cost functions under different production plans. One can find the optimal production rate by minimizing the total cost over the product's life cycle subject to any specified inventory or backlog constraints.

3.2. Analysis Based on Demand-Supply Interaction

In practical situations, it is unrealistic to have a demand model which is not supported by the production plan and still expect the demand to follow the same growth pattern. With the modified Bass model, the word-of-mouth effect is constrained by the quantity of sales at a given time. For example, in the first case where the production is so low that it will never satisfy the demand, Figure 7 gives the potential demand curve and the actual demand curve after considering the demand-sales interaction. Here, the sales is limited by production and the actual demand is determined by solving equation (4) with $S(t) = b$ and the initial condition $D(0) = 0$; hence,

$$D(t) = m(1 - e^{-pt - \frac{bqt^2}{2m}}). \qquad (20)$$

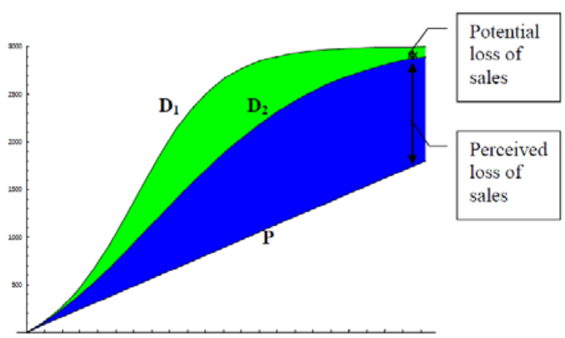

Figure 7: Case 1 – Demand-Sales Interaction

In this case, we have two demand curves: an assumed demand curve (D_1), which is the total potential of the market, and the actual demand curve which is the outcome of the demand-sales interaction due to the production plan (D_2). We define the perceived loss of sales as the total number of unfulfilled demand, which is the difference between actual demand and the corresponding production plan at the end of product's life cycle. We also realize that there is a potential loss of sales, which is the difference between the total potential of the market and the actual total demand. We call it potential because, for various reasons, there are potential customers in the market who have never heard about the product. Again the cost function for these losses of sales can be easily derived.

We developed cost functions for the cases as discussed previously. The optimal production rate can be sought by minimizing the total cost over the product's life cycle.

3.3. Analysis Based on Initial Inventory Buildup Strategy

Due to the capacity constraints and expectations of a higher than normal demand, firms build up enough inventories prior to the launch of the product. This helps prepare the firms for the steep increase in demand once the product is introduced into the market. There are two critical issues which need to be addressed in this strategy: First, how early should we start the inventory build-up (time)? And second, how much should we build-up for sales (quantity)? They can be answered after optimizing the total profit generated over the whole life cycle.

4. ILLUSTRATIVE NUMERICAL EXAMPLES

The examples presented in this section pertain to Case 3, in which the production plan completely satisfies the total market capacity and production is terminated when the total production quantity reaches the total demand quantity.

Figure 8 shows the discounted profits versus production rate plots.

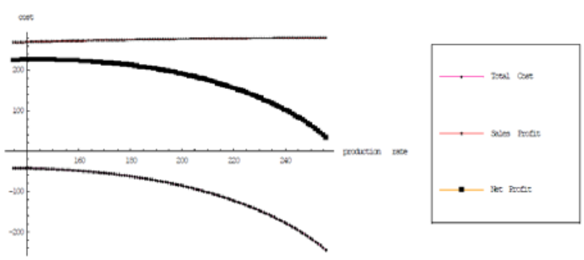

Figure 8: Case 3 – Discount Graph with m = 3000, p = 0.03 and q = 0.4

The various costs and sales revenue are each graphed, in Figures 9-13, as a function of production rate and inventory buildup.

We are then able to establish appropriate production plans for a given set of values of the parameters m, p, and q. We could also analyze different production plans based on the cost functions associated with each of the cases to establish the optimum strategy (in terms of production rates) to respond to the demand in the market.

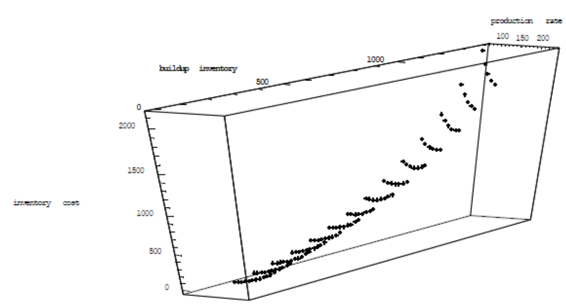

Figure 9: Case 3 – 3D Plot for Inventory Cost, Buildup Inventory, and Production Rate

