Chapter 1

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.

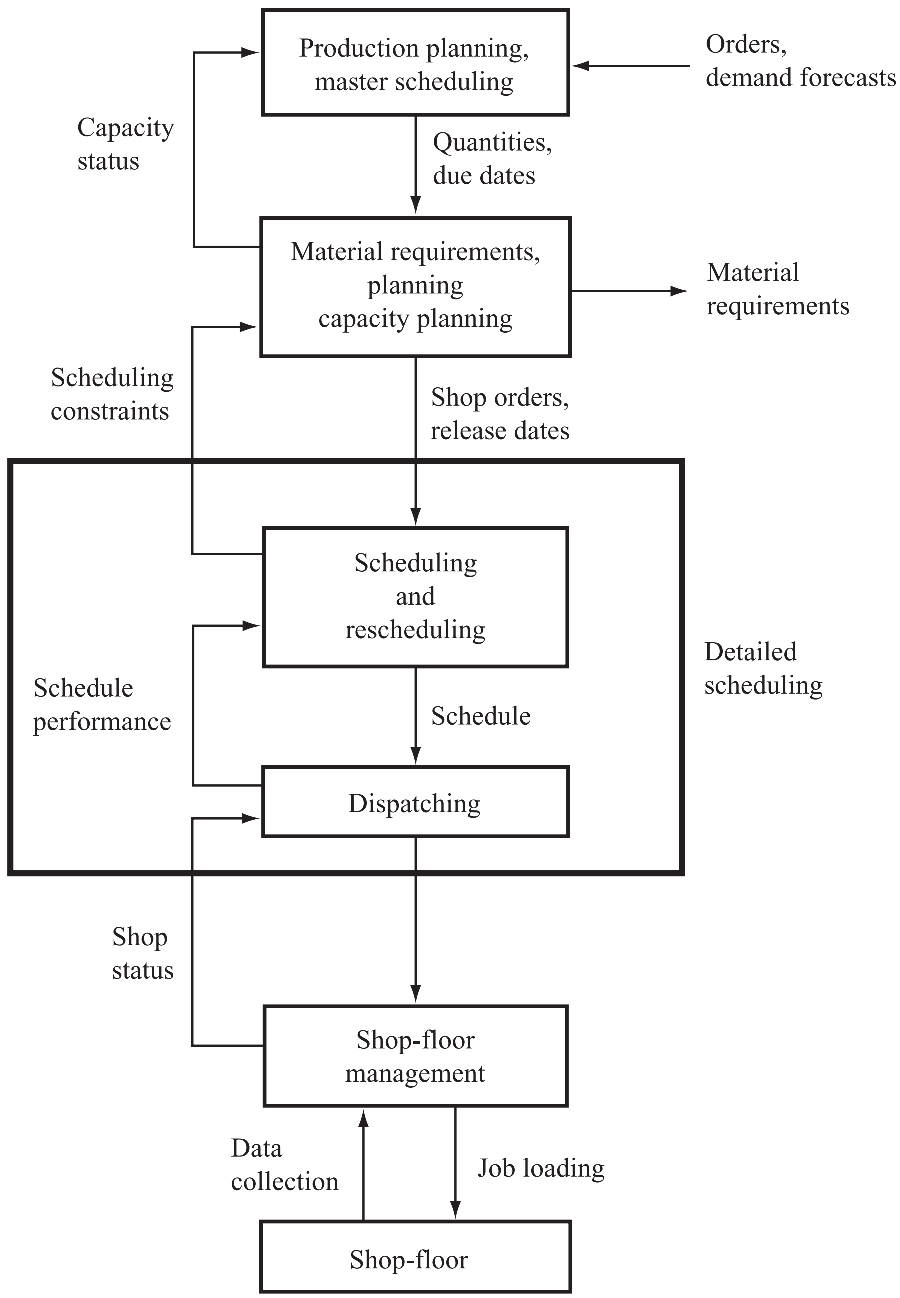

Fig. 1.1. Information flow diagram in a manufacturing system

In manufacturing, planning and scheduling has to interact with other decision making functions in the plant. One popular system that is widely used is the Material Requirements Planning (MRP) system. After a schedule has been set up it is necessary that all the raw materials and resources are available at specified times. The ready dates of the jobs have to be determined by the production planning and scheduling system in conjunction with the MRP system.

