Manufacturing capacity planning strategies

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ABSTRACT

When planning for a new manufacturing system to produce several products over a planning horizon, firms usually face an important decision regarding how to select the optimal quantity and portfolio of product-dedicated and flexible capacities. Flexible systems may alleviate the unfavorable effects of demand uncertainties, however they require higher investment costs compared to dedicated systems. In this paper, we formulate the optimal capacity selection problem and perform numerical studies to provide insights on how these decisions are affected by the investment costs, product revenues, demand forecast scenarios and volatilities over the planning period.

1. Introduction

In this paper, we consider optimal capacity investment decisions for a firm that produces several products over a planning horizon. This decision, which has long-term economic consequences, addresses two major issues: (1) how much capacity to build? (2) whether to invest in dedicated or flexible systems, or a portfolio consisting of both dedicated and flexible systems. As defined in [1,2], flexible capacities "possess the ability to change over to produce a set of products very economically and quickly". Therefore, flexible systems may alleviate unfavorable effects of demand uncertainties. However, the versatility to produce multiple products often requires higher investment costs compared to dedicated systems that can only produce one type of product [3].

In this study we formulate the optimal capacity investment problem and provide insights on how the investment decisions are influenced by (1) relative investment costs of dedicated and flexible systems, (2) marginal revenues from each product, (3) demand volatility during the planning horizon. Intuitively, we expect flexible capacities to be favored more as their investment costs are closer to those of dedicated systems and when profit margins and market volatilities are high.

There is a rich literature on optimal capacity investment and an extensive survey on the topic has been provided in [4]. Several studies consider both initial investments and optimal capacity adjustments over time [5,6]. However, as argued in [7], continuous capacity adjustments may not be possible in many settings due to irreversibilities. Therefore, investing in the optimum quantities and types of capacity at the beginning of a planning horizon is crucial for profitability in the long run. There exist many works showing the economic benefits of employing flexible systems. Particularly, Van Mieghem [8] studies optimal investment in dedicated and flexible capacities under uncertainty and shows how several problem parameters including investment cost and demand uncertainties effect optimal investment decisions.

The major contribution of our work is extending the analysis of optimal capacity investments to multiple selling periods, allowing nonstationary demand processes based on product life cycles, and limiting capacity purchases by discrete increments to study the effects of various demand and cost parameters. As discussed in [4], these extensions present analytical difficulties and have received relatively little attention. Other studies show the value of investing in flexible systems by adapting models from the theory of options in financial markets [2,7] and by studying the effects of uncertainties in future product prices [9,10].

The paper is organized as follows. In Section 2, we present the problem setting and provide a mathematical model of the capacity investment problem. In Section 3, we study a range of numerical results and discuss how optimal investment decisions are affected by factors such as investment costs, product revenues and demand volatilities. We present concluding remarks in Section 4.

2. Model description and problem formulation

In this section, we first present the main modeling assumptions on product demand and manufacturing capacity. We then provide a mixed-integer programming formulation for the capacity investment problem.

2.1. Product demand

We consider a manufacturing firm that produces two types of products over a time horizon consisting of several periods. Marginal revenues of p_A and p_B are received for each unit of type A and type B product, respectively.

Demands for each product at each period are uncertain. For capacity planning purposes, the firm employs demand forecasts for each type of product. These forecasts lead to probability density functions for product demands across periods. As a brief example, if the forecast for the sales of a product is: 100% confidence that at

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Table 1
An example of discrete probability density function for product demand.

Product demand	Probability density function
300,000	0.3
400,000	0.5
500,000	0.2

least 300,000 units will be sold, 70% confidence that at least 400,000 units will be sold, and 20% confidence that 500,000 units will be sold, then the discrete probability density function is given in Table 1.

As future periods possess higher levels of uncertainty, the forecast accuracy decreases with time. Therefore, in our analysis, we will assume higher demand variances for more distant time periods.