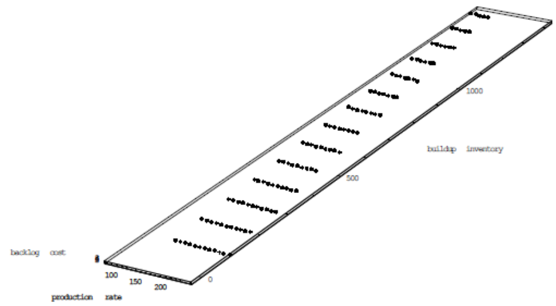

Figure 10: Case 3 – 3D Plot for Backlog Cost, Buildup Inventory, and Production Rate

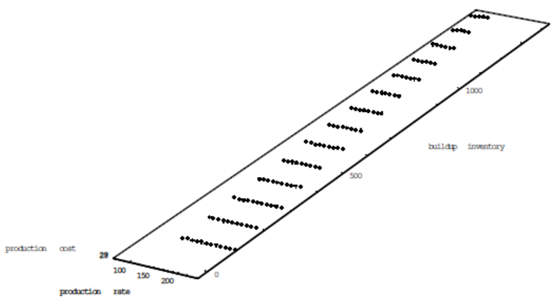

Figure 11: Case 3 – 3D Plot for Production Cost, Buildup Inventory, and Production Rate

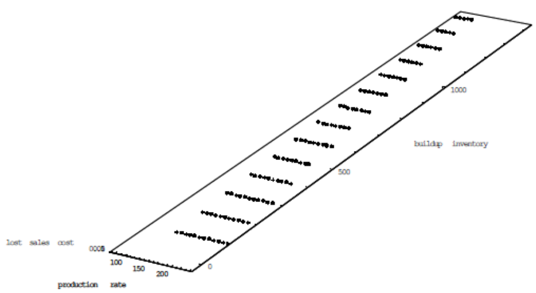

Figure 12: Case 3 – 3D Plot for Lost Sales Cost, Buildup Inventory, and Production Rate

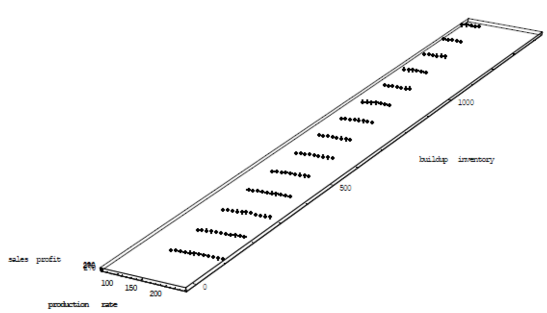

Figure 13: Case 3 – 3D Plot for Sales Revenue, Buildup Inventory, and Production Rate

5. CONCLUSIONS AND FUTURE RESEARCH

In this paper, we develop deterministic models to study the effect of production capacity on the demand and sales behaviors in products with short life-cycles. Cost functions over the entire product's life cycle are built and they can be utilized for finding the optimal production rate at the beginning of the life cycle. We also study the effects of an inventory build-up strategy to satisfy the sharp increase of demand at the growing stage of life cycle.

The contribution of this research is different from previously published papers (Ho, Savin, and Terwiesch 2002; Kumar and Swaminathan 2003). Our approach is more graphical in nature and the cost models associated with the different scenarios developed in Section 3 aid in developing an inventory buildup strategy. From several numerical/simulation studies (for brevity, those studies are not included in this report), we draw some observations.

5.1. Effect of Parameters *m*, *p*, *q* on Production Plan

We note that changing *m* (size of the target market) does not have much of an influence on the shape of the demand curve. However, the shape of the demand curve can drastically vary with a change in *p* (the coefficient of innovation) or *q* (the coefficient of imitation). As *p* increases, the curve tends to grow sharply which indicates that the product reaches a major percentage of the market capacity in a short period of time. This typically entails a scenario in the market where consumers are trying the new product without the word-of-mouth communication (this is typically applicable when there is plenty of advertisement in the news/entertainment media).

An increase in *q* (coefficient of imitation) would tend to boost the sales by generating consumers who are waiting and watching the product from the time it was introduced into the market.

5.2. Inventory Buildup Strategy

In the inventory buildup strategy, it is very important to establish the start time of production which would decide the total inventory quantity prior to the beginning of the sales period. Another important factor is the cost coefficient associated with the holding of the inventory at the beginning of the product's life cycle. As seen in Section 3, we have developed cost functions for the different scenarios presented.

5.3. Future Research

In this paper, we arbitrarily chose the end of the product's life cycle to be at the time demand reaches 99.9% of total market size. The production period is determined accordingly. However, further research could be done by finding the optimal cut-off point for a specific production plan. Moreover, only a constant production rate is discussed in this paper. Clearly choosing a proper time for production expansion or contraction to better match the demand curve will provide a better payoff. It would be very useful for management to have an interactive graphical tool, which will show cost components under different production plans. Finally, demand-supply interaction modeling with stochastic demands is yet to be researched and it will be considered in our future research.

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