DEMAND VARIATIONS ASK FOR COST-EFFECTIVE MANUFACTURING FLEXIBILITY

Petra W. Heijnen, Paulien M. Herder
Delft University of Technology, Dept. Technology, Policy and Management
PO Box 5015, 2600 GA Delft, The Netherlands

Johan Grievink
Delft University of Technology, Dept. Applied Sciences
PO Box 5045, 2600 GA Delft, The Netherlands

Abstract

The aim of the research project was to identify ways to maximise the flexibility of the plant by varying equipment utilization, while guaranteeing a certain level of profit. A case study was conducted at a company that makes various types of food additives, which are produced in a multi-product multi-purpose batch plant. At the time of the research, market demand was exceeding the company's production capacity. Operations management was, therefore, re-evaluating its current product portfolio and its medium-term production planning. A manufacturing planning LP model is developed that can support the manufacturing allocation decisions making in order to compose a medium-term planning, which is optimised for manufacturing flexibility. The results are depicted in a flexibility chart that gives the manufacturer valuable information on the flexibility - cost trade-off.

Keywords

Flexibility, Batch Processing, Planning, Uncertainty, Multi-Product

Introduction

Many companies need to use medium term planning in their product development and manufacturing processes in order to sustain the reliability of supply and the responsiveness to changing customer requirements.

As the inherent uncertainty in customers' demand forecasts is hard to defeat by a company, the industry's specific capabilities with respect to responding rapidly to new and changing orders must be improved. New technologies are required, including tools that can swiftly convert customer orders into actual production and delivery actions. On the production side, this may require new planning technologies or new types of equipment that are, for example, dedicated to product families, rather than to individual products.

Flexibility is often referred to in operations and manufacturing research as the solution for dealing with swift changes in customer demands and requests for in-time delivery (Bengtsson, 2001). The concept has received even more attention with the upcoming of e-business in the chemical industry. The actual meaning, interpretation and consequences of 'operating flexiblity' are, however, not instantly clear for a particular case or company (Berry and Cooper, 1999).

A number of uncertainties may induce organisations to seek more flexible manufacturing systems, as depicted in Figure 1.

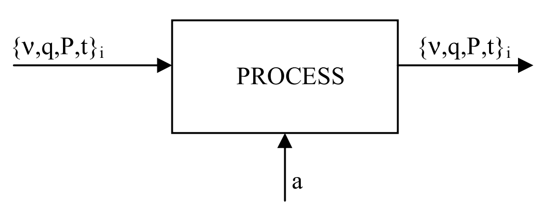

Figure 1: Types of uncertainties

On the input-side manufacturing systems have to deal with suppliers' reliability with respect to quantities, ν, feedstock quality, q, and with uncertainties in time, t, and cost, P. On the output side the same types of uncertainties can be found for each product. Thirdly, process inherent uncertainties exist, concerning equipment availability, a, and modeling uncertainties.

With respect to the uncertainty in the demanded quantity, which is the focus of our paper, many production markets experience a trend towards diversification. To achieve this diversification and to cope with shorter product lifespans, it seems preferable for manufacturing systems to have *flexible* resources.

Extensive research has been done into the flexibility of (chemical) processes that are subject to uncertainties on the input side and with respect to the availability of the processing equipment, possibly influencing the feasible operating region of the plant (e.g., Bansal et al, 1998; Swaney and Grossmann, 1985). Less research has been done, however, into flexibility that is characterised by the possibility to cope with changes in demand or product mix.

The right way to respond to change is always system specific, and dependent on the system's flexibility. Many approaches for dealing with uncertainties exist (Corrêa ,1994). As this paper concerns *product mix* variations and *demand* variations the "monitoring and forecasting technique" was selected.

A case was conducted at a company that makes various types of food additives which are produced in a multi-product and multi-purpose batch plant. In the business environment of this company, the demand from existing customers often moves gradually, but the unexpected attraction of new customers results in a stepwise growth of demand. In addition, total demand always exceeds production capacity. As the actual occurence of new demand often remains uncertain until the end of the sales process, the medium-term manufacturing planning contains considerable uncertainties.