In this study, we consider two demand scenarios. In the first scenario, a new product, designated as product B, is gradually replacing an existing product A. Fig. 1 illustrates typical demand distributions for the products where ψ_i^t and $\bar{d}_i^t$ denote, respectively, the probability density function and mean demand in period t for product i, $i = A, B$. We let $\mathbf{d} = (\mathbf{d}_A, \mathbf{d}_B)$ denote the realization of all product demands, where $\mathbf{d}_A = (d_A^1, d_A^2, d_A^3)$ and $\mathbf{d}_B = (d_B^1, d_B^2, d_B^3)$. In the second scenario we consider the case where both products have highly fluctuating and negatively correlated demand. Specifically, we study a problem instance where product A has high demand in periods 1 and 3 and low demand in period 2, and product B has low demand in periods 1 and 3 and high demand in period 2.

2.2. Manufacturing capacity

The manufacturing capacity investment decision is carried out at the beginning of the planning horizon when only forecasts for product demands are available.

Two major issues should be addressed when planning for the manufacturing system: (1) how much capacity to build? (2) whether to invest in dedicated or flexible capacity, or a combination of both. We let $\mathbf{k} = (k_A, k_B, k_{AB})$ denote the firm's capacity investment decision where k_A, k_B, k_{AB} are the investments in dedicated capacities for products A and B and the flexible capacity, respectively.

A dedicated capacity costs less than its flexible counterpart. Furthermore, flexible capacity is economically viable only if it costs less than the sum of the costs of dedicated capacities. Letting $\mathbf{c} = (c_A, c_B, c_{AB})$ denote the investment costs per unit capacity, we therefore assume $c_A, c_B \le c_{AB} \le c_A + c_B$.

As one of the main objectives of this study is to provide insights on how the relative costs of dedicated and flexible capacities influence investment decisions, we introduce the term "**flexible premium**", denoted by f, and defined as the additional cost of a unit of flexible capacity compared to that of a dedicated capacity. For example, a flexible premium of 40% indicates that a unit of flexible capacity costs 40% more than a unit of dedicated capacity.

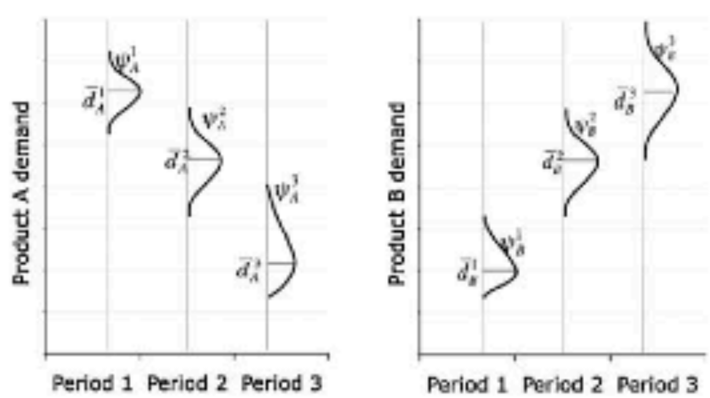

Fig. 1. Demand distributions for products A and B for a planning horizon of three periods.

We follow a similar capacity investment cost structure as presented in Koren et al. [3] and assume that both dedicated and flexible capacities are purchased in discrete batches where the increments of the dedicated capacity are much larger than that of the flexible capacity. In practice, firms may incur additional costs to simultaneously operate and maintain dedicated and flexible systems. Therefore, we apply lower bounds on capacity purchases; a certain type of capacity below the bound will not be purchased.

We let $k_j \in \{0, S_j\}$ where $S_j = \{k_j + w_j \delta_j | w_j \in Z^+\}$ for $j = A, B, AB$ denote the feasible set of capacity selections for each type of manufacturing system where k_j and δ_j denote the minimum capacity purchase and capacity increment sizes, respectively. Fig. 2 represents an example cost structure for dedicated and flexible capacity investments.

2.3. Problem formulation

The sequence of events is as follows: at the beginning of the planning horizon, the firm first makes a strategic investment decision on the quantity and types of manufacturing systems to purchase. Once the initial investment decisions are given, the firm continually makes operating decisions every period on how to allocate its resources in the most profitable way across products.

