Revenue Management in a Make-to-Order Environment

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Abstract. Manufacturing companies in a make-to-order environment sell customer specific products. Usually, a company offers more than one product, faces a stochastic demand, and a time-varying product price. The latter cannot entirely be set autonomously by the company due to competitors. The decision the company has to make for an incoming order is whether to accept or reject the order, depending on the remaining capacity, the contribution margin of the order and the orders expected for the future. In our contribution we will discuss if the methods for the airline revenue management are applicable to the described problem. After giving an overview about the requirements a decision support system ought to fulfill to improve the order selection process in a make-to-order environment, we will discuss the differences of such a system to existing revenue management approaches in service industries. Subsequently, we give a mathematical formulation for the described problem and apply it to a simplified practical example.

1 Make-to-Order Manufacturing, Introduction and Problem Definition

Manufacturing companies in a make-to-order environment sell products specific to consumer requirements. In general, an incoming order initiates the production process, i.e. the procurement of specialized materials and component parts, the in-house fabrication of parts, the production of subassemblies and the final assembly. Often the product itself or a variant of the product has been manufactured before, and hence, the bill of materials as well as measures for the expected processing time of the order at the resources are available [4].

We will focus in our contribution on the production processes in the iron and steel industry as an example of a make-to-order production process. Our reference production structure originates from the production structure of the Salzgitter AG, Germany. The steel making process [10] in general starts with the pretreatment of iron ores in a sintering plant which agglomerates the fine iron ores to sinter. In a blast furnace, the next production step, the ore is reduced to hot metal by adding coke, coal, oil or gas. The hot metal is then refined in a converter to liquid steel by an oxygen top-blowing process, subsequently ready to be cast and rolled. Nowadays, post-treatment is generally applied after refining, as an increasing demand in terms of quality and the ongoing development and diversity of steel grades produced do not allow sufficient accuracy when melting the steel in the refining vessel. This so-called secondary metallurgy aims at enhancing the quality of the metal by precisely alloying and lowering undesired elements or compounds. After this process liquid steel with the desired grade is available for transforming through a continuous casting process to solid cuboid-shaped slabs. The slabs are customized (in terms of steel grade and dimensions) semi-finished products and are the starting product for further processing in different types of rolling mills. Moreover they are tradable products with a market existing between different steel companies. Hence there is a possibility to procure additional slabs in order to increase production capacity. The finished products which are produced through different rolling processes are classified according to the shape of their cross-sections as long products and flat products. The long products being produced in our reference production structure are sectional steel products and steel beams with different geometry and application areas. The flat products produced by two different hot and one cold rolling mill are consequently subdivided into a hot-rolled and a cold-rolled fraction. The hot wide strip as a hot-rolled finished product marks the input for the cold rolling mill and the spiral tube welding plant. Some of the cold strip gets further refinement in the metallic and non-metallic coating plants to obtain corrosion-resistant and surface protected steel strips and sheets.

As a result of the analysis of the reference production structure we have found the following conclusions:

- The produced slabs are make-to-order semi-finished products in terms of steel grade and dimensions.
- There are multiple finished products produced from slabs, themselves constituting raw material for different industries (car industry, building industry, etc.).
- The processing times of orders at certain resources depend on specific order characteristics (steel grade and dimensions) and are known (as an average) before start of production.
- The company cannot entirely set prices autonomously because of competition.

The problem arising for the company is which orders to accept and which orders to reject in order to maximize profit or contribution margin respectively. Therefore we see a practical need to develop a decision support system with the purpose of improving mid-term sales planning and primarily short-term sales planning in advanced planning concepts [7]. This decision support system ought to improve sales planning thereby explicitly considering interdependencies of different orders in terms of production capacity incorporating the (stochastic) demand to come and the contribution margin to reach with the accepted orders.

Due to the parallelism of the described setting and the setting in the "classical" revenue management approach, we are interested in whether the methods of classical revenue management approaches are applicable to the introduced decision making process.

2 Analysis of the Applicability of Revenue Management

Harris and Pinder [2], Klein [3], McGill and van Ryzin [5], Tscheulin and Lindenmeier [9], and Weatherford and Bodily [11] have identified several common characteristics of environments revenue management methods can be successfully applied to.