At the time of our research, product mix demand was changing and uncertain. The aim of the research project was to identify possible sales opportunities and plan the existing production systems such that they could cope with the uncertain new demand. The new sales opportunities would have to maximise expected profit, and should still maintain a certain manufacturing flexibility.

In the next section we will introduce an LP model that supports making an optimal manufacturing planning subject to uncertain future demand. The use and usability of the LP model will be illustrated by a case study using real company data. The concluding section of this article will show that the integrative use of the planning model and the proposed flexibility analysis resulted in a suitable discussion tool that can be used for managing operating priorities subject to marketing goals.

Mathematical Formulation

In a multi-purpose multi-product plant, consisting of multiple production lines, the medium term planning is determined at the beginning of a new planning period. In this planning, customers and the plant owner agree on a fixed amount of products to be delivered in the upcoming period. Since demand exceeds production capacity at all times, the plant owner can sell the full production capacity. Flexibility towards favourable changes in mix or volume of products, however, will then become negligible, which may be unfavourable in the long run.

Assume that the plant has n products in its portfolio, to be produced on K production units. Taking into account capacity restrictions, the plant owner would like to determine the amount of each product to be sold in order to maximize overall profit. This results in the following LP optimization problem: Determine the amounts

$$v_{i,k}, 1 \le i \le n, 1 \le k \le K \text{ (in tons)} \tag{1}$$

of product i produced on production unit k, in such a way that the expected profit for the coming year,

$$EP = \sum_{i=1}^{n} \sum_{k=1}^{K} P_{i,k} v_{i,k}\ , \tag{2}$$

is maximized, where $P_{i,k}$ is the expected profit of one ton of product i produced on unit k. Several constraints have to be taken into account. Let $T_{i,k}$ denote the production time (in hours/ton) of product i produced on unit k and let t_k denote the total available production time on unit k in one year, then the constraint is the following:

$$\sum_{i=1}^{n} T_{i,k} v_{i,k} \le t_k, \quad \text{for } 1 \le k \le K, \tag{3}$$

Strong evidence exists that in the coming year demand for a new product will emerge. Provided that the new product has a high added value, it could be very favourable to reserve some of the plant's capacity for this new product.

The reservation of x% of the total capacity will change the optimisation problem. The question is now to find the amounts

$$v_{i,k}, 1 \le i \le n, 1 \le k \le K\ , \tag{4}$$

such that the expected profit

$$EP_x = \max \sum_{i=1}^{n} \sum_{k=1}^{K} P_{i,k} v_{i,k}\ , \tag{5}$$

subject to the following constraints

$$\sum_{i=1}^{n} T_{i,k} v_{i,k} \le t_k \text{ and } \sum_{k=1}^{K} \sum_{i=1}^{n} T_{i,k} v_{i,k} \le \frac{(100-x)}{100} \sum_{k=1}^{K} t_k . \quad (6)$$

For $x = 0\%$ no capacity will be kept free and the medium term flexibility is equal to zero. Increasing x will decrease the expected profit, when the free capacity is not used for anything else. The difference between the expected profit when all capacity is sold out at the beginning of the period and the expected profit when some capacity is reserved for a new product, should at least be compensated by the expected profit of the new, uncertain product in the coming year.

The demand for the new product, denoted by d, and the profit (depending on price and production costs) for selling one ton of the new product, denoted by p are both uncertain. The profitable combination of d and p is lower bounded by $d.p \ge EP_0 - EP_x$.

Let $T_{n+1,k}, k = 1..K$, denote the production time (hours/ton) of the new product on unit k, then the feasible demand d is upper bounded by

$$d \le \sum_{k=1}^{K} \frac{t_k - \sum_{i=1}^{n} T_{i,k} \hat{v}_{i,k}(x)}{T_{n+1,k}} =: C_x , \quad (7)$$

where $\hat{v}_{i,k}(x), i = 1..n, k = 1..K$ is the solution of the LP problem (Equation 5) for a reserved capacity of $x\%$.

