Capacity planning in two-tier manufacturing systems to support product variety

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Abstract

Long-term capacity planning in industries with limited short-term expansion flexibility is complicated by uncertainty in consumer demand, which in turn is aggravated by demand for a large variety of products. This paper studies such a capacity planning problem for a two-tier multi-product, multi-facility system. Assembly facilities have flexibility to produce limited quantities of multiple products at one facility. One of the ways in which variety in product offerings can be achieved is by allowing a number of configurations for each product, obtained by using different kinds of supplied parts. The objective of this study is to determine capacity requirements both at the assembly side and at the supply side of the system. An optimization model for this problem is developed. A simulation-based optimization approach is used to solve a restricted version of this
model. The restricted version explicitly represents capacity optimization only for the most important parts. Numerical results are obtained using a case study from the automotive industry.

Keywords: manufacturing flexibility, product variety, capacity planning.

1. Introduction

1.1 Problem statement

Manufacturing companies face uncertain customer demand concerning both quantity and variety of products required. Manufacturing flexibility is an often-considered strategy to deal with demand uncertainty (Zelenovic, 1992). It allows varying the production volume and to switch from production of one product to another at a reasonable cost. In industries with limited short-term flexibility such as the automotive industry, commitment to adopting the manufacturing flexibility strategy is a strategic-long term decision. That includes strategic capacity planning and adopting of manufacturing technologies and product design enabling flexible manufacturing. The capacity planning sets limits on system’s throughput. The technologies determine the ability to switch from production of one product to another. The product design determines requirements for assembly parts and influences the achievable level of product variety offered. Given that manufacturing of parts if often outsourced to suppliers, planning for flexibility must cover not only the final assembly stage but also the entire manufacturing supply chain.

1.2 Literature review

In order to achieve the full benefit of manufacturing flexibility, requirements for flexibility need to be defined at the strategic decision making level (Beach et al., 2000). Assuming the external demand as a driver for flexibility adoption, a primary question is how much flexibility is needed. The
extended research has been devoted to resolving conceptual issues of flexibility (see survey paper by Sethi and Sethi (1990), De Toni and Tonchia (1998, 2005) among others). The primary concern of this research is definition of types of flexibility and identification of flexibility enablers. Thus, Koste and Malhotra (1999) define manufacturing flexibility as a combination of product-mix flexibility, volume flexibility, expansion flexibility, modification flexibility and new product flexibility. Product mix flexibility can be associated with customer demand for variety and volume flexibility can be associated with customer demand for varying quantities of products (D'Souza and Williams, 2000). However, research on quantitative models of flexible manufacturing systems at the strategic level under demand uncertainty is scarce (Chen et al., 2002). Product mix flexibility has drawn the main attention. Jordan and Graves (1995) elaborate a framework for strategic analysis of flexibility in the automotive industry. They emphasize that partially flexible systems, if intelligently designed, are capable of yielding similar benefits to completely flexible systems. The authors demonstrate that the value of flexibility depends upon correlation in product demand and the system’s capacity. Guidelines for assigning vehicles to plants to achieve different levels of product mix flexibility are provided. Other authors who investigate the value and properties of flexibility by comparing different assignments of product to manufacturing facilities include Boyer and Keong (1996) and Bengtsson and Olhager (2002). The authors have analyzed characteristics of flexible systems at different levels of capacity. Fine and Freund (1990) develop a stochastic programming model for optimizing product-flexible capacity under a finite number of possible demand realizations. Gupta et al. (1992) develop a similar model for finding optimal investment policies in the presence of fixed initial capacities. Chen et al. (2002) optimize the capacity of a flexible manufacturing system using stochastic programming, where the evolution of stochastic demand is represented using demand scenarios. Although their model is designed to handle multiple-product and multiple-facility (technology) situations, their reported numerical results are restricted to a maximum of three
products and one technology. An optimization model by Van Mieghem (1998) analyzes the selection between dedicated and flexible resources in a two-product case. The author considers continuous demand and concludes that selecting flexible resources may be advantageous, even if demand for products is positively correlated. Tseng (2004) indicates that more emphasis is needed on other aspect of flexibility because current manufacturing technologies have largely resolved the problem of providing product mix flexibility.

Product mix flexibility is only one of the enablers that allows meeting customer demand for high product variety. Other enablers are studied in mass customization research (Da Silveira et al., 2001; Chandra and Kamrani, 2004) and product design is among the most important manufacturing related factors. Modular product design is an often-used approach to provide large variety of products (Lampel and Mintzberg, 1996). From this perspective, supply chain management is important to support outsourcing of production of modular components (Salvador et al., 2002), which causes an extension of flexibility analysis beyond the manufacturing stage. The quantitative models discussed earlier in the section do not include product design and do not account for the ability of supply channels to support flexible manufacturing. Barad and Sapir (2003) also point out that the flexibility research extending beyond one tier is virtually nonexistent.