MRP systems are normally fairly elaborate. Each job has a Bill Of Materials (BOM) itemizing the parts required for production. The MRP system keeps track of the inventory of each part. Furthermore, it determines the timing of the purchases of each one of the materials. In doing so, it uses techniques such as lot sizing and lot scheduling that are similar to those used in planning and scheduling systems. There are many commercial MRP software packages available. As a result, many manufacturing facilities rely on MRP systems. In the cases where the facility does not have a planning or scheduling system, the MRP system may be used for production planning purposes. However, in a complex setting it is not easy for an MRP system to do the detailed planning and scheduling satisfactorily.

Modern factories often employ elaborate manufacturing information systems involving a computer network and various databases. Local area networks of personal computers, workstations and data entry terminals are connected to a central server, and may be used either to retrieve data from the various databases or to enter new data. Planning and scheduling is usually done on one of these personal computers or workstations. Terminals at key locations may often be connected to the scheduling computer in order to give departments access to current scheduling information. These departments, in turn, may provide the scheduling system with relevant information, such as changes in job status, machine status, or inventory levels.

Companies nowadays rely often on elaborate Enterprise Resource Planning (ERP) systems, that control and coordinate the information in all its divisions and sometimes also at its suppliers and customers. Decision support systems of various different types may be linked to such an ERP system, enabling the company to do long range planning, medium term planning as well as short term scheduling.

Planning and Scheduling in Services. Describing a generic service organization and its planning and scheduling systems is not as easy as describing a generic manufacturing system. The planning and scheduling functions in a service organization may often face many different problems. They may have to deal with the reservation of resources (e.g., trucks, time slots, meeting rooms or other resources), the allocation, assignment, and scheduling of equipment (e.g., planes) or the allocation and scheduling of the workforce (e.g., the assignment of shifts in call centers). The algorithms tend to be completely different from those used in manufacturing settings. Planning and scheduling in a service environment also have to interact with other decision making functions, usually within elaborate information systems, much in the same way as

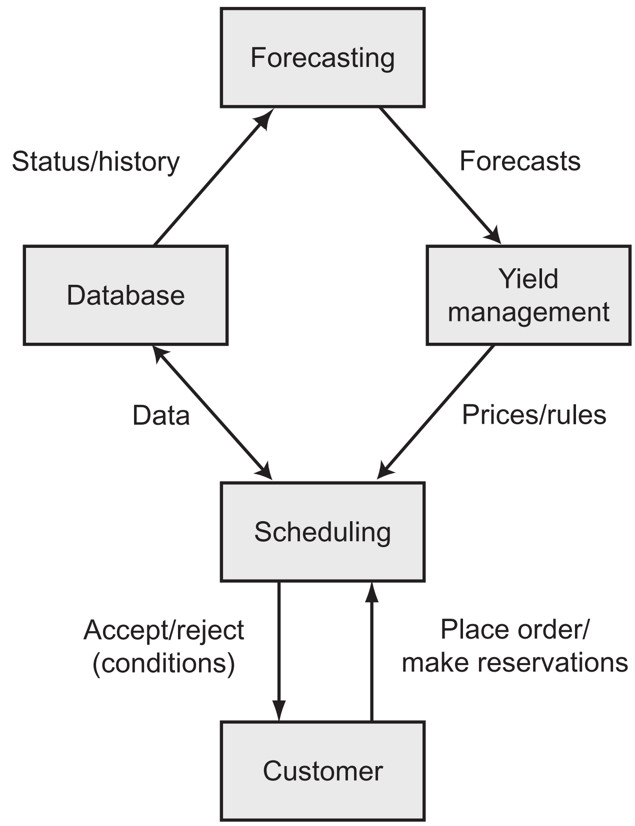

Fig. 1.2. Information flow diagram in a service system

the scheduling function in a manufacturing setting. These information systems typically rely on extensive databases that contain all the relevant information regarding the availability of resources as well as the characteristics of current and potential customers. A planning and scheduling system may interact with a forecasting module; it may also interact with a yield management module (which is a type of module that is not very common in manufacturing settings). On the other hand, in a service environment there is usually no MRP system. Figure 1.2 depicts the information flow in a service organization such as a car rental agency.

1.3 Outline of the Book

This book focuses on planning and scheduling applications. Although thousands of planning and scheduling models and problems have been studied in the literature, only a limited number are considered in this book. The selection is based on the insight the models provide, the methodologies needed for their analyses and their importance with regard to real-world applications.

