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Integrated maintenance and production planning with endogenous uncertain yield

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ABSTRACT

The relationships among production planning, maintenance decisions and machine yield are crucial in a number of manufacturing environments such as the semi-conductor industry. This paper presents an integrated maintenance and production decision making framework with stochastically proportional endogenous yield rate and random demand. Finding the solution for this two-stage nonlinear stochastic program with endogenous uncertainty is not straightforward, and has not been considered previously. An augmented probability simulation based method is utilized to solve for the proposed decision model. We demonstrate the use of the proposed approach by conducting a numerical study and sensitivity analysis. We discuss the trade-offs involved among the yield, and simultaneous decisions of production planning and maintenance.

1. Introduction

In many production environments, diminishing machine conditions and high production rates can adversely affect the product quality. The machine yield can be jointly impacted by both the production quantity and maintenance decisions. This impact is especially important where the maintenance cycles are short compared to production cycles. Increasing wear in machine shop tool bits may cause defects over time which would result with faulty products. For instance, as part of the etch operation in semiconductor water fabrication, chemicals are used to strip materials from the surface of the silicon wafers. The contamination of the inner chambers of the etch equipment rapidly increases with higher production levels. This results in defective products and in lower machine yield. It creates unique challenges in multi-stage maintenance and production planning, and can affect the inventory and outsourcing costs. Proper understanding of such relationships has the potential to result in significant savings in operational costs and improved efficiency for the overall production system. Therefore, production and maintenance decisions as well as their impact on uncertain yield need to be considered simultaneously. The complexity of these relationships makes the integrated system-based approaches crucial. This paper introduces a novel integrated decision making framework to investigate the trade-offs among production planning and maintenance decisions under random demand and endogenous (decision dependent) yield.

Decision makers need to adapt to dynamic behavior of the production environments because of the uncertainty involved with the markets. This motivates models that allow integrated decision making under uncertainty while addressing a high number of decision alternatives. Integrated and simultaneous production and maintenance models are shown to outperform traditional sequential approaches [4,41]. Within such integrated decision making frameworks, the machine yield can be a function of maintenance and/or production. However, most of the existing models can deal with only a relatively small number of decision alternatives. The main challenge is the computational complexity; especially for high levels of decision alternatives and when uncertainty is considered. Stochastic programming methods can be employed to deal with many alternatives for the decision variables under long term uncertainty [6]. Mula et al. [31] point out the frequent use of stochastic programming models in their survey of production planning models. However, the dependence of a random quantity on previous decisions require models that consider endogenous randomness. Particularly, the probability distribution of the random variable may depend on the previous decisions. The solution of such models is not straightforward, therefore mostly models with discrete random variables and small number of scenarios are considered. Recent computational and methodogical advances in simulation based optimization algorithms such as those in [11] can be utilized to address problems with continuous uncertainty which may depend on decisions with higher number of alternatives.

This paper contributes to the literature in two main ways. First, the integrated model lets the decision maker evaluate the trade-offs involved among production quantity, maintenance, outsourcing, salvaging decisions and uncertain endogenous machine yield in a two-stage setting with random demand. We utilize a stochastically proportional yield based approach in which yield rate is modeled via a Truncated Nor-

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mal distribution. This lets the decision maker to explicitly model variance independently from the batch size. Our approach is general enough to accommodate any discrete or continuous probability distribution as well as any form of objective function. In addition, our stochastic program is flexible enough to accommodate more decision alternatives than the existing literature such as [40] that can deal with relatively small number (up to 20) of maximum production quantities. Second, this is the first application of augmented probability simulation (APS) based stochastic programming solution approach of Ekin et al. [11] to solve a production planning and maintenance problem. Finding the solution for the proposed model with endogenous uncertainty is not straightforward and had not been considered previously. We solve the proposed two-stage nonlinear stochastic program using an augmented probability simulation based optimization method. This is one of the first applications of augmented probability simulation based optimization method, the first to solve a stochastic optimization model that includes direct endogenous randomness or nonlinearity.

The paper is organized as follows. Section 2 presents the relevant literature review. Section 3 presents the modeling framework and details about modeling yield. Section 4 describes the stochastic optimization method used to solve the proposed model. Section 5 provides a numerical illustration with a large numerical study and sensitivity analysis, and presents a discussion of the results. Section 6 concludes with a summary of findings and directions for future work.

2. Literature review

This section provides a literature review that is relevant to the proposed model and solution approach from three perspectives. First, the literature of modeling yield and integrated production models is presented. This is followed by a brief overview of endogenous stochastic models and simulation based stochastic programming approaches.

