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An Integrated View on Models, Methods and Tools

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To Carmen, Julio, and Daniel

Jose M. Framinan

To Karin, Steven, and Annemarie

Rainer Leisten

To Gema and Diego

Rubén Ruiz García

Preface

Obtaining economic and reliable schedules constitutes the core of excellence in customer service and of efficiency in manufacturing operations. While few areas have been more productive in decision sciences than scheduling, only a fraction of the vast amount of scheduling research has been translated into practice. On one hand, the inherent complexity of most scheduling problems has led to an excessively fragmented and specialised field in which different facets and issues are treated in an independent manner as goals themselves, lacking a unifying view of the scheduling problem. Aside, scientific brilliance and mathematical elegance has been sometimes prevalent to practical, hands-on approaches, producing specific procedures of narrow application. Finally, the nearly non-existence of research on implementation issues in scheduling as well as the scarcity of case studies has not helped in translating valuable research findings into industry.

In this book we attempt to overcome these limitations by presenting an integrated framework for formulating, developing and implementing systems that can be effectively used for supporting manufacturing scheduling decisions. To do so, we have intentionally avoided the traditional taxonomy style of many scheduling approaches and focused on the explanation and integration of the different issues into a (hopefully) coherent framework for modeling, solving and implementing scheduling decisions. Therefore, the book does not contain a detailed description of specific models and/or procedures, but rather will present a general overview of the scheduling field in order to provide the tools to conduct an up-to-date scheduling research and practice. To compensate this, we include a generous compilation and discussion of related literature for further reading, so the reader can easily track the main contributions of particular interest.

The book is intended for an ample audience who wish to get an overview of actual scheduling topics. It may constitute a starting point for researchers in the scheduling field. Also, post-graduate students with a focus on operations management can be attracted by the content of the book. Practitioners in the field would feel comfortable with many of the models and systems presented in the book as well, as they can easily see in them real-life cases. As a result, the book is not intended to be read sequentially, but is designed to support different itineraries, providing comprehensive introductory chapters/sections before detailed explanation of specific topics.

There are few but important prerequisites for this book. Knowledge of the most basic concepts of production management is required, although an effort is done in Chap. 2 to place scheduling into context. Maths will appear profusely in some parts of the book, mostly in the chapters devoted to scheduling models.

Organisation of the book

The book is structured into five parts. In the first part, we introduce the main definitions and notation, and present the framework that we will use throughout the book. In this framework, a scheduling system is defined as a collection of models (representations of scheduling problems), methods (procedures to obtain efficient solutions out of scheduling models), and tools (software devices to embed models and procedures in order to support the scheduling decision problem), together with the human elements operating the system. Models, procedures, and tools will constitute the next three parts of the book. A final part on scheduling systems is devoted to assemble all these elements together in a roadmap to guide the development of a scheduling system. The structure of the book is summarised in Fig. 1.