We first consider the operating decision stage, which is a multi-period extension to the model given in [8]. The result of the following optimization problem, $R(\mathbf{d}, \mathbf{k})$, depicts the maximum revenue that can be achieved for a given capacity investment decision $\mathbf{k}$, and for any realization of product demands $\mathbf{d}$ over the planning horizon.

$$
\begin{aligned}
R(\mathbf{d}, \mathbf{k}) = \max_{x,y} & \sum_{t=1}^{T} \beta^{t-1} [p_A(x_A^t + y_A^t) + p_B(x_B^t + y_B^t)] \\
\text{s.t} \quad & (a)\ x_A^t \le k_A \qquad \forall t = 1, \ldots, T \\
& (b)\ x_B^t \le k_B \qquad \forall t = 1, \ldots, T \\
& (c)\ y_A^t + y_B^t \le k_{AB} \qquad \forall t = 1, \ldots, T \\
& (d)\ x_A^t + y_A^t \le d_A^t \qquad \forall t = 1, \ldots, T \\
& (e)\ x_B^t + y_B^t \le d_B^t \qquad \forall t = 1, \ldots, T
\end{aligned} \tag{1}
$$

In the above optimization problem, the decision variables x_A^t and x_B^t denote, respectively, how many units of dedicated capacity A and B are utilized to fill period t demand, whereas the decision variables y_A^t and y_B^t denote the optimal allocation of the flexible capacity between products. In addition, β is the discount factor per period. Constraints (a)–(e) guarantee that the production quantities within a period do not exceed available capacity and are bound by the current period demand.

Having obtained the optimal production quantities under a given capacity choice and demand realizations, we now write the first stage problem of determining the optimal capacity investments, $\mathbf{k}$.

$$\max_{k} E_d(R(\mathbf{d}, \mathbf{k})) - \mathbf{c} \cdot \mathbf{k}' \tag{2}$$

In the above formulation, $E_d(R(\mathbf{d},\mathbf{k}))$ is the expected value of the operating revenue where the expectation is taken over demand distributions and $\mathbf{c} \cdot \mathbf{k}'$ represents the total investment costs. As was described in the previous subsection, we have $k_A \in \{0, S_A\}$ where $S_A = \{k_A + w_A \cdot \delta_A | w_A \in Z^+\}$ with $k_B \in \{0, S_B\}$ and $k_{AB} \in \{0, S_{AB}\}$ defined similarly as the feasible capacity choices.

3. Numerical results

In this section, we use the mathematical model described earlier to numerically explore how investment costs, product revenues and demand volatilities affect optimal capacity investment decisions.

3.1. Optimal capacity investment

In order to analyze the effects of the relative investment costs on optimal capacity investment decisions, we first consider a base case constructed by the following problem parameters. We assume

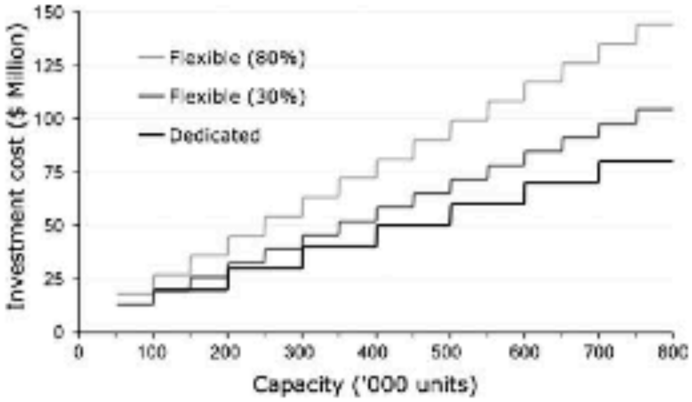

Fig. 2. Capacity investment cost structure.

