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Planning and Scheduling in Manufacturing and Services

Includes CD-ROM

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Preface

This book is an outgrowth of an earlier text that appeared in 1999 under the title "Operations Scheduling with Applications in Manufacturing and Services", coauthored with Xiuli Chao from North Carolina State. This new version has been completely reorganized and expanded in several directions including new application areas and solution methods.

The application areas are divided into two parts: manufacturing applications and services applications. The book covers five areas in manufacturing, namely, project scheduling, job shop scheduling, scheduling of flexible assembly systems, economic lot scheduling, and planning and scheduling in supply chains. It covers four areas in services, namely, reservations and timetabling, tournament scheduling, planning and scheduling in transportation, and workforce scheduling. Of course, this selection does not represent all the applications of planning and scheduling in manufacturing and services. Some areas that have received a fair amount of attention in the literature, e.g., scheduling of robotic cells, have not been included. Scheduling problems in telecommunication and computer science have not been covered either.

It seems to be harder to write a good applications-oriented book than a good theory-oriented book. In the writing of this book one question came up regularly: what should be included and what should not be included? Some difficult decisions had to be made with regard to some of the material covered. For example, should this book discuss Johnson's rule, which minimizes the makespan in a two machine flow shop? Johnson's rule is described in virtually every scheduling book and even in many books on operations management. It is mathematically elegant; but it is not clear how important it is in practice. We finally concluded that it did not deserve so much attention in an applications-oriented book such as this one. However, we did incorporate it as an exercise in the chapter on job shop scheduling and ask the student to compare its performance to that of the well-known shifting bottleneck heuristic (which is one of the better known heuristics used in practice).

The fundamentals concerning the methodologies that are used in the application chapters are covered in the appendixes. They contain the basics of mathematical programming, dynamic programming, heuristics, and constraint programming.

It is not necessary to have a detailed knowledge of computational complexity in order to go through this book. However, at times some complexity terminology is used. That is, a scheduling problem may be referred to as polynomially solvable (i.e., easy) or as NP-hard (i.e., hard). However, we never go into any NP-hardness proofs.

Because of the diversity and the complexity of the models it turned out to be difficult to develop a notation that could be kept uniform throughout the book. A serious attempt has been made to maintain some consistency of notation. However, that has not always been possible (but, of course, within each chapter the notation is consistent). Another issue we had to deal with was the level of the mathematical notation used. We decided that we did have to adopt at times the set notation and use the $\in$ symbol. So $j \in S$ implies that job j belongs to a set of jobs called S and $S_1 \cup S_2$ denotes the union of the two sets S_1 and S_2.

The book comes with a CD-ROM that contains various sets of powerpoint slides. Five sets of slides were developed by instructors who had adopted the earlier version of this book, namely Erwin Hans and Johann Hurink at Twente University of Technology in the Netherlands, Siggi Olafsson at Iowa State, Sanja Petrovic in Nottingham, Sibel Salman at Carnegie-Mellon (Sibel is currently at Koç University in Turkey), and Cees Duin and Erik van der Sluis at the University of Amsterdam. Various collections of slides were also made available by several companies, including Alcan, Carmen Systems, Cybertec, Dash Optimization, Ilog, Multimodal, and SAP. Both Ilog and Dash Optimization provided a substantial amount of additional material in the form of software, minicases, and a movie. The CD-ROM contains also various planning and scheduling systems that have been developed in academia. The LEKIN system has been especially designed for the machine scheduling and job shop models discussed in Chapter 5. Other systems on the CD-ROM include a crew scheduling system, an employee scheduling system, and a timetabling system.

This new version has benefited enormously from numerous comments made by many colleagues. First of all, this text owes a lot to Xiuli Chao from North Carolina State; his comments have always been extremely useful. Many others have also gone through the manuscript and provided constructive criticisms. The list includes Ying-Ju Chen (NYU), Jacques Desrosiers (GERAD, Montreal), Thomas Dong (ILOG), Andreas Drexl (Kiel, Germany), John Fowler (Arizona), Guillermo Gallego (Columbia), Nicholas Hall (Ohio State), Jack Kanet (Clemson), Chung-Yee Lee (HKUST), Joseph Leung (NJIT), Haibing Li (NJIT), Irv Lustig (ILOG), Kirk Moehle (Maersk Line), Detlef Pabst (Arizona), Denis Saure (Universidad de Chile), Erik van der Sluis (University of Amsterdam), Marius Solomon (Northeastern University), Chelliah Sriskandarajah (UT Dallas), Michael Trick (Carnegie-Mellon), Reha Uzsoy (Purdue), Alkis Vazacopoulos (Dash Optimization), Nitin Verma (Dash Optimization), and Benjamin Yen (Hong Kong University).

