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Yield and allocation management in a continuous make-to-stock system with demand upgrade substitution

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A B S T R A C T

Yield management is crucial for high-tech industries to reduce over-production. However, it is very challenging for a manufacturer to make a yield decision under the circumstance of uncertain demand and stochastic product quality. For example, in semiconductor manufacturing industry, products are produced in batches within certain production cycle time. Even if the same raw material is put into the production system, the product qualities (measured by performance) usually are not identical due to random yield in the manufacturing process. Since products have overlapped performance specifications, products of the same batch are classified into different classes according to their qualities at the allocation stage. Products with higher performance can substitute for demand for products with lower performance. This type of production and allocation system can be specified as a make-to-stock system with single material, multi-products, multi-periods, upward demand substitution under random yield and uncertain demands. In order to maximize profit, the manufacturer needs to decide on the optimal input material quantity and the optimal allocation policy. The problem is formulated as a stochastic dynamic programming model. Because manufacturer's profit is affected by the allocation policies, ATP-r allocation policy is proposed to help manufacturer make real time allocation decisions. A numerical experiment shows that ATP-r allocation policy performs better than the traditional Myopic allocation policy. To reduce the computation burden involved in ATP-r allocation policy, we further propose a simplified algorithm and our experimental studies provide proof of the effectiveness of the proposed simple algorithm.

1. Introduction

The production processes of a high-tech product are very complex and the yield rate of products with certain performances is often stochastic (Mart et al., 2013). For example, over 500 processes are taken to manufacture semiconductor chips, which begin with drawing ingots that are made of either silicon or gallium arsenide. Each ingot resulted from the drawing process is sliced into wafers with a specific size. After the above two steps, each wafer is polished and cut down into individual chips. Depending on the complexity of circuits involved, each wafer may yield between 10 and 100,000 chips. Since the production quality sensitively relies on production conditions, the electrical performances of chips are dramatically distinct (Kothari, 1984). The individual chips then are tested against one or more dimensions and classified into different product specifications. In other words, the yield rate of each semiconductor product is stochastic, so it is a challenge to make an optimal production decision.

When products have overlapped performance specifications, a product originally targeted to satisfy one type of demand may be used to satisfy other types of demands if it conforms to their specifications. In semiconductor industry, chips with higher performance specification can substitute for demand for chips with lower performance specification (Bassok and Akella, 1999). Hence, the percentage of acceptable units and the relative proportions of products of different performance specifications in each production lot could be different from batch to batch. Decisions are further complicated by the fact that semiconductor chips have short life cycles (typically one or two years), a semiconductor chip may lose 60% of its value within the first half year of its life cycle. Hence, the challenges faced by the semiconductor manufacturer can be characterized by random periodic demand, long production lead time, expensive setup cost and high obsolescence cost due to rapid technology improvement. All these indicate that effective

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yield management is critical for semiconductor manufacturers to mitigate risks.

Our study is motivated by the practice in semiconductor manufacturing industry, where products are produced in batches. When one batch of products is produced, the manufacturer can use them to satisfy demands immediately (Mor and Mosheiov, 2014). Since the down grade demands can be satisfied by the upgrade products, the manufacturer also needs to determine the allocation policy. Hence, both the production input quantity and the allocation policy are important for the manufacturer to maximize its profit.

Two streams of research are related to our study. The first stream of related literature focuses on joint inventory and allocation decisions with demand substitution. Pasternack and Drezner (1991) consider a stochastic inventory model for two substitutable products in a single period. They show that the expected profit function is concave and optimal stocking levels for the two products exist. Other researchers study the problem under more general settings. For example, Stavrulaki (2011) considers inventory policy for two substitutable products with inventory dependent demands. Rao et al. (2004) consider a single period multi-products inventory problem with uncertain demand and one-way downward substitution. Both papers provide heuristic solutions. Bassok and Akella (1999) consider a single period multi-products inventory models with full downward substitution. Since the model is too complex to derive closed form solution, they present a greedy allocation algorithm and show the benefits of substitution in a case study with two demand structure. Frank et al. (2003) study a periodic review inventory model with two substitutable products. Xu et al. (2011) study optimal control of inventory replenishment and demand substitution for two mutually substitutable products in multi-periods. They assume demands for both products follow a non-stationary Poisson process and consider supplier-driven and customer-driven schemes in substitution. Both Frank et al. (2003) and Xu et al. (2011) provide simple policy to solve the allocation problems in their models. Shumsky and Zhang (2009) examine a multi-periods inventory allocation model with one-step substitution and propose an optimal allocation policy. They also propose an approximate solution for the optimal allocation quantity in each period. Yu et al. (2013) extends the work of Shumsky and Zhang (2009) to consider full upgrading substitution structure. Tan and Karabati (2013) study an inventory control problem of multi-products with fixed review period in multi-periods. They present a computational method to find the optimal order-up-to inventory levels. Our paper differs from this stream of research in two important aspects. First, we consider production yield in our model. Second, the focus of our study is to find the optimal material input quantity and optimal allocation policy for substitutable demands.