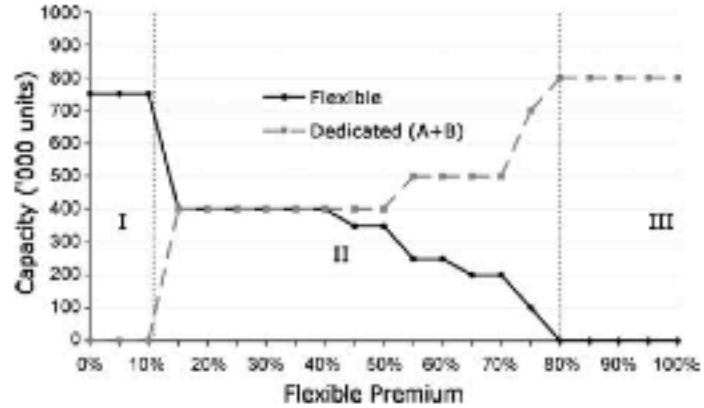

Fig. 4. The portfolio of flexible and dedicated capacities.

demands for products A and B generate revenues of $p_A = p_B = 75$ and, for a 3-period horizon, they are characterized by triangular distributions with mean values (600, 350, 100) and (125, 450, 700), and standard deviations (50, 70, 70) and (25, 70, 70). In terms of investment costs, we use $c_A = c_B = 100$ and vary the unit cost for the flexible capacity from 100 to 200 corresponding to a flexible premium of 0–100%. Finally we assume a discount factor of $\beta = 0.8$.

Fig. 3 shows profits obtained from three different investment strategies: (1) dedicated capacity only, (2) flexible capacity only, and (3) a portfolio consisting of both dedicated and flexible systems.

Noting that the strategies of investing in only dedicated or flexible systems are special cases of investing in a portfolio, we observe that a portfolio strategy yields profits at least as much as those from investing in pure flexible or dedicated systems. Furthermore, we observe three distinct regions in the above figure. In region I, the optimal capacity portfolio converges to the flexible only strategy. Similarly, in region III, the optimal portfolio converges to the dedicated only strategy. In region II however, a portfolio strategy results in strictly higher profits.

In summary, there exist lower and upper bounds, F_0 and $\bar{F}_0$, on the flexible premium, f such that the optimal policy is to invest in only flexibility capacity if $f < F_0$, only dedicated capacity if $f > \bar{F}_0$ and a portfolio of dedicated and flexible capacities if $F_0 \leq f \leq \bar{F}_0$. For the base case discussed above, we note that $F_0 = 10\%$ and $\bar{F}_0 = 80\%$.

Fig. 4 depicts the quantities of capacity purchases that lead to the optimal profits shown in Fig. 3. Specifically, we observe that as the unit cost for the flexible capacity increases, a portfolio consisting of gradually increasing share of dedicated capacities becomes optimal.

Fig. 5 illustrates both the total capacity investment and its constituents in terms of each capacity type. We see that the total capacity may be higher or lower as flexible premium increases, a result partly due to the discreteness and lower bounds applied to capacity purchases.

3.2. *Product revenue*

Next, we consider the effects of product revenues on optimal capacity investments. Fig. 6 below illustrates the capacity

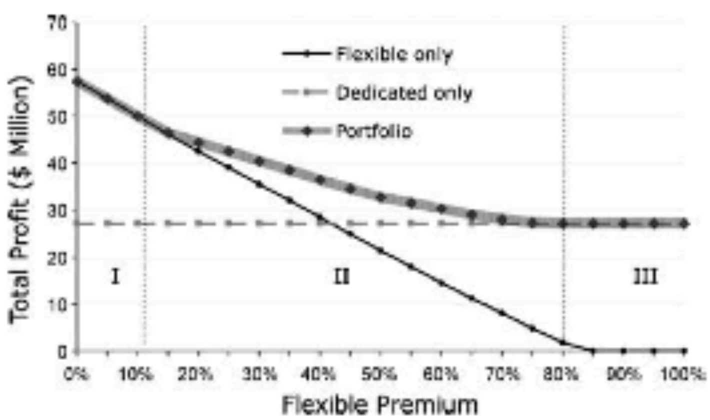

Fig. 3. Profits resulting from the investment strategies.