The technical production of this book and CD-ROM would not have been possible without the help of Berna Sifonte and Adam Lewenberg. Thanks are also due to the National Science Foundation; without its support this project would not have been completed.

A website for this book will be maintained at

`http://www.stern.nyu.edu/~mpinedo`

This site will keep an up-to-date list of the instructors who are using the book (including those who used the 1999 version). In addition, the site will contain relevant material that becomes available after the book has gone to press.

New York
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Michael Pinedo

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Introduction

1.1 Planning and Scheduling: Role and Impact

Planning and scheduling are decision-making processes that are used on a regular basis in many manufacturing and service industries. These forms of decision-making play an important role in procurement and production, in transportation and distribution, and in information processing and communication. The planning and scheduling functions in a company rely on mathematical techniques and heuristic methods to allocate limited resources to the activities that have to be done. This allocation of resources has to be done in such a way that the company optimizes its objectives and achieves its goals. Resources may be machines in a workshop, runways at an airport, crews at a construction site, or processing units in a computing environment. Activities may be operations in a workshop, take-offs and landings at an airport, stages in a construction project, or computer programs that have to be executed. Each activity may have a priority level, an earliest possible starting time and a due date. Objectives can take many different forms, such as minimizing the time to complete all activities, minimizing the number of activities that are completed after the committed due dates, and so on.

The following nine examples illustrate the role of planning and scheduling in real life situations. Each example describes a particular type of planning and scheduling problem. The first example shows the role of planning and scheduling in the management of large construction and installation projects that consist of many stages.

Example 1.1.1 (A System Installation Project). Consider the procurement, installation, and testing of a large computer system. The project involves a number of distinct tasks, including evaluation and selection of hardware, software development, recruitment and training of personnel, system testing, system debugging, and so on. A precedence relationship structure exists among these tasks: some can be done in parallel (concurrently), whereas others can only start when certain predecessors have been completed. The goal is to complete the entire project in minimum time.

Planning and scheduling not only provide a coherent process to manage the project, but also provide a good estimate for its completion time, reveal which tasks are critical and determine the actual duration of the entire project.

The second example is taken from a job shop manufacturing environment, where the importance of planning and scheduling is growing with the increasing diversification and differentiation of products. The number of different items that have to be produced is large and setup costs as well as shipping dates have to be taken into account.

Example 1.1.2 (A Semiconductor Manufacturing Facility). Semiconductors are manufactured in highly specialized facilities. This is the case with memory chips as well as with microprocessors. The production process in these facilities usually consists of four phases: wafer fabrication, wafer probe, assembly or packaging, and final testing.

Wafer fabrication is technologically the most complex phase. Layers of metal and wafer material are built up in patterns on wafers of silicon or gallium arsenide to produce the circuitry. Each layer requires a number of operations, which typically include: (i) cleaning, (ii) oxidation, deposition and metallization, (iii) lithography, (iv) etching, (v) ion implantation, (vi) photoresist stripping, and (vii) inspection and measurement. Because it consists of many layers, each wafer undergoes these operations several times. Thus, there is a significant amount of recirculation in the process. Wafers move through the facility in lots of 24. Some machines may require setups to prepare them for incoming jobs. The setup time often depends on the configurations of the lot just completed and the lot about to start.

The number of orders in the system is often in the hundreds and each has its own release date and committed shipping or due date. The scheduler's objective is to meet as many of the committed shipping dates as possible, while maximizing throughput. The latter goal is achieved by maximizing equipment utilization, especially of the bottleneck machines. Minimization of idle times and setup times is thus also required.

In many manufacturing environments, automated material handling systems dictate the flow of products through the system. Flexible assembly systems fall in this category. The scheduler's job in this kind of environment is to develop the best schedule while satisfying certain timing and sequencing conditions. The scheduler thus has less freedom in constructing the schedule. The next illustration describes a classical example of this type of environment.

