1. Introduction

Most manufacturing operations are extremely complex. Production typically involves multiple products which are composed of multiple different raw materials, often processed by multiple production stages by a variety of different workers with different skills, inventoried at multiple points along the way, and shipped to multiple customers, sometimes from several locations using several different means of transportation. Managing such systems is made more difficult by the dynamic and stochastic nature of most production environments, as well as the many interdependencies that arise among the various decisions that must be made. Effective management, however, is critical, since manufacturing decisions can have a substantial impact on cost, and therefore, on competitiveness.

The field of production management largely concerns itself with the question of how to configure and operate manufacturing facilities. It has long been recognized that the answer to this question depends on the time horizon under consideration (Anthony, 1965). At one extreme, the longest horizon activity is *strategic planning* (one year or more), in which most of the above mentioned areas can be affected, at least to some degree. These include decisions regarding products, facilities, capital, resources and policies. Medium term planning is sometimes called *tactical planning* (one month or more), in which only a very limited subset of decisions can be affected. Usually, decisions about resource levels and to some degree, policies and facilities, can be made. *Operational control* (one week or less) is the shortest horizon activity, in which only small changes in production resources are possible. At this level we are typically concerned with how to most efficiently utilize the available resources to meet certain goals, such as filling customer orders or minimizing cost. Clearly, the time horizons which are appropriate for each of these three categories may vary by industry, but the general ideas should remain basically the same. For example, in aircraft assembly, a month may be a fairly short period of time compared to the manufacturing leadtime, while in certain electronic industries, a month may be a long period of time relative to the life-cycle of the product.

If we accept the above framework as valid for thinking about production management, then we can conclude that different models may be appropriate for different time horizons, e.g., a tactical planning model is not likely to be appropriate for operational control. Indeed, this view is also consistent with the concept of hierarchical planning (Hax and Meal, 1975), in which we acknowledge that we can not globally optimize the entire system, and instead attempt to achieve a good solution by solving the problem in a hierarchical fashion.

Figure 1.1 presents a proposed hierarchy in which important production decisions must be made at each level. In the next section, we will present a brief overview of our work and describe how it fits within this hierarchy.

Overview

This thesis is divided into three distinct parts: (i) analysis of a machine that is subject to random failures and random repair times, (ii) study of the operational decision of when to run overtime on an unreliable machine, and (iii) comparison of the performance of several different policies for controlling a production/inventory system when the machine is unreliable. The common thread that connects them is the focus on the planning and control of a single unreliable machine with setups that produces multiple products to stock. We now discuss each in turn.

The first part (Chapter 2) analyzes a machine where the times between failures are i.i.d. exponential and times to repair are i.i.d. exponential. Two random variables are defined for study: the amount of machine time required to produce a fixed number of parts, and the number of parts produced over a time interval of fixed length. A relationship between these two random variables is identified and exploited. In total, we derive the moments, probability density functions, cumulative distribution functions and Laplace transforms for the two random variables. We believe several of these results to be new. These results are used extensively in subsequent chapters.

Strategic Decisions	Product Design/Redesign Supplier Selection Facility Layout & Location Product/Plant Assignment Capital Expenditures Customer service targets
Tactical Decisions	Lot sizes Inventory buffer placement Safety stock levels Labor levels Line balancing
Operational Decisions	Scheduling of batches Overtime (when and how much) Crew assignment Maintenance scheduling Production rates

Figure 1.1 Partial decision hierarchy

The second part of this thesis (Chapter 3) uses the probabilistic results from the first part to study the operational decision of when to run overtime on an unreliable machine. We characterize this model as operational for two reasons. First, we will assume that *tactical* decisions (such as the setting of lot sizes and reorder points) have already been made. Second, we will consider only a finite and short time horizon, such as a day or a week. This will have two important implications. First, we assume that this horizon is short enough so that perfect demand information is available. We will view demand as occurrences at particular known points in time, in known quantities. Secondly, we assume that within this time horizon, random machine failures and random repair times can have significant impact on the output of the production stage, and are the greatest source of variability over this short horizon.

The development of this model is motivated by applications at GM metal stamping plants. These models could be used as part of a manufacturing control system in such a manufacturing operation. One can (and should) envision these models embedded in a software tool that would receive data in real-time from the shop floor and assist plant management in decision making.