The book consists of four parts. Part I describes the general characteristics of scheduling models in manufacturing and in services. Part II considers various classes of planning and scheduling models in manufacturing, and Part III discusses several classes of planning and scheduling models in services. Part IV deals with system design, development and implementation issues.

The remainder of Part I consists of Chapters 2 and 3. Chapter 2 discusses the basic characteristics of the manufacturing models that are considered in Part II of this book and Chapter 3 describes the characteristics of the service models that are considered in Part III. These characteristics include machine environments and service settings, processing restrictions and constraints, as well as performance measures and objective functions.

Part II focuses on planning and scheduling in nanufacturing and consists of Chapters 4 to 8. Each one of these chapters focuses on a different class of planning and scheduling models with applications in manufacturing; each chapter corresponds to one of the examples discussed in Section 1.1. At first, it may appear that the various chapters in this part are somewhat unrelated to one another and are selected arbitrarily. However, there is a rationale behind the selection of topics and the chapters are actually closely related to one another.

Chapter 4 focuses on project scheduling. A project scheduling problem usually concerns a single project that consists of a number of separate jobs which are related to one another through precedence constraints. Since only a single project is considered, the basic format of this type of scheduling problem is inherently easy, and therefore the logical one to start out with. Moreover, an immediate generalization of this problem, i.e., the project scheduling problem with workforce constraints, has from a mathematical point of view several important special cases. For example, the job shop scheduling problems discussed in Chapter 5 and the timetabling problems considered in Chapter 9 are such special cases.

Chapter 5 covers the classical single machine, parallel machine, and job shop scheduling models. In a single machine as well as in a parallel machine environment a job consists of a single operation; in a parallel machine environment this operation may be done on any one of the machines available. In a job shop, each job has to undergo multiple operations on the various machines and each job has its own set of processing times and routing characteristics. Several objectives are of interest; the most important one is the makespan, which is the time required to finish all jobs.

Chapter 6 focuses on flexible assembly systems. These systems have some similarities with job shops; however, there are also some differences. In a flexible assembly system there are several different job types; but, in contrast to a job shop, a certain number has to be produced of each type. The routing constraints in flexible assembly systems are also somewhat different from those in job shops. Because of the presence of a material handling or conveyor system, the starting time of one operation may be a very specific function of the completion time of another operation. (In job shops these dependencies are considerably weaker.)

The problems considered in Chapter 7, lot sizing and scheduling, are somewhat similar to those in Chapter 6. There are again various different job types, and of each type there are a number of identical jobs. However, the variety of job types in this chapter is usually less than the variety of job types in a flexible assembly system. The number to be produced of any particular job type tends to be larger than in a flexible assembly system. This number is called the lot size and its determination is an integral part of the scheduling problem. So, going from Chapter 5 to Chapter 7, the variety in the order portfolio decreases, while the batch or lot sizes increase.

Chapter 8 focuses on planning and scheduling in supply chains. This chapter assumes that the manufacturing environment consists of a network of raw material and parts providers, production facilities, distribution centers, customers, and so on. The product flows from one stage to the next and at each stage more value is added to the product. Each facility can be optimized locally using the procedures that are described in Chapters 5, 6 and 7. However, performing a global optimization that encompasses the entire network requires a special framework. Such a framework has to take now transportation issues also into account; transportation costs appear in the objective function and the quantities to be transported between facilities may be subject to restrictions and constraints.

Part III focuses on planning and scheduling in services and consists of Chapters 9 to 12. Each chapter describes a class of planning and scheduling models in a given service setting, and each chapter corresponds to one of the examples discussed in Section 1.1. The topics covered in Part III are, clearly, different from those in Part II. However, Chapters 9 to 12 also deal with issues and features that may be important in manufacturing settings as well. However, adding these features to the models described in Chapters 4 to 8 would lead to problems that are extremely hard to analyze. That is why these features are considered separately in Part III in relatively simple settings.

Chapter 9 considers reservation systems and timetabling models. These classes of models are basically equivalent to parallel machine models. In reservation models, jobs (i.e., reservations) tend to have release dates and due dates that are tight; the decision-maker has to decide which jobs to process and which jobs not to process. Reservation models are important in hospitality industries such as hotels and carrental agencies. In timetabling models the jobs are subject to constraints with regard to the availability of operators or tools. Timetabling models are also important in the scheduling of meetings, classes, and exams.