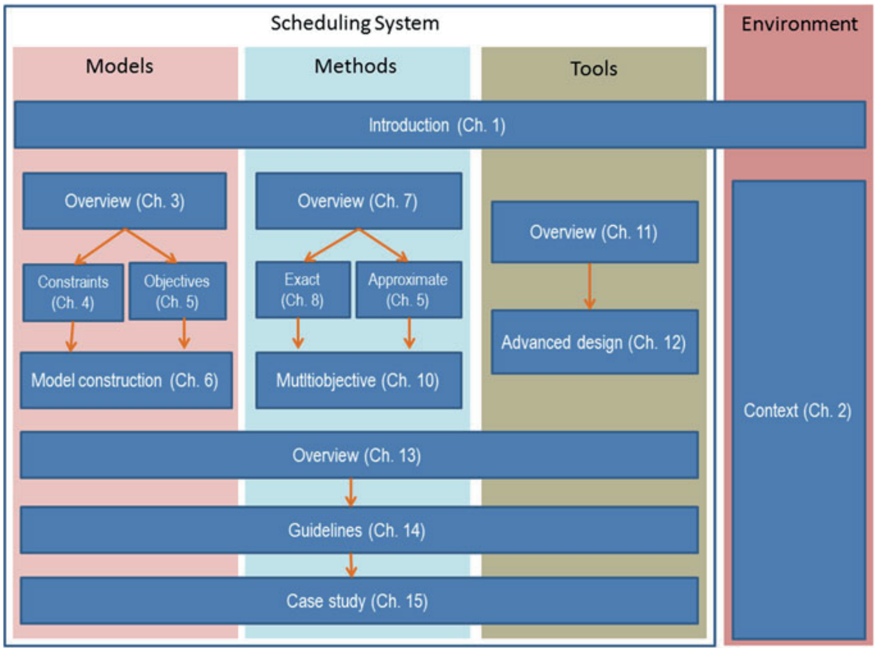

Fig. 1 Structure of the book

As mentioned before, the book does not have to be read comprehensively and sequentially. Manufacturing scheduling constitutes a topic of interest for different professional (including managers and top/intermediate staff in charge of operations management) and academic profiles (including production/manufacturing engineers, computer scientists, and different bachelors in operations research and management science). When used as a textbook, the instructors would have a clear idea about the content, sequence, and depth in which the different topics contained in the book should be learnt. Therefore, the subsequent lines are mainly intended as a rough advice whenever such supervision is not present.

We believe that a rather basic knowledge of the scheduling field can be gained by reading the introductory chapters of each part, i.e. Chaps. 1, 3, 7, 11, and 13. A more classical (although, in our opinion, also more theoretical) itinerary for the scheduling field would exclude Chap. 11 to Chap. 15, and would stress issues related to modeling and solution procedures. Modeling would be reinforced by adding Chaps. 4, 5, and 6. These three chapters are heavily interdependent and therefore should be read together, although readers with some scheduling background may skip some parts of Chaps. 4 and 5, and focus instead on the discussions in Chap. 6. A rather comprehensive understanding of solution procedures is provided in Chaps. 8 and 9, whereas multiobjective scheduling issues are treated in Chap. 10. Since multiobjective scheduling is a hot topic with practical and theoretical interest, we would favor its inclusion even at a basic level course. Nevertheless, most of it could be skipped if the reader adopts a more classical/basic view of the topic.

We think that Chaps. 11 and 12 would be of particular value for an audience interested in the design and implementation of scheduling tools. Chapter 11 would serve to grasp a general view on the topic, whereas Chap. 12 is intended for readers with some background and experience on business information systems, and –in our opinion– should be spared for basic scheduling courses, unless they are heavily geared toward information systems/computer science.

We hope that users and consultants of manufacturing scheduling systems would find interesting Chaps. 13 to 14, as the practical issues treated there are not usually subject of classical scheduling books. Despite the verbosity and apparent simplicity of some of the ideas contained in these chapters, they are mainly intended for an experienced reader who may better grasp the inherent complexity of the deployment of manufacturing scheduling systems and their integration with the human schedulers. We are not sure that many of the ideas contained there could be fully appreciated at a more basic level, although we think that at least a glimpse of those in Chap. 13 should be given in order to avoid an excessively technical approach to the field, which in our opinion is and has been a rather common flaw in scheduling teaching and research.

Finally, Chap. 15 may be used in many different itineraries, ranging from a basic level in which modeling and solution procedures issues are seen into practice, to a more advanced discussion case in which success factors, shortcomings, lost opportunities, and learnt lessons can be debated.

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In the process of writing this book, we are indebted to many people. The authors benefited from the careful reading of earlier versions of the book done by Manu Dios, Paz Perez-Gonzalez and Natalia Prischepov. The authors are also indebted to the many members and colleagues of their institutions at Seville, Duisburg, and Valencia. The collaborations, help and working atmosphere have proven to be key when writing this book. They also had to endure many of our absences when writing "the book" and we are really thankful for their support and patience.

January 2014

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Contents

Part II Scheduling Models

Part I
Introduction to Manufacturing Scheduling

This part of the book consists of Chaps. 1 and 2. In the first chapter, we move from a general definition of scheduling as the allocation of resources to tasks along time to a definition of manufacturing scheduling, where we identify its main features and context in which it takes place. Then we define a scheduling system as a collection of methods, models and tools that support scheduling-related decisions in a company. These three elements are heavily influenced by the organisational context in which the scheduling-related decisions have to be taken. All these three parts: models, methods and tools together with the organisation (humans) involved in the process constitute a framework that we will use throughout the book.