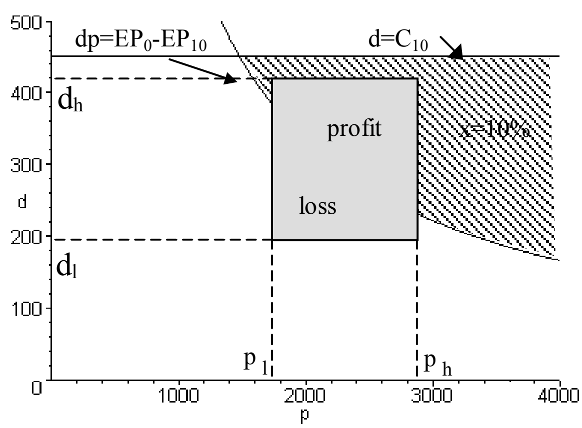

Figure 2: Profitable region for profit and demand of the new product

In Figure 2 the shaded part of the rectangle is the profitable region for certain values of p and d when $x = 10\%$. Assuming that the expected profit of the new product lies between p_l and p_h and the expected demand of the new product between d_l and d_h, profit can be expected when the real p and d are in the upper right part of the rectangle and loss should be expected when p and d are in the lower left part of the rectangle.

A fixed reservation of capacity of $x\%$ will increase the profit of the plant when $p.d \ge EP_0 - EP_x$ or decrease the profit of the plant when $p.d < EP_0 - EP_x$.

The optimization problem now reads: Find the minimal x such that

$$d_l . p_l \ge EP_0 - EP_x \text{ and } d_h \le C_x . \quad (8)$$

Case study at a food additives plant

A case study was conducted at a company that makes various types of food additives, which are produced in a multi-product multi-purpose batch plant. The present product portfolio contains two product groups A and B. Having strong indications about a growing demand for one new product C, operations management wanted to re-evaluate the current product portfolio and the medium production planning for the coming year.

Table 1: Capacities in ton/h

Product	Reactor 1 (ton/h)	Reactor 2 (ton/h)
A	6.5	3.5
B	1.8	2.0
C	0.2	0.2

Products A and B are manufactured in two reactors. The production capacities of the units were estimated by the planning personnel of the plant (Table 1). Figures from the sales database are used to determine the average profit of product A to be 1086 \$/ton and of product B to be 1478 \$/ton. The price levels are considered constant on the medium-term. The availability of the reactors is estimated based on the current Annual Operation Plan. The total amount of available operating time for the reactors is determined by the available time in a year minus 15% down and change-over time, resulting in 4625 hours for reactor 1 and 4390 hours for reactor 2.

Reserving $x\%$ of the total plant capacity, the LP-problem is now formulated as: Find $v_{i,k}$, $1 \le i, k \le 2$, such that

$$EP_x = \sum_{i=1}^{2} \sum_{k=1}^{2} P_{i,k} v_{i,k} = 1086(v_{1,1} + v_{1,2}) + 1478(v_{2,1} + v_{2,2}) \quad (9)$$

is maximized, subject to the following constraints:

$$6.5 v_{1,2} + 1.8 v_{2,2} \le 4625,$$
$$3.5 v_{1,3} + 2 v_{2,3} \le 4390 \quad (10)$$

and

$$6.5v_{1,2}+1.8v_{2,2}+3.5v_{1,3}+2v_{2,3}\le\frac{(100-x)}{100}9015. \quad (11)$$

Solving the maximisation problem for several values of x yields the following results:

Table 2: Maximum profit for reserved capacity

Reserved capacity	Maximum profit	Profit loss
0%	7040000	0
5%	6710000	330000
10%	6380000	660000
15%	6050000	990000
20%	5710000	1320000

Table 2 shows that the shadow price for the reservation of 1% of total capacity equals \$66000, so $EP_0-EP_x=66000x$, and here $C_x=45.08x$.