Chapter 10 describes scheduling and timetabling in sports and entertainment. The scheduling of tournaments (e.g., basketball, baseball, soccer, and so

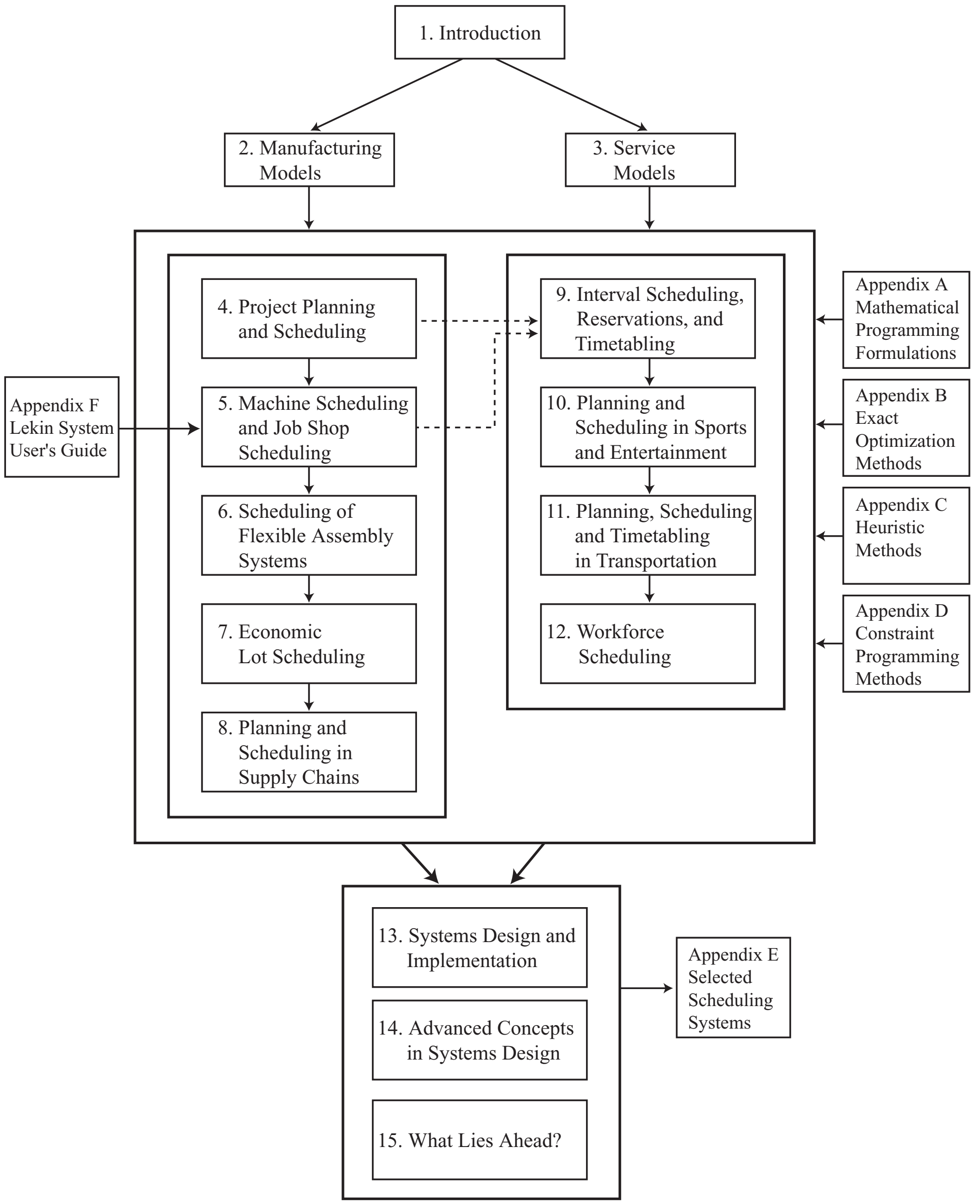

Fig. 1.3. Overview of the Book

on) tends to be very difficult because of the many preferences and constraints concerning the schedules. For example, it is desirable that the sequence of games assigned to any given team alternates between games at home and games away. This chapter discusses an optimization approach, a constraint programming approach, as well as a local search approach for tournament scheduling problems. It also describes how to schedule programs in broadcast television so as to maximize the ratings.