The second chapter is devoted to describing the context in which manufacturing scheduling decisions are taken. Quite often, specialized scheduling literature fails to acknowledge that scheduling decisions are usually integrated into a more general (explicit or implicit) decision system, which influences (and is influenced by) scheduling decisions. In addition, the aforementioned decision system is not restricted to an individual company, but extended along a whole supply network composed of independent enterprises. Therefore, we review the concept of operations management and its place in obtaining competitive advantages for a firm. After exemplifying the complexity and interdependency of different decisions that constitute the management of operations, we introduce the different approaches to handle this complexity, including hierarchical planning and decentralised approaches (agent-based systems). In the centralised approach, we identify the main decision blocks, place scheduling decisions and discuss its relation with other decision blocks. The difference between scheduling and rescheduling (which can be interpreted as the frontier among planning and control) is discussed. Next, we discuss the interrelation of scheduling decisions with other manufacturing-related decisions, such as simultaneous lot-sizing and scheduling, and emphasize the need of alignment of these decisions with the goals in the company. Finally, we also present the context of the supply chain, discuss the concept of supply chain management and present how this affects scheduling decisions.

Chapter 1
Overview of Manufacturing Scheduling

1.1 Introduction

Broadly speaking, scheduling deals with the allocation of resources to tasks along time. In general, such definition may encompass a huge number of real-life applications, such as allocating nurses to the shifts of their hospitals, aircraft scheduling in airports, processing units in a computing environment, etc. In this book, we will focus onto *production scheduling* or *manufacturing scheduling*, i.e. assigning the various resources in the company to the manufacturing of a range of products that are requested by the customers. Since, as we will see later, certain level of abstraction is required to manage these resources, many of the models and methods that will be shown here may be applied outside the manufacturing scope. Nevertheless, manufacturing scheduling presents a number of features that cannot be, in general, extrapolated to other decision sciences. Most notably, scheduling is not carried out in an isolated manner, as on one hand it uses as input the results of a previous plan that determined the set of products to be manufactured by the company along with the real (or expected) demand of these products, among other issues. On the other hand, the usually highly variable shop floor conditions may complicate or impede the fulfilment of a schedule, no matter how detailed it is, so there are further decisions to be taken, possibly implying the review or modification of the existing schedule. As a consequence, manufacturing scheduling cannot be considered an isolated process, but integrated into a set of managerial decisions collectively known as production management (or operations management).

More specifically, in this chapter we:

- briefly summarize the context in which manufacturing decisions take place (Sect. 1.2),
- review a number of features in scheduling common to most manufacturing companies (Sect. 1.3),
- use the previous understanding of the nature of scheduling decisions to elaborate the concept of a *manufacturing scheduling system* (Sect. 1.4),

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- briefly introduce the basic concepts regarding manufacturing scheduling (Sect. 1.5), and
- provide some hints for further analysis on the issues discussed in this chapter (Sect. 1.6)

1.2 Manufacturing Scheduling into Context

Production management is a managerial process in which a large number of decisions are taken over time in order to ensure the delivery of goods with the maximum quality, minimum cost, and minimum lead time. These decisions differ—among other issues—on their impact in the company, their scope, and on the time period to take them. They range from strategic, high-impact, long-range decisions such as deciding whether certain plant will manufacture or not a new product, to short-term, low-level, small-impact decisions such as which product is next to be manufactured in certain machine in the shop floor.

Given the different nature and timing of these decisions, and the different decision makers involved, production management has been traditionally decomposed by adopting a hierarchical structure in which the different decision problems are successively solved. At the top of this structure, there are decisions related to the *strategic design of the manufacturing network*, and include the selection of providers, the location of the plant(s) to manufacture the products, the design of the plant layout and the structure of the distribution network, among others. Broadly speaking, these decisions—called *strategic decisions*—serve to establish, on an aggregate level, the capacity of the manufacturing and distribution resources, including the co-operation with the providers. Obviously, these decisions are strategic the sense that they have an enormous impact on the bottom line of the companies and that the economic and physical resources involved make them unlikely or even impossible to be reviewed within less than a horizon usually measured in years.