Example 1.1.3 (An Automobile Assembly Line). An automobile assembly line typically produces many different models, all belonging to a small number of families of cars. For example, the different models within a family may include a two-door coupe, a four-door sedan, and a stationwagon. There are also a number of different colors and option packages. Some cars have automatic transmissions, while others are manual; some cars have sunroofs, others have not.

In an assembly line there are typically several bottlenecks, where the throughput of a particular machine or process determines the overall production rate. The paint shop is often such a bottleneck; every time the color changes the paint guns have to be cleaned, which is a time consuming process.

One of the objectives is to maximize the throughput by sequencing the cars in such a way that the workload at each station is balanced over time.

The previous examples illustrate some of the detailed and short term aspects of planning and scheduling processes. However, planning and scheduling often deal with medium term and long term issues as well.

Example 1.1.4 (Production Planning in a Paper Mill). The input to a paper mill is wood fiber and pulp; the output is finished rolls of paper. At the heart of the paper mill are its paper machines, which are very large and represent a significant capital investment (between 50 and 100 million dollars each). Each machine produces various types of paper which are characterized by their basis weights, grades and colors.

Master production plans for these machines are typically drawn up on an annual basis. The projected schedules are cyclic with cycle times of two weeks or longer. A particular type of paper may be produced either every cycle, every other cycle, or even less often, depending upon the demand.

Every time the machine switches over from one grade of paper to another there is a setup cost involved. During the changeover the machine keeps on producing paper. Since the paper produced during a changeover does not meet any of the required specifications, it is either sold at a steep discount or considered waste and fed back into the production system.

The production plan tries to maximize production, while minimizing inventory costs. Maximizing production implies minimizing changeover times. This means longer production runs, which in turn result in higher inventory costs. The overall production plan is a trade-off between setup and inventory costs.

Each one of the facilities described in the last three examples may belong to a network of facilities in which raw material or (semi)finished goods move from one facility to another; in a facility the product is either being stored or more value is added. In many industries the planning and scheduling of the supply chains is of crucial importance.

Example 1.1.5 (Planning and Scheduling in a Supply Chain). Consider the paper mill of the previous example. A mill is typically an integral part of a complex network of production facilities that includes timberland (where trees are grown using advanced forest management technology), paper mills where the rolls of paper are produced, converting facilities where the rolls are transformed into paper products (e.g., bags, cartons, or cutsize paper), distribution centers (where inventory is kept) and end-consumers or retailers. Several different modes of transportation are used between the various stages of the supply chain, e.g., trucks, trains, and barges. Each mode has its own characteristics, such as cost, speed, reliability, and so on. Clearly, in each stage of the supply chain more value is added to the product and the further down the supply chain, the more product differentiation. Coordinating the entire network is a daunting process. The overall goal is to minimize the total costs including production costs, transportation costs and inventory holding costs.

In many manufacturing environments customers have close relationships with the manufacturer. The factory establishes its production schedule in collaboration with its customers and may allow them to reserve machines for specific periods of time. Conceptually, the scheduling problem of the manufacturer is similar to the scheduling problems in car rental agencies and hotels, where the cars and rooms correspond to the machines and the objective is to maximize the utilization of these resources.

Example 1.1.6 (A Reservation System). A car rental agency maintains a fleet of various types of cars. It may have full size, midsize, compact, and subcompact cars. Some customers may be flexible with regard to the type of car they are willing to rent, while others may be very specific. A customer typically calls in to make a reservation for certain days and the agency has to decide whether or not to provide him with a car. At times it may be advantageous to deny a customer a reservation that is for a very short period when there is a chance to rent the car out to another customer for a longer period. The agency's objective is to maximize the number of days its cars are rented out.

Scheduling and timetabling play also an important role in sports and entertainment. Sport tournaments have to be scheduled very carefully. The schedule has to be such that all the participating teams are treated fairly and that the preferences of the fans are taken into account. Timetabling plays also an important role in entertainment. For example, television programs have to be scheduled in such a way that the ratings (and therefore the profits) are maximized. After the programs have been assigned to their slots, the commercials have to be scheduled as well.