These characteristics can be subdivided into characteristics concerning the capacity and characteristics concerning the demand. We will give a brief introduction to these characteristics and will discuss if our problem satisfies these characteristics. Based on this we will discuss whether existing revenue management concepts are applicable to our problem.

2.1 Characteristics Concerning the Capacity

Characteristics that have been identified concerning the capacity in service operation environments are the fixed amount available, the high share of fixed costs and the perishability of capacity.

Fixed capacity
In all successful application areas of revenue management it is almost impossible to adjust the prevalent capacity to demand because of significant costs and/or a significant time lag to do so. This fixed capacity is often accompanied by stochastic demand, which makes balancing availability of products and fulfillment of demand difficult. Therefore it is important to optimally utilize this fixed capacity.

In the described problem setting we do obtain fixed capacity, too. But in addition to the hosted capacity we have the possibility to buy slabs in order to extend the capacity of the steel mill. Weatherford and Bodily [11, p. 832] argue that the presence of fixed capacity is not necessary to practice revenue management but variable capacity is significantly more complex to manage in this context. As an example for not entirely fixed capacity they mention the hotel industry where revenue management has been successfully implemented in practice. In this industry the point customers check out is stochastic therefore the capacity to be rented must be forecasted.

High fixed costs
In all successful applications of revenue management in the service industry there are relatively low variable costs for production, which allow a wide range of prices over which selling the service is better than letting the capacity be idle. In general this leads to high contribution margin for additional orders. The significant costs in this applications are fixed costs (e.g. the purchase of a car for a car rental company).

In the problem setting described we do obtain significant variable costs depending on the steel grade. This phenomena is due to the alloying of steel in accordance with the customer needs as prices for and ratios of alloying elements differ. That means that maximizing the expected revenue as a central objective of revenue management must be replaced by maximizing the expected contribution margin. Nevertheless revenue management in general seems to be practicable. Although the rewards of an effective revenue management are higher when high fixed costs are combined with high contribution margins [11].

Perishability of capacity
An additional characteristic of settings in which revenue management is established is the perishability of capacity. There is a certain date at which the product or service becomes available and after which it is either no longer available (typically for the service industry) or it depreciates (e.g. fashion goods). The product or service cannot be stored, unless accepting significant costs or the aging of the product. If the storage of the product is possible than one has to consider inventory control strategies in addition.

It is of course possible to store steel products but the make-to-order characteristic of the presented production structure does not permit a considerable production in advance. As a result manufacturing capacity specific to customer orders is perishable, too.

2.2 Characteristics Concerning the Demand

The characteristics that have been identified concerning the demand in service operation environments are the possibility of segmenting customers, the stochastic demand and the possibility of advance sales/bookings of capacity.

Possibility of segmenting customers
Revenue management is most effective when demand can be segmented and price sensitivity varies between market segments [2]. The variable or characteristic used to segment the market must truly differentiate the resulting products (fencing mechanism). The mechanisms generally used to segment customers in revenue management situations are the time of purchase and the quantity discounting practice [11].

In the described problem setting the segmentation of customers is not critical, because of the different and distinctive products. Nevertheless production of all relevant products employs the same resources during production and thus segments the capacity itself.

Stochastic demand
Fluctuations in demand create problems for efficient capacity management. In this situation revenue management is able to improve decisions of which orders to accept/reject [2].

The steel price determination in European Community has been investigated by Richardson [6]. He identifies three distribution channels for steel products: direct contract market (e.g. car industry), steel stockholder and a spot market. While the contract market accounts for only a small share of the total sales of each relevant product (about a quarter in the UK) and the stockholder market contracts are short for a large chunk of the market, the spot market price reflects more accurately the process of pricing in the market [6]. In times of high demand, spot prices move above contract prices; when demand is weak, the relationship reverses. As a result of our research and of the research of Richardson we notice a volatile market with respect to pricing of the different products and demand resulting.

Possibility of advance sales/bookings
The possibility of advance sales or bookings respectively is a key precondition for effectively applying revenue management in practice. This leads to one central issue of revenue management: How much capacity to reserve for late-arriving high-margin demand.

This is one of the main decisions to make in the described problem setting, too. But the identification of the most profitable orders is less straight forward, because of the multistage problem mentioned and the order-specific capacity utilization.