Once the manufacturing and distribution structure has been designed, there are a number of decisions related to how to make the best usage of this structure. These decisions are again usually decomposed into medium-term decisions (*tactical decisions*), and short-term decisions (*operating decisions*). This distinction may seem a bit arbitrary—and indeed it may blur for some manufacturing scenarios—but it is usually related to the complexity of the manufacturing process and to the granularity and quality of the data required to make the decisions. When planning the usage of the manufacturing resources for the next year (something that must be done to decide on the workforce required, to plan the contracts with the providers, etc.), the key information driving the whole manufacturing process (i.e. the orders from the customers) is not known and it can only be guessed or estimated (even for the best of the cases) via historical or casual data. However, it is clear that the quality of this estimation decreases with the level of detail, as it is easier to estimate the yearly sales of a model of a car than to estimate the weekly sales of the cars of a certain model including left-side steering wheel. Therefore, it is usual to make an *aggregated production plan* in which the input for this decision is not the estimation of the actual products to be sold each day, but an estimation of the families or groups of products with similar usage of resources and/or similar behaviour with respect to the demand that are to be sold over a period of time ranging from weeks to months. As a consequence, this aggregated production plan will serve to estimate the (aggregated) capacity to be used, the amount of raw materials to be purchased, etc., but not as a detailed indication of the production orders that have to be released to the shop floor. This exhaustive plan is usually left for a later stage in which a detailed status of the shop floor and on the firm orders to be processed is known, and this is precisely the mission of *manufacturing scheduling*: matching the jobs (tasks) to be executed against the resources in the company. The result of this process is, ideally, a *schedule* where it is specified which job should enter each resource, and when.

As plans rarely occur as estimated (this may be an overstatement for many environments, but certainly not for manufacturing scheduling), modifications to clear the way for unforeseen events (machine breakdown, urgent orders, cancelation of existing orders,...) have to be carried out continuously. Therefore production plans may have to be *rescheduled*. Note that this rescheduling process may actually consist of making a full detailed new plan (schedule) capturing the new situation on the shop floor, but for us, the distinction between scheduling and rescheduling would lie basically in the aims sought in the decision: While scheduling decisions would aim at improving certain performance measure in the shop floor, rescheduling aims to minimize some measure of the disturbance of the current status on the shop floor, usually upon the arrival of unexpected events. An implicit assumption behind is that—at least under certain circumstances—it may be more interesting to modify an existing schedule to accommodate new events occurring in the shop rather than generating a new schedule (almost) from scratch in order to fully take into account these new events. While under ideal circumstances the later would always render a better solution, there are costs associated to this so-called *nervousness* resulting from the scheduling process.

Note that sometimes different definitions are employed to distinguish between scheduling and rescheduling, as some authors use the terms predictive scheduling and reactive scheduling instead. A predictive schedule is an instruction to the shop floor, causing the shop to execute events in the sequence and time indicated in the schedule, while the process of modifying the predictive schedule in the face of executional disruptions is denoted as reactive scheduling. Note that the definition of reactive scheduling not only encompasses our definition of rescheduling, but also generating a completely new schedule that is followed until the next disruption occurs. These aspects will be discussed in detail in Sect. 2.3.1.

It is clear that the scope and the time period to take these decisions greatly influences the quality of the data used to support the decision process. Broadly speaking, long-term decisions usually involve speculations on the evolution of the market and on the internal resources in the company, and thus are by nature less amenable to be formalised using quantitative techniques that require a high quality in the input data to make a sensible decision. Besides, there is little sense in formalising the decision process itself, since the changing nature of the business and the long intervals among two consecutive decisions of this nature makes them to be unique in practice. Here, human judgement based on expertise and on a few key estimations is usually what is required to make this type of decisions. On the contrary, the repetitive nature of short-term decisions make them suitable to be formalised and possibly encapsulated into decision models, which can produce remarkable results as one can reasonably trust on data related to the current state of the shop floor, the average processing times of the machines, and on the (relative) stability of the list of orders to be completed to be able to capture the decision process into a quantitative model that can possibly be solved as an optimisation problem. Indeed, these two aspects (repetitive nature of the decision process, and the high volume of data required to support it) make quantitative, procedural techniques to be competitive as compared to the human subjective expertise.