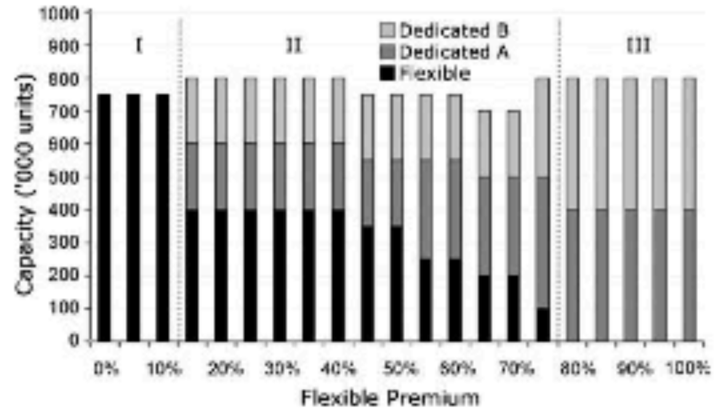

Fig. 5. Total capacity purchase and its constituents.

purchases for a problem instance with $p_A = p_B = 60$ while all remaining parameters are set identical to their values in the base case.

As implied by a comparison of Figs. 4 and 6, lower product revenues lead to an increase in the pure flexible and dedicated capacity regions (regions I and III) while the range where a portfolio strategy is beneficial (region II) is reduced. In other words, if we let F_R and $\bar{F}_R$ denote the new lower and upper bounds on flexible premium for low revenue products, we have $F_R \geq F_0$ and $\bar{F}_R \leq \bar{F}_0$. In this example, we have $F_R = 15\%$ and $\bar{F}_R = 50\%$.

Conversely, high product revenues enlarge the range over which the optimal strategy is of a portfolio type. As product revenues get higher, it is more profitable for firms to increase production in order to reduce missed demand opportunities. Since dedicated capacity costs less, it makes sense to build the increased level of total capacity partially by dedicated systems. On the other hand, employing flexible capacity is also crucial as it allows allocating capacity where needed and hence enables a higher demand fill rate and revenues in the presence of demand uncertainties. Therefore a portfolio of flexible and dedicated systems is optimal over a larger flexible premium range.

Fig. 7 illustrates the optimal investment strategies over a range of product revenues. We again note that higher product revenues

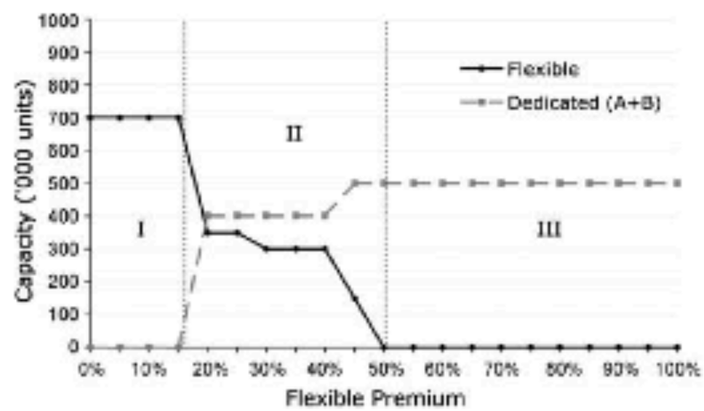

Fig. 6. The portfolio of flexible and dedicated capacities based on low product revenue.

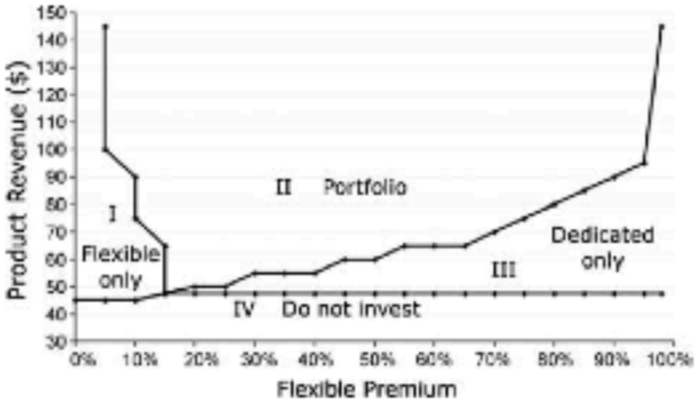

Fig. 7. Effect of product revenue on optimal capacity investment strategies.