Chapter 11 discusses planning, scheduling and timetabling in transportation settings. The transportation settings include the scheduling of oil tankers, the routing and scheduling of airplanes, and the timetabling of trains. Tankers have to move cargoes from one point to another within given time windows and aircraft have to cover flight legs between certain cities also within given time windows. One important objective is to assign the different trips or flight legs to the given tankers or airplanes in such a way that the total cost is minimized. There are important similarities as well as differences between the scheduling of oil tankers, the routing and scheduling of aircraft, and the timetabling of trains.

Chapter 12 focuses on workforce scheduling. There are various different classes of workforce scheduling models. One class of workforce scheduling models includes the shift scheduling of nurses in hospitals or operators in call centers. A different class of workforce scheduling models includes crew scheduling in airlines or trucking companies.

Part IV concerns systems development and implementation issues and consists of the three remaining chapters. Chapter 13 deals with the design, development, and implementation of planning and scheduling systems. It covers basic issues with regard to system architectures and describes the various types of databases, planning and scheduling engines, and user interfaces. The databases may be conventional relational databases or more sophisticated knowledge-bases; the user interfaces may include Gantt charts, capacity buckets, or throughput diagrams.

Chapter 14 describes more advanced concepts in systems design. The topics discussed include robustness issues, learning mechanisms, systems reconfigurability, as well as Internet related features. These topics have been inspired by the design, development and implementation of planning and scheduling systems during the last decade of the twentieth century; in recent years these concepts have received a fair amount of attention in the academic literature.

Chapter 15, the last chapter of this book, discusses future directions in the research and development of planning and scheduling applications. Issues in manufacturing applications are discussed (which often concern topics in supply chain management), issues in service applications are covered, as well as issues in the design and development of complex systems that consist of many different modules. Important issues concern the connectivity and interface design between the different modules of an integrated system.

There are six appendixes. Appendix A covers mathematical programming formulations. Appendix B focuses on exact optimization methods, including dynamic programming and branch-and-bound. Appendix C describes the most popular heuristic techniques, e.g., dispatching rules, beam search, as well as local search. Appendix D contains a primer on contraint programming. Appendix E presents an overview of selected scheduling systems and Appendix F provides a user's guide to the LEKIN job shop scheduling system.

Figure 1.3 shows the precedence relationships between the various chapters. Some of these precedence relationships are stronger than others. The stronger relationships are depicted by solid arrows and the weaker ones by dotted arrows.

This book is intended for a senior level or masters level course on planning and scheduling in either an engineering or a business school. The selection of chapters to be covered depends, of course, on the instructor. It appears that in most cases Chapters 1, 2 and 3 have to be covered. However, an instructor may not want to go through all of the chapters in Parts II or III; he or she may select, for example, most of Chapters 4 and 5 and a smattering of Chapters 6 to 12. An instructor may decide not to cover Part IV, but still assign those chapters as background reading.

Prerequisite knowledge for this book is an elementary course in Operations Research on the level of Hillier and Lieberman's *Introduction to Operations Research*.

Comments and References

Over the last three decades many scheduling books have appeared, ranging from the elementary to the advanced. Most of these focus on just one or two of the nine model categories covered in Parts II and III of this book.

Several books are completely dedicated to project scheduling; see, for example, Moder and Philips (1970), Kerzner (1994), Kolisch (1995), Neumann, Schwindt, and Zimmermann (2001), and Demeulemeester and Herroelen (2002). There are also various books that have a couple of chapters dedicated to this topic (see, for example, Morton and Pentico (1993)). A survey paper by Brucker, Drexl, Möhring, Neumann, and Pesch (1999) presents a detailed overview of the models as well as the techniques used in project scheduling.

Many books emphasize job shop scheduling (often also referred to as machine scheduling). One of the better known textbooks on this topic is the one by Conway, Maxwell and Miller (1967) (which, even though slightly out of date, is still very interesting). A more recent text by Baker (1974) gives an excellent overview of the many aspects of machine scheduling. An introductory textbook by French (1982) covers most of the techniques that are used in job shop scheduling. The more advanced book by Blazewicz, Cellary, Slowinski and Weglarz (1986) focuses mainly on job shop scheduling with resource constraints and multiple objectives. The book by Blazewicz, Ecker, Schmidt and Weglarz (1993) is also somewhat advanced and deals primarily with computational and complexity aspects of machine scheduling models and their applications to manufacturing. The more applied text by Morton and