Example 1.1.7 (Scheduling a Soccer Tournament). Consider a tournament of a soccer league. The games have to be scheduled over a fixed number of rounds. An important consideration in the creation of a schedule is that, ideally, each team should have a schedule that alternates between games at home and games away. However, it often cannot be avoided that a team has to play two consecutive games at home or two consecutive games away. There are many other concerns as well: for example, if a city has two teams participating in the same league, then it is desirable to have in each round one team at home and the other team away. If two teams in a league are very strong, then it would be nice if none of the other teams would have to face these two teams in consecutive rounds.

Planning and scheduling play a very important role in transportation. There are various modes of transportation and different industries focus on different ways of moving either cargo or passengers. The objectives include minimizing total cost as well as maximizing convenience or, equivalently, minimizing penalty costs.

Example 1.1.8 (Routing and Scheduling of Airplanes). The marketing department of an airline usually has a considerable amount of information with regard to customer demand for any given flight (a flight is characterized by its origin and destination and by its scheduled departure time). Based on the demand information, the airline can estimate the profit of assigning a particular type of aircraft to a flight leg under consideration. The airline scheduling problem basically focuses on how to combine the different flight legs into so-called round-trips that can be assigned to a specific plane. A round trip may be subject to many constraints: the turn-around time at an airport must be longer than a given minimum time; a crew cannot be on duty for a duration that is longer than what the Federal Aviation Administration (FAA) allows, and so on.

In many manufacturing and service industries planning and scheduling often have to deal with resources other than machines; the most important resource, besides machines, is usually personnel.

Example 1.1.9 (Scheduling Nurses in a Hospital). Every hospital has staffing requirements that change from day to day. For instance, the number of nurses required on weekdays is usually more than the number required on weekends, while the staffing required during the night shift may be less than that required during the day shift. State and federal regulations and union rules may provide additional scheduling constraints. There are thus different types of shift patterns, all with different costs.

The goal is to develop shift assignments so that all daily requirements are met and the constraints are satisfied at a minimal cost.

From the examples above it is clear that planning and scheduling is important in manufacturing as well as in services. Certain types of scheduling problems are more likely to occur in manufacturing settings (e.g., assembly line scheduling), while others are more likely to occur in service settings (e.g., reservation systems). And certain types of scheduling problems occur in both manufacturing and services; for example, project scheduling is important in the shipbuilding industry as well as in management consulting.

In many environments it may not be immediately clear what impact planning and scheduling has on any given objective. In practice, the choice of schedule usually has a measurable impact on system performance. Indeed, an improvement in a schedule usually can cut direct and indirect costs significantly, especially in a complex production setting.

Unfortunately, planning and scheduling may be difficult to implement. The underlying mathematical difficulties are similar to those encountered in other branches of combinatorial optimization, while the implementation difficulties are often caused by inaccuracies in model representations or by problems encountered in the retrieval of data and the management of information. Resolving these difficulties takes skill and experience, but is often financially and operationally well worth the effort.

1.2 Planning and Scheduling Functions in an Enterprise

Planning and scheduling in either a manufacturing or a service organization must interact with many other functions. These interactions are typically system-dependent and may differ substantially from one setting to another; they often take place within a computer network. There are, of course, also many situations where the exchange of information between planning and scheduling and other decision making functions occurs in meetings or through memos.

Planning and Scheduling in Manufacturing. We first describe a generic manufacturing environment and the role of its planning and scheduling function. Orders that are released in a manufacturing setting have to be translated into jobs with associated due dates. These jobs often have to be processed on the machines in a workcenter in a given order or sequence. The processing of jobs may sometimes be delayed if certain machines are busy. Preemptions may occur when high priority jobs are released which have to be processed at once. Unexpected events on the shopfloor, such as machine breakdowns or longer-than-expected processing times, also have to be taken into account, since they may have a major impact on the schedules. Developing, in such an environment, a detailed schedule of the tasks to be performed helps maintain efficiency and control of operations.

The shopfloor is not the only part of the organization that impacts the scheduling process. The scheduling process also interacts with the production planning process, which handles medium- to long-term planning for the entire organization. This process intends to optimize the firm's overall product mix and long-term resource allocation based on inventory levels, demand forecasts and resource requirements. Decisions made at this higher planning level may impact the more detailed scheduling process directly. Figure 1.1 depicts a diagram of the information flow in a manufacturing system.