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A risk management-based approach for inventory planning of engineering-to-order production

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ABSTRACT

Engineering-to-order has steadily increased shares of total production. By its own nature, the order specific products often come without pre-defined bills-of-materials which undermines the starting point of prevailing inventory planning methods. Manufacturers often have to confront with difficult, if not impossible, choices for meeting the highly responsive service level without investing in costly inventory, particularly for long lead time items.

In this paper, a novel inventory planning approach is presented. Based on predetermined inventory budget, customer responsiveness can be optimized by considering risks associated with supply chain uncertainty, component commonality, substitution possibility, market intelligence, and other salient factors.

1. Introduction

Engineering-to-order (ETO) has emerged with growing domination in production systems, particularly for delivering customized products. In order to cope with deep order penetration points (OPP), ETO companies have to find better ways to integrate engineering, manufacturing and supplier capacities [1]. However, often a few unique long-lead time parts become bottlenecks to meet the customers' expected delivery dates. Unless, customers accept renegotiation, ETO companies have to prepare material in advance to buffer such risks. However, the bill-of-material (BOM) can only be finalized in the later stages of the order fulfilment life cycle, both enterprise resource planning (ERP) and just-in-time (JIT) systems lack the key input to start the planning process [1]. Hence, inventory planning has to make a number of important but unrealistic assumptions and part unavailability becomes unavoidable. Consequently, the delivery can be haphazard, if not unpredictable, for ETO supply chains [1].

Furthermore, high volatility of demand and supply in today's turbulent manufacturing industry further complicate the difficulties of inventory planning. Companies often resort to using additional inventory to achieve target customer satisfaction level. The cost of doing so may quickly drain the company's financial resources. Thus, a viable inventory planning approach requires conscientious inventory budget control to decide the right quantity and right type of stocking points in order to provide the best customer satisfaction while avoiding excessive inventory.

To this end, this paper reports the results of a research project that extends the conventional supply chain approach by taking into account the insights of product design, such as commonality, substitution possibility and others, in conjunction with delivery risks in supply and demand in economic terms. For instances, ETO companies may make conscientious business decision to commit some long lead time common modules before order arrival to reduce supplier lead time uncertainty.

The target is that ETO companies can align the marketing planning with the financial planning to meet the corporate strategic goals. That is, the objective of this paper is to establish a framework for a given inventory budget to decide inventory placement to maximize customer responsiveness in ETO production scenarios where bill of materials can't be committed in normal production planning stage.

2. Literature review

A detailed literature review on ETO supply chain management, [1] has been done to include underpinning definition of ETO definition, operational strategies and the relationships between supply chain structures, and manufacturing responsiveness.

However, there are few papers on inventory management for ETO production [2], several research projects on make-to-order (MTO) inventory management have been reported. In particular, their approaches in determining which items to store and how much to store of each for finished goods (FG) distribution can be applicable in this project. Cases of inventory management under substitution are covered most widely for the make-to-stock (MTS) retail sector where substitution is customer-driven [3,4]. The two prevailing substitution models in the retail literature are deterministic, i.e. a given fraction of demand is willing to swap, and stochastic, i.e. each customer experiencing stock out decides whether or not to accept a substitute. In contrast to the single-echelon, FG-only discussion of retailers, the presented model can consider all of the firm's production stages simultaneously.

Substitution in a company-driven planning process, is discussed in the area of engineering changes [5] and their integration

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in ERP [6], and have also been included in the discussion of demand shaping literature [7]. But company-driven substitution is directed at managing the change itself, not taking advantage of the substitutability in the inventory planning process of the firm's entire inventory.

Thus, there is a need for a framework to objectively plan inventory in a multi-echelon production system with company-driven substitution in the ETO manufacturing industry considering budget limitations. Customer satisfaction levels are increased by avoiding stock outs due to unbalanced inventory investment while preventing excessive inventory levels, which can easily occur in the ETO business where high demand uncertainty dominates.

The presented inventory planning model is buttressed by a number of initiatives ETO companies pursue in the areas of product and process design, and sales and operations integration [8]. The product designs are generally modularized, and parts and process steps largely standardized facilitating demand risk pooling, configuration and substitution. The manufacturing processes benefit from agile manufacturing technology [9] and postponement facilitating shop-floor routing and response to customized specifications. The order process is supported by configurators, available-to-promise, and demand shaping enabling faster negotiations with customers based on visibility of the manufacturing system's status.

3. Modelling framework

The approach taken in this paper is based on the assumption that with a given inventory budget, the probability of meeting the delivery of an ETO product increases by considering the contribution of each component in terms of its own merit to hedge against uncertainty risks.

Extending the inventory planning model presented in [10], an analytical model framework is built by calculating the items' contribution toward reducing the risk of missing the delivery due date. The model includes consideration of item cost, lead time, supplier reliability, and an item's capability to act as a substitute. The main parameter to represent substitutability is stored in a substitution matrix, containing information on the ability of an item to substitute items that are out of stock.