To summarize the literature review, quantitative modeling of volume flexibility and the impact of supply chain characteristics and product design on value of flexibility are inadequately investigated. Additionally, there are still difficulties to apply elaborated models in practice because of their limited scope and restrictive assumptions.

1.3. Contribution

This paper analyses a flexible manufacturing system consisting of assembly facilities and suppliers. The system is aimed to meet customer demand for product variety, which is mainly achieved by
assembling different configurations of base products using modular parts with varying degree of commonality among them. An optimization model for this problem is developed. A simulation-based optimization approach is used to solve this model. Numerical studies based on a case from the automotive industry are conducted to quantify impact of product variety on the value of flexibility. This paper updates and extends results of an ongoing investigation presented in Chandra et al. (2005). A quantitative strategic planning model for determining the overall business value of flexible was developed in that investigation. The realistic size and scope of the model and inclusion of supply capacity related factors were the main distinctive characteristics. The main extensions presented in this paper are explicit accounting for product design that affects the level of product variety and treatment of the supply side of the manufacturing system, and analysis of relationships between manufacturing flexibility and product variety offered.

The rest of the paper is organized as follows. Section 2 analyses interactions between flexibility and product variety. The capacity planning model for a specific problem from the automotive industry is developed. Experimental results describing value of flexibility depending upon product variety are presented in Section 3.

2. Flexibility and product variety

The primary research focus is on long-term capacity planning in flexible manufacturing systems. A manufacturing system consists of multiple assembly plants and parts suppliers. It faces stochastic customer demand with regard to both quantity and variety. Modular product design is adopted to provide product variety. Each product can have different configuration depending on parts used in assembly. Parts are classified either as common parts and or as unique parts. The common parts are shared across whole range of products or across a family of products. Unique parts are specific to each product. Both common and unique parts can be further itemized. Manufacturing flexibility is
considered dealing with demand uncertainty. Particularly, product mix flexibility and volume flexibility are used. The product mix flexibility is characterized by the ability to produce several products at one manufacturing facility or by one resource without incurring a major cost penalty (Gerwin, 1993). Deployment of appropriate manufacturing technologies is required to achieve this ability. However, from the strategic planning point of view, product mix flexibility is enabled by allowing flexible product to assembly facility assignments. During the manufacturing process, product mix flexibility allows allocating existing resources to products with higher demand, if some other products have demand lower than expected, or to products, whose production is more attractive. Volume flexibility is defined as the ability to operate profitably at different total production volumes (Browne et al., 1984). It implies having little excess capacity in low-demand situations while preserving the ability to increase manufacturing output in the case of high demand. Enablers of volume flexibility are slack capacity, inventory buffers, flexible workforce including overtime, flexible product to assembly facility assignments and supply chain management related enablers such as outsourcing and strategic partnership (Jack and Raturi, 2002).

Manufacturing flexibility in turn enables offering a large variety of products to customers (Da Silveira et al., 2001). Supply chain management and product design are other two important enablers of product variety. These two enablers associate manufacturing flexibility and product variety problems.

Figure 1 shows a conceptual model, which summarizes entities pertinent to analysis of multi-tier flexible manufacturing systems and links these entities with enablers of product mix flexibility and volume flexibility. Customers, assembly facilities and part suppliers form the manufacturing supply chain. Assembly facilities are responsible for final assembly of products, while suppliers supply these facilities with parts as required according to a product design specification. The manufacturing system is required to meet customer demands for product variety and volume. That is achieved by
considering various enablers of product mix flexibility and volume flexibility. For instance, volume flexibility can be achieved by planning for manufacturing facilities having slack capacity or product mix flexibility can be achieved by planning for manufacturing facilities having flexible product-to-facility assignments.

This model can be used as the basis for further analysis and development of problem specific models.

Figure 1. Conceptual model of factors influencing manufacturing flexibility.

### 3. Model

On the basis of the conceptual model, a problem-specific optimization model is developed. The specific problem considered is an extension of the capacity planning case study investigated by Chandra et al. (2005), where the detailed description of the case can be found. This case study considers a manufacturing system of a major OEM. The system consists of multiple assembly plants and parts manufacturers. The parts manufacturers are represented by parts supply capacity. The planning problem is to determine both assembly and supply capacity requirements in order to maximize profit. The planning horizon is five years. Product mix flexibility is achieved by having
some plants capable of producing several products (but not all plants can produce all products). Out of the volume flexibility enablers discussed, overtime, slack capacity and flexible product-to-plant assignments are relevant to this problem. The slack capacity is used both at the assembly and supply stages. Volume flexibility is affected by two problem specific factors, namely, marketing cost and industry-wide regulatory requirements.