In case multiple product alternatives are available, composite, probabilistic equations may be used to determine the optimal combination of products to be produced within the free capacity space. In this industrial case study, however, only one alternative product, C, was expected to become profitable and strong evidence exists that profit will be in between \$2900 and \$3200 and that demand will be at least 250 ton and at most 400 ton per year. Finding the lower limit x% of reserved capacity such that the total expected profit is maximized, leads to solving the problem (Eq. 8):

Find minimum x such that $725000\ge 66000x$ and $400\le 45.08x$ which results into $x=9\%$ (see Figure 3).

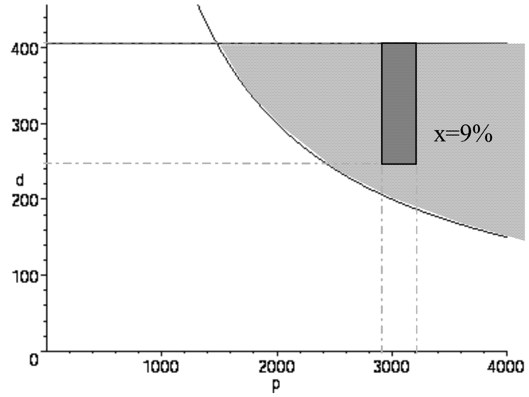

Figure 3: Feasible and Profitable regions for the maximum and minimum profit and demand of C

In Figure 4, the minimum and maximum expected profit levels are depicted for different percentages of free capacity. The minimum expected profit for a given x is to be expected when $p=p_l=\$2900$, $d=d_l=250$ ton. The maximum expected profit for a given x is when $p=p_h=\$3200$ and $d=d_h=400$ ton. The bold line shows the profit when no capacity is kept free for the new product C.

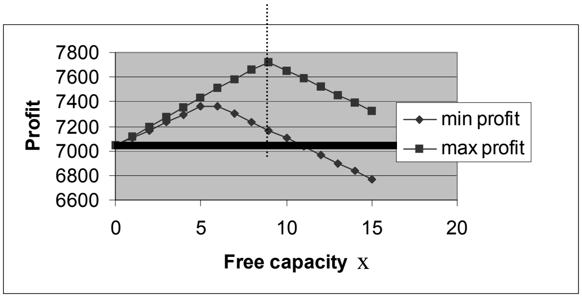

Figure 4: Profit-flexibility chart

This profit-flexibility chart is a practical tool for operations management in their decision how much of their capacity they would reserve for the new product in the coming planning period. Although 9% would the rational choice in this case, a safer choice may be 5%, taking into account that not all demand for the new product C will be satisfied, while maintaining a more certain expected profit.

Conclusions

The flexibility chart gives the manufacturer valuable information about the maximum profit to be expected under uncertain future product demand. The flexibility information is presented in relation to conventional manufacturing planning objectives, giving quantitative insight in the trade-offs that can be considered. The flexibility chart is a suitable and easy to use means for discussion, which comes to its full value when the results are interpreted by managers that have expert knowledge on the product's market and production technologies.

References

Bansal, V., Perkins, J.D., Pistikopoulos, E.N. (1998), Flexibility analysis and design of dynamic processes with stochastic parameters, *Comp.Chem.Engng.*, 22 (Suppl), pp.S817-S820.

Bengtsson, J. (2001), Manufacturing flexibility and real options: A review, *Int.J.Prod.Ec.*, 74 (2001), pp 213-224.

Berry, W.L., Cooper, M.C. (1999), Manufacturing flexibility: methods for measuring the impcat of product variety on performance in process industries, *J.Op.Mgmt*, 17 (1999), pp. 163-178.

Corrêa, H.L. (1994), *Managing unplanned change in the automotive industry*, Ph.D. thesis, University of Sao paulo, Warwich Business School, Avebury, Aldershot.

Swaney, R.E., Grossmann, I.E. (1985), An Index for Operational Flexibility in Chemical Process Design, *AIChE Journal*, Vol. 31, 4, pp 621-641.