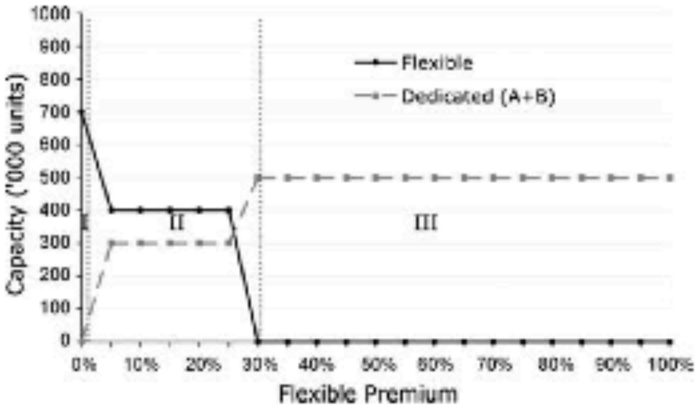

Fig. 8. The portfolio of flexible and dedicated capacities based on low demand uncertainty.

lead to a wider region of portfolio-type investments. The figure also shows that for low revenues, if it is profitable to invest in capacity, it is optimal to invest in pure flexible systems since dedicated systems may not be profitable alternatives.

3.3. *Demand variance*

We now analyze the effect of demand variance on optimal capacity investment decisions. We first consider a problem instance where the demands within a period have less uncertainty. We reduce the standard deviation and set it to 25 for each product across all periods.

Fig. 8 shows that as product demands for each period have less uncertainty, the value of the pure flexible investment strategy diminishes. In other words, when market is more predictable, an optimal investment strategy favors dedicated systems.

Finally, we consider the second demand scenario described in the model description where demands across periods show high volatility. We set the mean demand values for products A and B as (600, 150, 600) and (125, 600, 150), respectively, with standard deviations as given in the base case.

Fig. 9 displays the constituents of the optimal capacity investments. In the case of high demand volatility across periods, we observe that optimal capacity investment favors flexible systems. In this example, the portfolio region consists of solely one type of dedicated system as the flexible system provides the capacity to produce the other item.

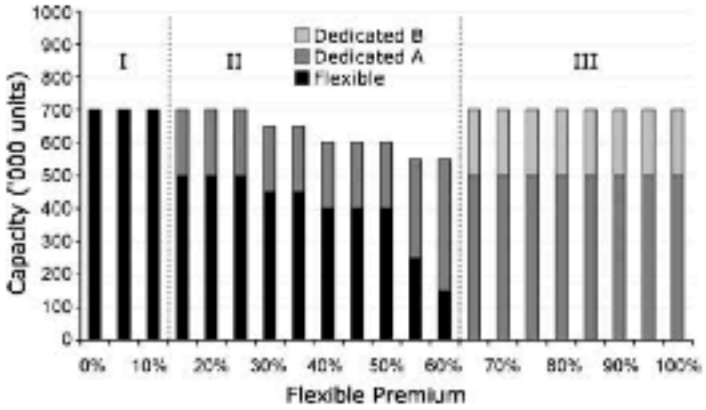

Fig. 9. Total capacity purchase and its constituents for high market volatility across periods.

4. Conclusions

In this paper, we studied optimal capacity investment strategies for firms producing two products over a planning horizon during which product demands possess uncertainties.

Through a variety of numerical examples, we showed how a range of investment cost parameters, product revenues and demand uncertainties influence the optimal strategy to whether invest in pure flexible, pure dedicated or a portfolio of both types of systems. Our analysis indicates that optimal investment strategies include a larger share of flexible systems under low flexible investment cost, high product revenues, and high demand uncertainties within and across periods.

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