The extension developed is aimed to reveal an impact of product variety on the value of flexibility. It explicitly distinguishes different configurations of products and customer demand is given for a specific configuration. Products and their configurations differ from one another by their profitability and contribution to regulatory constraints. In order to keep the optimization model manageable, only one part, which is of the most interest and referred here as an A part, is treated separately. This part has multiple models. A customer demands a product configuration with a specified model of the A part installed. However, the customer choice is limited because not all models of the part are available for all products. Requirements for other parts are represented using a set of common parts and a set of unique parts needed to assemble a product.

Mathematically, profit is calculated as a function of income from product sales and expenses due to assembly plant capacity investments and maintenance, parts supply capacity investments (split among investments in common parts capacity, unique parts capacity and capacity for the A part) and marketing. The optimization problem is solved subject to demand satisfaction, assembly capacity restrictions, supply capacity restrictions and legislative constraints. Mathematically, the profit $E[P]$ maximization is expressed as (a detailed description of the objective function and constraints is given in the Appendix)

$$Z = \max_{\delta, \lambda, \kappa, \rho, \phi, \Omega} E[P].$$  (1)
Capacity adjustment coefficients $\delta = \{\delta_1, \ldots, \delta_M\}, \phi = \{\phi_1, \ldots, \phi_L\}, \nu$ and $\lambda$ are used to change the supply capacity for unique parts for each product, the supply capacity for the A part for each of its model, common parts capacity and assembly capacity (aggregated for all plants), respectively. $M$ is the number of products. $L$ is the number of models for the A part. The adjustment coefficients are used in the optimization instead of directly altering the capacity in order to limit the size of the optimization space. Multiplication of capacity adjustment coefficients and initial capacity yields the optimized capacity requirements. Increase of the optimized capacity compared to the initial capacity represents the slack capacity created to provide volume flexibility. Matrices $\Delta, \Phi, \Omega$ and $\Lambda$ represent sets of predefined values for the coefficients. The matrix $Q = \{Q_{it}\}, i = 1, \ldots, M, l = 1, \ldots, L, t = 1, \ldots, T$ represents the quantity of the $i$th product having the $l$th model of the A part produced and sold in the $t$th time period, where $T$ is the planning horizon. Some of the produced products are assembled during overtime. The fixed product to assembly plant assignments are input data to the model. These assignments provide limited product mix flexibility.

Optimization of the capacity adjustment coefficients is performed without knowing the future demand in a deterministic sense, but rather by obtaining the best average result over an ensemble of demand scenarios. For each demand scenario another "inner" optimization is performed to allocate existing capacity so as to produce an optimal sales decision variable $Q$.

Demand $D_{it}$ for $i$th product at $t$th time period is given by its distribution

$$D_{it} \sim I_i G(\bar{D}_{it}, \sigma_{it})$$

(2)

where $I_i \sim G(1, \sigma_i)$ is an indicator describing total industry demand, $G$ is a probability distribution, $\bar{D}_{it}$ is average demand for $i$th product having the $l$th model of the A part at $t$th time period, $\sigma_{it}$ is standard deviation of product demand aside from that part due to total industry
demand and $\sigma_t$ is standard deviation of the total industry demand indicator (the average value of the indicator is 1).

A simulation based optimization procedure is used to solve the model similar to that described in Chandra et al. (2005).

**4. Experimental analysis**

The model is used to conduct explorative studies on the impact of product variety on value of flexibility. If profitability of products remains constant (i.e., product variety only allows preserving the market position), product variety is expected to reduce the total profitability of the system because higher demand uncertainty requires increase in slack capacity at the assembly level and pooling of parts capacity is possible to a lesser degree. On the other hand, in the case of higher variety, the manufacturing system improves ability to allocate overloaded resources to manufacturing of more profitable products and their configurations.

Experimental factors used are level of product variety and flexibility of product to assembly plant assignments. Two levels of product variety considered are:

1. all products are assembled using the same model of the A part (no configurations are offered) (denoted as V1);

2. at least two models of the A part can be used to assemble each product (at least two configurations of each product are available) (denoted as V2).