We begin by showing how to evaluate a production schedule for an unreliable machine when the requirements over a finite horizon are known. Considering overtime opportunities at fixed points in time and of fixed size, a dynamic program is formulated to determine when overtime should be used. This basic model is extended to include variable sized overtime opportunities, selection among a set of overtime opportunities, and constraints on the amount of overtime that can be used over a given time interval. We show how to compute the sensitivity of the optimal policy to the input parameters, and how this information can be used for rescheduling. In the special case of a single demand point that is shared by all of the parts, we present a model that determines the cost minimizing overtime quantity in the presence of stochastic demand.

The third part of this thesis (Chapter 4) looks at the issue of selecting a policy for operating a single stage production / inventory system with setups. These are long-term planning decisions, since changing from one operating policy to the next may be quite difficult. By comparing the performance of several different policies, our goal is to obtain a better understanding of the strengths and weaknesses of different policies in different environments. Indeed, we will see that the selection of the operating policy can have a significant impact on the performance of the system.

This study considers only replenishment policies that base production decisions on the quantity of inventory that has been depleted, rather than policies that base production decisions on forecasts of future demand (e.g., MRP). We provide a framework for classifying replenishment policies, and enumerate the possible policies suggested by this framework. Of the 14 policies suggested, we select seven for detailed study. In terms of the production process, three types of variability are included: demand, production, and waiting for setup crews. We propose a set of metrics for comparison of the policies, and use basic analytical reasoning to compare and contrast the policies. For further inferences of phenomena that are difficult to estimate, we turn to simulation of the policies. For these simulations, real data from two production lines at a General Motors metal stamping plant are used.

Context and literature review

In the 1980's, many authors recognized the need for new models of manufacturing planning and scheduling. Wagner (1980) outlined many areas of production and inventory theory that were lacking in applicability to practical problems. For example, Wagner noted the lack of planning models that account for uncertainties. Graves (1981) and Abraham et al. (1985) expressed disappointment with the scheduling literature for its focus on static and deterministic problems, as most every real-world problem is both dynamic and stochastic. McKay et al. (1988) echoed this sentiment, and validated it by means of a survey of practitioners, through a case study, and in seminars with real-world schedulers. Abraham et al. (1985) also identified a need for "fresh modeling approaches" to model production systems with disruptions, and to integrate production scheduling and planning activities.

The work presented here has been developed partly in response to these calls for new models. The control models presented in Chapter 3 are inherently dynamic and stochastic in nature, addressing the important real-world issue of how much overtime should be used, and when. We also describe how our models can support rescheduling. In Chapter 4, we study operational control policies for production environments in which there is considerable uncertainty, including machine reliability.

Fortunately, our efforts are not the first. Since the time that the above papers were written, numerous other authors have studied problems in stochastic scheduling, real-time dynamic control, and overtime decisions. We will not review all of this literature here; each chapter will present its own literature review. At this point, we single out two papers in particular that are closely related to our work. As described earlier, the models in Chapter 3 require as input a production schedule and information about the current state of the system, and are designed to be embedded as part of a real-time decision support tool that could be used on the shop floor. Bean et al. (1991) describe a model that fits this description for the case of make-to-order (MTO) systems with disruptions, with the objective of minimizing total tardiness. Similarly, Gallego (1990) presents a model of make-to-stock (MTS) systems that operate according to a cyclic schedule, and finds an approximate cost minimizing strategy to recover the cyclic schedule after a disruption. While these authors consider a broad class of discrete disruptions (such as the unexpected arrival of additional demand), our models will assume that the major source of variability in the system is machine unreliability and thus “disruptions” are often almost continuously occurring. Further, our treatment is unique in that we consider the option to run overtime to help recover from disruption.

In summary, the portfolio of models presented here attempt to contribute to an area of the literature in which there is an undesirable gap between theory and practice. Further, we hope that the models and framework presented will serve as a good starting point for others to continue research in this area.

Structure of this thesis

As described above, the next three chapters will present the three major parts of this thesis. Although these chapters are intended to be readable independent of one another, Chapters 3 and 4 make extensive use of the results in Chapter 2. We will refer the reader to the relevant sections of Chapter 2 when necessary. Each chapter will present its own literature review and contain its own references. In Chapter 5 we identify some opportunities for further research.

References for Chapter 1

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