It is also interesting to note that scheduling does not only serve to generate detailed plans to be executed, but can be also used to provide a source of information for different business functions in the company. For instance, it may serve to provide a capacity-check for the Materials Requirement Planning (MRP) system, or to help quoting an incoming order from customers, or to decide about its acceptance/rejection. Again, we can see the close interrelation of scheduling to other business functions, and quite often the distinction between scheduling and these functions would blur. For purely practical purposes, in this book we would exclude from scheduling those decisions for which the level of detail considered with respect to time, resources, products, or customers is not enough to provide a specific plan to be immediately translated into actions on the shop floor.

Given the high level of interrelation among different production management decisions (including scheduling) shown in the previous paragraphs, one may be tempted to try establishing a prioritisation of these decisions, in order to more efficiently allocate the usually scarce financial and human resources to those decisions with higher impact in the bottom line of the company. However, we believe that discussing whether the scheduling function is more important than quality management, supply chain coordination, or product design (to name a few examples of operations management decisions) is a useless discussion for any practical purpose. It is obvious that without an overall good operations management, better scheduling will not help to improve the results of a company no matter how well the scheduling function is performed, and the same can be said about the different decisions. Nevertheless, it should be clear that scheduling is a core business decision for industrial companies. As such, its importance greatly depends on the strategic importance of manufacturing decisions to gain competitive advantage. For instance, it may not be as critical for companies trying to sell a small range of new products avidly accepted by the market with little opposition from competitors, but it would help companies manufacturing a large range of products in obtaining a competitive advantage as compared to their competitors. Indeed, the quality of scheduling is often cited as a key factor if the products and the factory are well-designed.

Since scheduling is closely related to the allocation of resources, it is also obvious that its importance would increase with the possibility of having a conflict for the usage of these resources. Along the history of manufacturing, this conflict for the usage of resources (which is not desirable) has been traditionally avoided by designing shop floors manufacturing a limited range of products with similar technological requirements. Unfortunately, the trend towards mass customisation, shortening of product life-cycles, time-based competition, and the globalisation (with the corresponding increase of competition) has made this solution unacceptable for most companies. Another option has been what is described as 'management by buzzword' (Hopp and Spearman 2008) meaning the vast stream of three letter acronyms encompassing the ultimate solutions for production management. While these apparent business panaceas (one every few years, just another proof that they are not panaceas at all) may contain valuable insights, mostly translate into approaches neglecting or ignoring the realities of manufacturing scheduling. Given the wrong answer provided by the two previous options, we believe that there is no other way than addressing scheduling in full detail, with its complexities and their enormous opportunities for operational improvement.

1.3 Features of Scheduling

Scheduling decisions may be very different from one company to another, but all they share a number of common features. In this section, we will discuss these features in order to obtain certain degree of abstraction that may serve us to formulate a generic framework useful for different companies. These features are:

- They are complex decisions, as they involve developing detailed plans for assigning tasks to resources over time. Although this may vary greatly from one company to another, there is a universal trend on increasing the sophistication of the products and on their customisation, which in turn affects to the complexity of the manufacturing process.
- Scheduling decisions are short time interval decisions to be taken over and over. The average lifetime of a schedule is very short, and indeed many authors refer to a continuous scheduling decision process. Here we mean that what is repeated is the decision process, which is different from stating that the outcome of a single decision is put into practice rhythmically again (cyclic scheduling).
- Despite being a short-time decision, scheduling is relevant for companies' bottom line, as it determines the lead times and the cost of the products, which on the long run affects the service level of the company as well as its ability to compete both in manufacturing costs and on delivery times.
- As a decision process at the core of the operations of a manufacturing company, the constraints and objectives affecting scheduling are extremely company-specific. The nature and usage of the resources in a plant producing chemical commodities has little in common with manufacturing ball bearers, or assembly of highly customised electronic devices.
- Finally, scheduling decisions are—as we already discussed—relatively structured decisions, at least as compared to other decision problems within the company. Its

operational nature makes scheduling to require fairly well-defined data, constraints and objectives.