2.3 Conclusions

The application of revenue management concepts to the described make-to-order production system seems to be possible though more complex as compared to the service industry. The complexity is due to the explicit consideration of variable costs. Since variable costs are significant in the described setting an appropriate objective of a decision support system is the maximization of the (expected) contribution margin. To determine the contribution margin of potential orders the availability of a sophisticated cost accounting system is necessary. Furthermore the capacity utilization in the described problem setting is different from the "classical" areas of revenue management application. While in "classical" revenue management approaches the capacity utilization is always one unit, in the illustrated context capacity utilization depends on the order characteristics and therefore is a random parameter itself. Another challenge is the necessary forecasting of demand to come in an appropriate manner i.e. concerning different products, steel grade and dimensions. Further research on this topic will show if it is possible to aggregate the demand in order to allow a practical forecasting with respect to frame a sufficient decision support.

3 Mathematical Formulation

Our focus in this contribution is on effectively allocating capacity to a stochastic demand. Since no-shows and cancellations do not occur in our production environment we are not interested in overbooking strategies for the decision support system.

Our problem is a network problem where we are interested in applying existent revenue management methods of seat inventory control. In general we define a similar problem definition as Bertsimas and Popescu [1]. We host a network with e edges, the resources, which are used to produce p products. The initial resource capacity is given by a vector $\mathbf{N} = (N_1, \ldots, N_e)$ and the vector $\mathbf{n}$ denotes capacity left. The network is described by an $e \times p$ matrix $\mathbf{A}$, with entries a_{ij} the resource utilization of product j on resource i. In this first approach we do not consider resource utilization as a random parameter depending on the order characteristics. The column vector $\mathbf{A}^j$ indicates the capacity utilization of one product j at the resources. The p-vector $\mathbf{M} = (M_1, \ldots, M_p)$ denotes the contribution margin M_j gaining from selling a product j. The described problem is a problem with an infinite production time horizon that we decompose in intervals of constant time length with an appropriate interval of one week. Therefore we obtain a finite booking horizon problem lasting T periods in advance to production. The time line is furthermore discretized, so as to allow at most one request per time period. Time is counting backwards, i.e. $t = T$ is the beginning of our booking horizon and $t = 0$ is the end of the reservation period. The random vector of cumulative demand to come at time t is denoted by $\tilde{\mathbf{D}}^t$, that is, $\tilde{D}_j^t$ is a random variable representing the number of class j requests to come from time t until the end of the reservation period. The expected demand to come is denoted by the vector $\mathbf{D}^t = E[\tilde{\mathbf{D}}^t]$.

The decision to accept or reject an incoming order is a function of the current network configuration $\mathbf{n}$, the time-to-go t, the order specific contribution margin M_j and further information from demand forecasts. If we accept an order the state of our network becomes $(\mathbf{n}\text{-}\mathbf{A}^j, t\text{-}1)$, if we reject the order, only the time component of the state is changed into $t\text{-}1$.

The optimal policy for our network problem is provided by a stochastic dynamic programming model which can be found in Bertsimas and Popescu [1] and Talluri and van Ryzin [8]. It is optimal to accept an order when the corresponding contribution margin exceeds the opportunity cost of accepting the order which is calculated by the dynamic programming model. We are interested in methods that are applicable to our problem environment and therefore analyze integer and linear programming models as the deterministic analogues of the stochastic dynamic programming model. These models use only the expected demand information and are usually much easier to solve.

The integer programming model computes the optimal allocation $\mathbf{y}^*$ of available capacity $\mathbf{n}$ to the expected demand $\mathbf{D}^t$, by maximizing the total contribution margin subject to capacity and demand constraints.

For all $\mathbf{n} \le \mathbf{N}$ and $t \le T$, we have ($\mathbf{M}^T$ denotes the transpose of vector $\mathbf{M}$)

$$\begin{aligned} \text{IP}(\mathbf{n}, \mathbf{D}^t) = \max\ & \mathbf{M}^T \mathbf{y} \\ \text{s.t.}\ & \mathbf{A}\,\mathbf{y} \le \mathbf{n} \\ & \mathbf{y} \le \mathbf{D}^t \\ & \mathbf{y} \ge \mathbf{0} \text{ and integer} \end{aligned}$$