Pentico (1993) presents a detailed analysis of a large number of scheduling heuristics that are useful for practitioners. The survey paper by Lawler, Lenstra, Rinnooy Kan and Shmoys (1993) gives a detailed overview of machine scheduling. Recently, a number of books have appeared that focus primarily on machine scheduling and job shop scheduling, see Dauzère-Pérès and Lasserre (1994), Baker (1995), Parker (1995), Pinedo (1995), Ovacik and Uzsoy (1997), Sule (1996), Bagchi (1999), Pinedo (2002), and Brucker (2004). The books edited by Chrétienne, Coffman, Lenstra and Liu (1995) and Lee and Lei (1997) contain a wide variety of papers on machine scheduling. Baptiste, LePape and Nuijten (2001) cover the application of constraint programming techniques to job shop scheduling. The volume edited by Nareyek (2001) contains papers on local search applied to job shop scheduling.

Several books focus on flexible assembly systems, flexible manufacturing systems, or intelligent systems in general; see, for example, Kusiak (1990, 1992). These books usually include one or more chapters that deal with scheduling aspects of these systems. Scholl (1998) focuses in his book on the balancing and sequencing of assembly lines.

Lot sizing and scheduling is closely related to inventory theory. Haase (1994) gives an excellent overview of this field. Brüggemann (1995) and Kimms (1997) provide more advanced treatments. Drexl and Kimms (1997) provide an exhaustive survey with extensions. Lot scheduling has also been covered in a number of survey papers on production scheduling; see, for example, the reviews by Graves (1981) and Rodammer and White (1988).

Planning and scheduling in supply chains have received a fair amount of attention over the last decade. A number of books cover supply chains in general. Some of these emphasize the planning and scheduling aspects; see, for example, Shapiro (2001) and Miller (2002). Stadtler and Kilger (2002) edited a book that has various chapters on planning and scheduling in supply chains.

Interval scheduling, reservation systems and timetabling are fairly new topics that are closely related to one another. Interval scheduling has been considered in a couple of chapters in Dempster, Lenstra and Rinnooy Kan (1982) and timetabling has been discussed in the textbook by Parker (1995). Recently, a series of proceedings of conferences on timetabling have appeared, see Burke and Ross (1996), Burke and Carter (1998), Burke and Erben (2001), and Burke and De Causmaecker (2003).

A fair amount of research has been done on planning and scheduling in sports and entertainment. As far as this author is aware of, no book has appeared that is completely dedicated to this area. However, the book edited by Butenko, Gil-Lafuente and Pardalos (2004) has several chapters that focus on planning and scheduling in sports.

No framework has yet been established for planning and scheduling models in transportation. A series of conferences on computer-aided scheduling of public transport has resulted in a number of interesting proceedings, see Wren and Daduna (1988), Desrochers and Rousseau (1992), Daduna, Branco, and Pinto Paixao (1995), Wilson (1999), and Voss and Daduna (2001). A volume edited by Yu (1998) considers operations research applications in the airline industry; this volume contains several papers on planning and scheduling in the airline industry.

Personnel scheduling has not received the same amount of attention as project scheduling or job shop scheduling. Tien and Kamiyama (1982) present an overview on manpower scheduling algorithms. The text by Nanda and Browne (1992) is completely dedicated to personnel scheduling. The Handbook of Industrial Engineering has a chapter on personnel scheduling by Burgess and Busby (1992). Parker (1995) dedicates a section to staffing problems. Burke, De Causmaecker, Vanden Berghe and Van Landeghem (2004) present an overview of the state of the art in nurse rostering. Several of the books on planning and scheduling in transportation have chapters on crew scheduling.

Recently, a Handbook of Scheduling appeared edited by Leung (2004). This handbook contains numerous chapters covering a wide spectrum that includes job shop scheduling, timetabling, tournament scheduling, and workforce scheduling.

A fair amount has been written on the design, development and implementation of scheduling systems. Most of this research and development has been documented in survey papers. Atabakhsh (1991) presents a survey of constraint based scheduling systems using artificial intelligence techniques and Noronha and Sarma (1991) give an overview of knowledge-based approaches for scheduling problems. Smith (1992) focuses in his survey on the development and implementation of scheduling systems. Two collections of papers, edited by Zweben and Fox (1994) and by Brown and Scherer (1995), describe a number of scheduling systems and their actual implementation.