2.1. Modeling yield and integrated models

In a production environment, yield is generally defined as the percentage of working products that emerge from the process. Uncertainty of yield is extensively studied in production and maintenance problems. These variable yield models can be classified depending on the uncertainty structure and whether process condition is under decision maker's control or not. Yano and Lee [48] present a comprehensive review of production models with uncertain yield. The simplest yield model assumes that each produced unit follows a Bernoulli process, and models the total number of working products using Binomial distribution. The decision maker only needs to specify the probability of each item working properly and assume the independence of products in a batch. This can be appropriate for systems that are in statistical process control for long durations. However, such models as in [40] do not explicitly model variance and are dependent on the batch size. In contrast, stochastically proportional yield models can specify both the mean and variance of the yield rate, independently from the batch size. Hence, they are more generally applicable especially when the variation of the batch size from production run to production run tends to be small. In most cases, the fraction of good units is between zero and one. Therefore, Truncated Normal distribution [26] and Beta distribution [41] are natural candidates when both the mean and variance are of interest.

Most of these models assume that the uncertainty of the yield is beyond the control of decision maker, and do not explicitly link the effect of the equipment condition to the yield. The limited literature that models yield as a function of previous decisions mainly focus on dependence from one perspective. A number of models consider the adverse impact of increasing production on yield, for instance see [29] and [21]. Sana [38] models the total number of defective items in and out-of control environment using a function of production amount and run-time. The sole impact of maintenance on yield is generally studied with a focus on time of the repair, see the review of Wang [47].

The decision models that consider both maintenance and production mainly focus on a single dimension, the effects of failures on production and inventory decisions [41]. However, increasing complexities in production systems make the system based approaches more crucial and an area of interest from researchers [18]. In terms of such combined models of production planning and maintenance with endogenous yield, the literature is relatively recent and limited. [42] examine the joint determination of production and maintenance schedules in a single stage multi-product setting under deterministic demand. They model the probability of transition of machine states as a function of deterministic yield within a Markov decision process. Sloan [41] extends this by incorporating imperfect maintenance and the uncertain time between decisions. Yield based simultaneous model is shown to outperform yield based traditional sequential approach. Batun and Maillart [4] reassess these models and present further evidence for the advantages of simultaneous maintenance and production planning. However, none of these models consider the impact on inventory or backholding costs. Sloan [40] presents an integrated decision model to determine the production quantity and maintenance schedule that minimizes the sum of expected production, backlog, holding costs while dealing with a discrete stochastic demand. The product yield has a binomial distribution that depends on the equipment condition and previous decisions. Simultaneous maintenance and production decision making is shown to be more cost-effective compared to the traditional sequential approaches. These Markov decision process based models are utilized for a small number of decision alternatives. Thus, the dependence of yield is considered only for a limited number of actions.

In relevant work, Kazaz and Sloan [28] propose joint maintenance and production schedules for additional problems that do not meet the conditions of Sloan [41]. Aramon Bajestani et al. [3] address the problem of integrated maintenance and production scheduling in a multi-machine production environment over multiple periods. Hong et al. [20] model the dependent stochastic degradation of components and formulate the maintenance decision problem using the minimum expected cost and the stochastic dominance rules. Peng and van Houtum [35] consider a joint optimization model to determine the production and condition based maintenance policy while using a continuous time and state degradation process. Sana [39] uses various product reliability parameters to account for different production and maintenance environments and initial machine conditions.

2.2. Two-stage endogenous stochastic programs with recourse

Two-stage stochastic programs with recourse allows the decision maker to postpone some decisions to the second stage after observing the realizations of the uncertain variables [6]. These corrective decisions are also referred to as the recourse decisions. The objective of the decision maker is to choose a first stage decision that is feasible for all potential realizations of the uncertain variable so that the expected objective function associated with both stages is optimized. The objective function of the second stage, (a.k.a recourse function) depends on both the first stage decision and the uncertain variable. The second stage decision is determined by solving the second stage problem for the specific combination of the first stage decision and the realization of the random variable.

Most of these models assume that the random variables are independent from the previous decisions. Our focus is on the models with endogenous uncertainty where the probability distribution of the uncertain variable depends on the first stage decision. Goel and Grossmann [17] classifies these into two groups. Firstly, the probability distribution of the random variable can be a direct function of the previous decisions [1]. For instance, within a pre-disaster investment decision model for a highway network, the survival probabilities of highway links after a disaster can be modeled as a function of investment decisions [34]. Secondly, the decision maker could resolve the uncertainty partially and can have an updated probability distribution based on previous deci-