3.1. Assumptions and notations

The marketing plan for FG i, D_i is assumed to be a multivariate normal distribution with mean vector $\mu = [E(D_i)]$ for $i = 1, 2, \ldots, I$ and covariance matrix $\sum = [\mathrm{cov}(D_i, D_j)]$ for $i, j = 1, 2, \ldots, I$. The unit price for FGs is captured in the row vector $\mathbf{p} = [p_i]^T$, $i = 1, \ldots, I$. To simplify the discussion in this paper, two echelons, FG and raw material (RM), are considered. The amount of each RM item k, $k = 1, 2, \ldots, K$, consumed to produce one unit of FG i is captured in the usage matrix $\mathbf{U} = [u_{ki}]$ for $k = 1, \ldots, K$, $i = 1, \ldots, I$. Matrix $\mathbf{U}$ can be interpreted as the collection of BOMs and usage in case of substitutions.

Unit cost and replenishment lead time for item k are represented by vectors $\mathbf{c} = [c_k]$ and $\mathbf{r} = [r_k]$ for item k, $k = 1, \ldots, K$, respectively.

The inventory budget is denoted IB. The operators '.*', './', and '.^' are the element-wise multiplication, division, and raise to the power of a real number applied to a vector, respectively.

By assuming that the ETO manufacturing system is highly flexible and responsive [11], capacity and setup cost are negligible. Then, in conjunction with the modularized, substitution-supporting product design, the model presented here can focus on the inventory planning process of matching demand and supply for each inventory stocking point, without considering each particular manufacturing process. The value of inventory for each item k is represented by $v = [v_k]$, $k = 1, \ldots, K$. Its elements will be determined in the following sections.

3.2. Inventory budget allocation based on the value of inventory

A previously developed model [10] determines target inventory levels by allocating limited inventory budget based on the weight of an item in inventory. This weight is determined by the value of each item as its being inventory on hand, in particular, reduces the risk of stock-out under demand uncertainty, decouples manufacturing complexity, and buffers against lead time delays.

The value of inventory is based on a marketing plan, BOM data, and the given inventory budget. FG sales plans including any risk pooling effects from the production system and substitution possibilities, usage data from the BOM and lead time determine the required amount of inventory to ensure production flow. This inventory pipeline is transcribed into monetary units by multiplication with unit costs. The actual inventory level is then calculated so that it meets the inventory budget target. This approach ensures that in case of excessive demand, the current replenishment policy does not undermine service levels, while the inventory budget constraint is met.

First, recognize that in prevailing inventory models target inventory levels, as well as replenishment quantities, can be described as the sum of expected demand, and a multiple of demand standard deviation [12]. The multiplicative factor z, is a real number, $z \in R$, and derived from holding cost, stock out cost and resulting customer satisfaction targets, while inventory budget is observed.

In this paper, the multiplicative factor z, is adjusted to meet a target inventory budget, while customer satisfaction targets are observed. This marks the paradigm shift from treating inventory as a dependable variable to independent decision parameter.

The uncertain part of demand for an item k, and hence the risk of stock out, may differ significantly between items depending on how common or unique an item is, and which production step differentiates the subassemblies. To ensure production flow the hedging against the probability of particularly high demand should be the same for all items on the same echelon, i.e. the z value should be the same, and increasing on lower echelons to avoid stock out during replenishment of higher echelons.

In addition to considering the BOM routing and any risk pooling capabilities from component commonality, demand from substitution for an item k is considered, too.

3.3. Substitution modelling

In contrast to the substitution at FG level reported in MTS retail distribution, substitution in the case of ETO is at component or RM level. On upstream levels, often more than one item can substitute for out of stock items. Thus, several attempts to substitute for out-of-stock items shall be allowed. Substitution shall only occur when the original item to be used is out of stock. And only if all possible substitute components or materials are out-of-stock, the order is lost.

The substitution matrix $\mathbf{S} = [s_{ki}]$, $i = 1, \ldots, I$, $k = 1, \ldots, K$ with elements

$$s_{ki} = \begin{cases} 0 & \text{for unemployable parts} \\ y_{ki} & \text{for substituion parts} \\ 1 & \text{for standard parts} \end{cases}$$

where y_{ki} is the share of past orders for which substitution would have been possible. It can be defined by the company with consideration of technical feasibility, additional cost and utility loss. Substitution tends to incur higher cost for substituted items, which has to be smaller than the profit margin. Any potential loss of utility for the customer is assumed to be estimable by the company and can be incorporated in the substitution matrix.

3.4. Inventory budget allocation for engineering-to-order production

The model first determines the value of each inventory item to hedge against uncertainty risk including substitution considerations,