Random yield in production is a common problem in practice (Sayin et al., 2014). There are papers that focus on specific industries with random yield. Han et al. (2012) study yield management in semiconductor manufacturing. As'ad and Demirli (2010) consider yield management in steel rolling manufacturing. Kazemi Zanjani et al. (2010) study production planning in sawmill manufacturing with random yield. Another stream of literature that addresses joint yield and allocation problems is closely related to our study. Joint yield and allocation problems in a single period model are studied by Gerchak et al. (1996), Hsu and Bassok (1999) and Duenyas and Tsai (2000). Gerchak et al. (1996) focus on the structure properties of the optimal policy. Hsu and Bassok (1999) consider a single period, multi-products model with downward substitution. They present three different methods to solve the problem and propose a greedy heuristics to find the optimal decisions. Duenyas and Tsai (2000) characterize the structure of the optimal decisions in the case of two products and propose a Myopic based algorithm to find optimal decisions when there are multiple (more than two) products. Many researchers study joint yield and allocation decisions in a multi-periods model with different settings. Bitran and Dasu (1992) consider the case when the product demands are deterministic, but the production quantity is stochastic due to random yield. The objective is to maximize expected profit. Bitran and Gilbert (1994) study the same problem and incorporate shortage cost in the analysis with the objective of minimizing cost. Bitran and Leong (1992) take into account the service constraints in the model. Gallego et al. (2006) consider lead time constraints in the model. The above papers assume the demands in each period are realized either at the beginning or at the end of each period. However, in our paper we assume the demands are realized continuously over time in each period.

Our model can be characterized as single input material, multi-products, multi-periods with random yield and substitutable stochastic demands. The problem is formulated as a stochastic dynamic programming model. The structure of the model is complicated. When the optimal policy is difficult to solve, researchers often develop algorithm to simplify the solution procedure. For example, the heuristic method is adopted by Bitran and Dasu (1992), and the Myopic based algorithm is adopted by Bitran and Leong (1992), Gallego et al. (2006) and Bitran and Gilbert (1994). In this paper, we also propose a simple algorithm based on ATP-r allocation policy to simplify our solution procedure.

The paper is organized as follows. In Section 2 we formulate the manufacturer's problem as a dynamic programming model and prove the existence of the optimal solution. In Section 3, we propose an ATP-r allocation policy to find the optimal decisions that maximize the manufacturer's total expected profit and compare its performance to the traditional allocation policies. In Section 4, we perform a computational study to test the accuracy and effectiveness of the ATP-r policy that we propose. In the concluding section, we summarize our findings and discuss some directions for future research.

2. Modeling

We assume that a single input material yields n types of products with different quality performances. There are n corresponding classes of demands. The demands begin to realize after the first batch of products are produced. The demand horizon consists of T periods. The demand for product i at period t is denoted as D_i^t, which is stochastic and follows a random distribution and the probability distribution function (p.d.f.) is $f_i(d_i^t)$. The manufacturer puts Q quantity of the material into the system, and then n types of products are produced in each period. The yield rates of products are random. Let $\mu^t = \{\mu_1^t, \mu_2^t, \ldots, \mu_n^t\}$ denote the yield rates vector for period t, where the subscript stands for product type. We assume that the demands of different products across different periods are independent. The sequences of the production and allocation events are depicted in Fig. 1.

Hence, the system is characterized by 1 single input material, n classes of products and T production–allocation periods. We call it $1 \times n \times T$ system in this paper. Let p_i denote the price of product i. Let v_i denote the shortage cost of product i. That is the

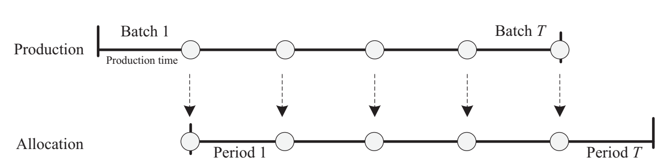

Fig. 1. Production and allocation stages.