Two levels of flexibility of product to plant assignments considered are standard (S) and higher (H) levels as defined in Chandra et al. (2005). The proportion of common parts 0.25 and the regulatory restrictions are imposed.
The value of flexibility is determined using the expected profitability of the optimized manufacturing system. Volume flexibility achieved is described by a function relating the expected profitability to the total demand. Product mix flexibility achieved is described by a distribution of the sales to demand ratio (i.e., the ratio between units manufactured and units demanded by customers). If this distribution is uniform then the manufacturing system is capable of producing all products at the similar rate. However, this distribution is also affected by other factors such as availability of unique parts. The experimental procedure is organized similarly as described in Chandra et al. (2005).

Table 1 reports the value of flexibility depending upon the level of product variety and the level of flexibility of product to plant assignments. The increased product variety results in significant loss of profitability because capacity slack needs to be maintained for each model of the A part (the model does not include an eventual cost penalty for offering low variety). There is some evidence that having more flexible product to plant assignments is more beneficial in the case of larger product variety. That is indicated by a slightly quicker relative increase of profitability when moving from the S flexibility level to the H profitability level in the case of V2.

### Table 1. The value of flexibility according to product variety and the level of flexibility of product to assembly plant assignments.

<table>
<thead>
<tr>
<th>Level of flexibility</th>
<th>Level of product variety</th>
<th>$E[P]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>V1</td>
<td>9564 (±125)</td>
</tr>
<tr>
<td>S</td>
<td>V2</td>
<td>8954 (±113)</td>
</tr>
<tr>
<td>H</td>
<td>V1</td>
<td>9922 (±118)</td>
</tr>
<tr>
<td>H</td>
<td>V2</td>
<td>9358 (±121)</td>
</tr>
</tbody>
</table>

Measurements of volume flexibility are shown in Figure 2. The volume flexibility curve (it is obtained by polynomial smoothing of original data) shows that the system is expected to operate...
profitably for majority of plausible demand scenarios. The profitability falls below zero if the total demand is lower than approximately 670,000 units. This margin is relatively stable for all experimental cases considered. If the total demand is low profitability is higher in the V2 case, especially, if the standard product mix flexibility level is considered. That can be explained by impact of the supply capacity slack for unique parts (not shown) because it is higher for the V1 case and results in more substantial losses in the case of low total demand.

In the case of S and V1, the distribution of the sales to demand ratio has the average value equal to 0.9 and the standard deviation equal to 0.1. In the case of S and V2, the distribution of the sales to demand ratio has the average value equal to 0.88 and the standard deviation equal to 0.11. That indicates that the higher customer service can be achieved if less variety is offered (again, there is no penalty for not providing variety). The product mix flexibility achieved is also higher as indicated by the lower standard deviation of the distribution. The shortage of particular models of the A part demanded causes this reduction of product mix flexibility achieved in the case of V2. Therefore, volume flexibility represented mainly by supply slack capacity is also an important enabler of product mix flexibility.
Figure 2. Measurements of volume flexibility (a) for S flexibility level (b) for H flexibility level.
5. Conclusion

A flexible manufacturing system including both assembly facilities and suppliers has been investigated in this paper. The model for optimization of capacity requirements in this system has been developed. Explicit representation of product design allowing analyzing impact on product variety on value of flexibility is the main distinctive feature of this model. The experimental studies conducted reveal that:

If offering lower product variety is not penalized by lower customer demand or other factors then the increase of product variety results in loss of profitability for the system considered. Volume flexibility, if measured by the total demand level required to break-even, is relatively insensitive to the level of product variety. However, increased product variety reflects negatively on system’s ability to meet customers’ demand for each product at the same level of the sales to demand ratio. Higher product mix flexibility is more valuable in the case of larger product variety.

Main future directions of this research are exploration of relationships between slack capacity requirements at the manufacturing side and at the supply side and improvement of computational efficiency of the optimization model solving.

References


Appendix

Notation

Indices $i, j, l$ and $t$ refer to particular product, plant, model of the A part and year, respectively. $M, N, L$ and $T$ denote the number of products, the number of plants, the number of models for the A part and the planning horizon, respectively.