In any case, we should recall that there is no way to escape from making (implicit or explicit) scheduling decisions in manufacturing companies. Perhaps ironically, this fact has led sometimes to the underestimation of the potential advantages of efficient scheduling, since, as some plant managers put, ‘we already do scheduling’. The truth is that, most often, such scheduling is accomplished in a non-structured, expertise-dependent manner, with partial information both about the inputs of the process and with respect to the desired output. The consequences of this approach are obvious: underutilisation of resources, longer lead times than required, higher inventories, ... to name a few. This book is about how to conduct this process in a systematic, efficient manner.

1.4 A Framework for Manufacturing Scheduling System

As we have seen in the previous sections, scheduling consists of a dynamic and adaptive process of iterative decision making related to assigning resources in the plant to manufacture a range of products over time. This process is carried out by humans (schedulers or decision makers) which may be assisted by a software tool that helps them to model some decision problems arising during this process, and to find a solution for these by employing methods (or solution procedures) on these models. Four remarks are inherent to this definition:

- First, scheduling is a *process*. It is not about formulating and solving a specific problem once, or even repeatedly solving the same problem again and again. This dynamic view contrasts with the static approach found in most scheduling literature, and emphasizes the fact that manufacturing scheduling is a business process that should be managed over time. As such business process, it is a dynamic, evolving situation for which ‘cooked’, monolithically designed procedures seldom work.
- Second, the scheduling process is directed by a human, a team, or an organisation. The vision of fully automated systems that perform and execute scheduling decisions without human guidance does not reflect the current reality in most shop floors. Therefore, there is a need to understand and incorporate the human element into this decision process.
- Third, the relatively structured nature of the scheduling process *and* its inherent complexity leads naturally to the convenience of formulating the decision problem in terms of mathematical models to better assess the decisions to be taken by the schedulers, as well as the corresponding methods to solve these models. However, the formulation of such models and the implementation of the solutions provided by the corresponding methods is far from being trivial/immediate and should be driven by the human element mentioned in the previous item.

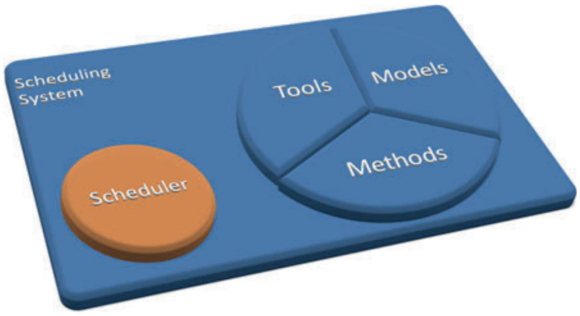

Fig. 1.1 Framework for manufacturing scheduling systems

- Fourth, although strictly speaking there is no need of a tool to support the schedulers in their decisions, in most cases it is completely unpractical to conduct them without any help from a software tool. Simply the sheer volume of data referring to resources and tasks found in most shop floors would be sufficient to justify the need of such tool. Whether this software is a spreadsheet, an 'off-the-shelf' software, or an advanced planning and scheduling tool is a question that will be discussed later in this book, but from now on we will assume that some type of support exists.

From the above paragraph, it should be clear that, in order to effectively perform scheduling decisions, a system—i.e., a collection of pieces—is needed. The combination of *models*, *methods* and *tools*—together with the human schedulers involved in the process—is what we call a *scheduling system*. Scheduling models, solution procedures and software tools all play an important part alone, but they have to be put together to make up scheduling decisions. Therefore, a holistic view—in contrast to the more extended technical or optimization-related view—is needed to have a complete picture of scheduling.

This book is thus adapted to the above view, which is summarised in Fig. 1.1. In the next chapters, the different elements of the scheduling system will be described one by one. To start this discussion, a number of basic concepts are defined in the next section.

1.5 Basic Concepts

By formalising the ideas given in the previous sections, we can define manufacturing scheduling as the decision-making process consisting of assigning the set of operations/tasks required to manufacture a set of products to the existing resources in the shop floor, as well as the time periods to initiate these operations/tasks. A *schedule* is defined as a specific assignment of these operations/tasks to the resources on a time-scale. A schedule thus fully determines when each operation/task should start and it is regraded as the main output of manufacturing scheduling.