The linear programming relaxation LP $(\mathbf{n}, \mathbf{D}^t)$ of this problem computes the fractional solution to our problem by relaxing the integrality constraints. The dual problem to the LP problem is given by

$$\begin{aligned} \text{LPD}(\mathbf{n}, \mathbf{D}^t) = \min\ & \mathbf{n}^T \mathbf{v} + (\mathbf{D}^t)^T \mathbf{u} \\ \text{s.t.}\ & \mathbf{A}^T \mathbf{v} + \mathbf{u} \ge \mathbf{M} \\ & \mathbf{u}, \mathbf{v} \ge \mathbf{0} \end{aligned}$$

Where $\mathbf{v}$ determines the vector of shadow prices corresponding to the resources and $\mathbf{u}$ determines the vector of shadow prices corresponding to the demand.

The corresponding approximations of the opportunity cost OC of an order j are

$$\text{OC}_j^{\text{IP}}(\mathbf{n}, t) = \text{IP}(\mathbf{n}, \mathbf{D}^{t-1}) - \text{IP}(\mathbf{n} - \mathbf{A}^j, \mathbf{D}^{t-1})$$

$$\text{OC}_j^{\text{LP}}(\mathbf{n}, t) = \text{LP}(\mathbf{n}, \mathbf{D}^{t-1}) - \text{LP}(\mathbf{n} - \mathbf{A}^j, \mathbf{D}^{t-1})$$

$$\text{OC}_j^{\text{LPD}}(\mathbf{n}, t) = (\mathbf{v}^{(\mathbf{n},t)})^T\, \mathbf{A}^j$$

Where the last one is the bid-price control which is a popular method in network revenue management [1], [8].

Example

Consider a simple network with three edges and four nodes. The edges represents a continuous caster and subsequently two hot rolling mills, supplied with slabs by the continuous caster. We are selling only two products: hot wide strip (p_1) and hot rolled heavy plate (p_2) with a contribution margin of $M_1 = 100$ and $M_2 = 90$, respectively. The capacity left at our resources $\mathbf{n}$ and the resource utilization matrix $\mathbf{A}$ are given by

$$\mathbf{n} = \begin{pmatrix} 4 \\ 5 \\ 6 \end{pmatrix} \qquad \mathbf{A} = \begin{pmatrix} 4 & 3 \\ 2 & 0 \\ 0 & 1 \end{pmatrix}$$

Suppose we are at $t = 2$ and the expected demand for hot wide strip to come is denoted by $D_1^2 = 3$ and for the hot rolled heavy plate by $D_2^2 = 3$. Obviously it is optimal to accept no order for the heavy plate and one order for the hot wide strip due to the capacity restriction at the caster. The optimal contribution margin to achieve is 100.
Let us assume that at $t = 2$ one order for heavy plate occurs and at $t = 1$ another one for hot wide strip. The corresponding approximations of the opportunity cost OC of this order pattern at $t = 2$ are

$$\mathrm{OC}_2^{\mathrm{IP}}((4,5,6)^{\mathrm{T}},2) = \mathrm{IP}((4,5,6)^{\mathrm{T}},\mathbf{D}^1) - \mathrm{IP}((1,5,5)^{\mathrm{T}},\mathbf{D}^1) = 100 - 0 = 100$$

$$\mathrm{OC}_2^{\mathrm{LP}}((4,5,6)^{\mathrm{T}},2) = \mathrm{LP}((4,5,6)^{\mathrm{T}},\mathbf{D}^1) - \mathrm{LP}((1,5,5)^{\mathrm{T}},\mathbf{D}^1) = 120 - 30 = 90$$

$$\mathrm{OC}_2^{\mathrm{LPD}}((4,5,6)^{\mathrm{T}},2) = 30 \cdot 3 + 0 \cdot 0 + 0 \cdot 1 = 90$$

The LP Approximation and the bid-price control will accept the order and the IP approximation will reject the order, which is the optimal strategy. At $t = 1$ the IP approximation calculates the same opportunity cost and the order will be accepted. Therefore only the IP approximation finds the optimal solution in the described example.

4 Perspective

The presented practical problem has to be further investigated. In order to verify the mathematical formulation and results real world stochastic demand data has to be incorporated and the benefit of the implementation has to be pointed out. Moreover an extended model explicitly considering the resource utilization as a random parameter depending on the order characteristics has to be formulated.

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