$\alpha_t$ - discount factor in year $t$

$p_{it}$ - profit for product $\{i,l\}$ (i.e., product $i$ with model of the A part $l$)

$\varphi_{it}$ - contribution to regulatory constraints for product $\{i,l\}$

$Q_{it}$ - quantity of the product $\{i,l\}$ produced and sold in year $t$

$Q'_{ijlt}$ - quantity of the product $\{i,l\}$ produce at the plant $j$ in year $t$

$D_{it}$ - demand per product $i$ in year $t$

$\bar{D}_{it}$ - yearly average demand per product $i$ in year $t$

$\gamma_1$ - unique parts supply capacity build-up cost per capacity unit, $\gamma_1 < \gamma_2$

$\gamma_2$ - plant capacity build-up cost per capacity unit

$\gamma_3$ - yearly capacity maintenance cost per capacity unit, $\gamma_3 < \gamma_1$

$\gamma_4$ - overtime cost per capacity unit used, $\gamma_4 < \gamma_3$

$\gamma_5$ - savings for avoiding capacity build-up per capacity unit, $\gamma_5 < \gamma_2$

$C^1_i$ - supply capacity of unique parts per product $i$

$C^2_j$ - capacity per plant $j$
\( C_j^4 \) - overtime capacity per plant \( j \)

\( C_j^5 \) - product-specific plant capacity for the product \( i \) at the plant \( j \) (shows how many capacity units at this plant are available for this product regardless of model of the A part used), \( \leq C_j^2 \)

\( C_l^6 \) - the A part supply capacity per model \( l \)

\( U_t \) - units produced in overtime per plant \( j \) in year \( t \)

\( F_i \) - a function describing marketing costs per unit, function of actual demand/forecast demand

\( C^* \) - initial capacity

\( \beta \) - proportion of common parts

\( \kappa_1 \) - common parts supply capacity build-up cost per capacity unit, \( \kappa_1 < \gamma_2 \)

\( \kappa_2 \) - the A part supply capacity build-up cost per capacity unit, \( \kappa_1 < \gamma_2 \)

**Optimization model**

\[
Z = \max_{\delta, \lambda, \kappa, \nu, \phi, Q} E[P]
\]

\[
P = \sum_{t=1}^{M} \sum_{l=1}^{T} \sum_{i=1}^{T} C_l^6 \nu_i Q_{ilt} - \sum_{t=1}^{M} \sum_{l=1}^{T} \sum_{i=1}^{T} \alpha_i F_i (Q_{ilt} / D_{ilt}) Q_{ilt}
- (1 - \beta) \gamma_1 \sum_{t=1}^{M} \sum_{l=1}^{T} \gamma_2 \sum_{l=1}^{T} (C^* + C^3) - \gamma_2 \sum_{t=1}^{N} \sum_{j=1}^{T} \alpha_j C_j^2 - \gamma_2 \sum_{t=1}^{N} \sum_{j=1}^{T} \alpha_j U_t + \gamma_2 C_3
- \beta \kappa_1 v C P C - \kappa_2 \sum_{l=1}^{L} \phi_l D_l
\]

\[
Q_{ilt} \leq D_{ilt}, i = 1, ..., M, l = 1, ..., L, t = 1, ..., T \quad \text{sales-demand balance}
\]

\[
\sum_{l=1}^{L} Q_{ilt} \leq C_i^u, i = 1, ..., M \quad \text{unique parts supply capacity requirements per product}
\]
\[ Q_{ilt} = \sum_{j=1}^{N} Q_{ijlt}, t = 1, ..., M, l = 1, ..., L, t = 1, ..., T \]

\[ C_i^1 = \sum_{l=1}^{L} \bar{D}_{ilt} + \delta \sum_{l=1}^{L} \bar{D}_{ilt} \]
adjusted unique parts supply capacity

\[ \sum_{i=1}^{M} \sum_{l=1}^{L} Q_{ijlt}' \leq \lambda C_i^2 + U_{jt} \]
production-capacity balance

\[ U_{jt} \leq \lambda C_j^4 \]
overtime limit

\[ \sum_{l=1}^{L} Q_{ijlt}' \leq \lambda C_{ij}^5 \]
plant capacity requirements per product

\[ C^* = \sum_{j=1}^{N} C_j^2 \]
initial system’s capacity

\[ C^{3+} = \max \left( C^* - \lambda \sum_{j=1}^{N} C_j^2, 0 \right) \]
positive difference between initial and adjusted capacities

\[ C^{3-} = \max \left( \lambda \sum_{j=1}^{N} C_j^2 - C^*, 0 \right) \]
negative difference between initial and adjusted capacities

\[ CPC = C^* + \nu C^* \]
adjusted common parts supply capacity

\[ \sum_{i=1}^{M} \sum_{l=1}^{L} Q_{ilt} \leq CPC, t = 1, ..., T \]
availability of common parts

\[ \sum_{i=1}^{M} Q_{ilt} \leq \phi_i C_l^6, l = 1, ..., L, t = 1, ..., L \]
availability of the A part supply capacity

\[ FE \leq \sum_{i=1}^{M} \sum_{l=1}^{L} \phi_n Q_{ilt}, t = 1, ..., T \]
regulatory requirements, where \( FE \) is a threshold required