The products to be manufactured, or the units of work that the manufacturing activity can be divided into are usually referred to in the scheduling literature simply as *jobs*. Although in most of our book we will assume naturally the existence of such units of work, the concept of job is by no means unambiguous as it might be dependent on the company, context, and manufacturing setting. Clients' orders might be broken down into different Fabrication Orders (FO). Several FOs coming from different client orders might be coalesced to form larger FOs that might be more economical to produce. Later, these large FOs could be again broken down, at a shop level, into smaller, but not necessarily and immediately consecutive, sublots into what is called a lot streaming process. We will discuss these aspects in Sect. 3.4.

The operations/tasks required by the jobs are provided by different productive resources available in the shop floor. These could range from cheap tooling and fixtures to human resources and expensive machinery. Again, we will assume that it is possible to identify units of resources that can perform these operations/tasks, and, accordingly to the scheduling literature, we will refer to them simply as *machines*. As with the jobs, the concept of 'machine' is an abstraction (or mental model) of real-world operations and is therefore subject to the purposes of the modeling activity, i.e.: for estimating the throughput of a factory, the whole factory with all its resources can be considered as a 'machine', while for providing a daily timetabling of the work that the operator of a drilling machine in this factory must perform, the previous assumption of machine is clearly insufficient.

In addition, there are many technical/production/economic characteristics of the jobs, of the machines, and of the operation of a job on a machine that must be taken into account in the scheduling process. Although these will be formalised and extended in Sect. 3.1, let us state perhaps the most obvious:

- There exists machine specialisation: Not all machines can perform every operation required by each job, as manufacturing resources are usually capable to perform just one or at most few operations. Even in the case that such a thing is possible (e.g. by polyvalent workers or general-purpose machines), it is extremely doubtful that their efficiency is operation-independent, so at least preferences/exclusions would have to be defined.
- The order in which the different operations have to be performed on a job is usually fixed given the specific technology of the product to be manufactured, i.e. there exists a predefined order (or orders) of operations for each job that must be strictly followed. This order is labelled *job processing route* and will be further formalised in Sect. 3.2.2.
- In general, different jobs have different requirements with respect to the technical, production management, and economic aspects. From a technical viewpoint, even if two jobs have the same processing route, some characteristics of the operation (such as e.g. processing time, or set-up times) may be different. From a production management/economic viewpoint, technically identical jobs may have different

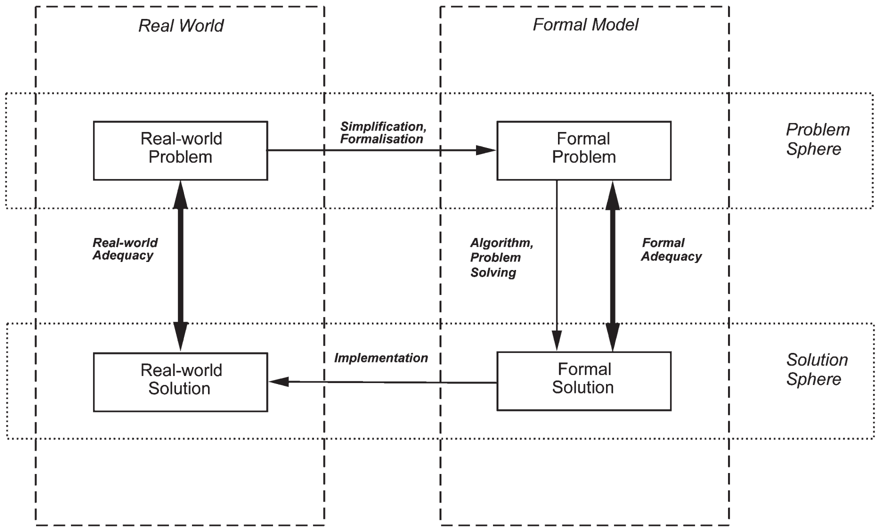

Fig. 1.2 Real world and formal model, problem sphere and solution sphere for decision-making

due dates committed to the customer(s), or are to be sold with different benefits, or may require raw materials which are not served by the provider at the same time.

- All/some of operations/tasks may allow the so-called *preemption*, which refers to the possibility (for all/some jobs) of interrupting the operation once it has started. If such a possibility exists, the execution of the operation can be stopped and resumed later with/without any/some penalty (these cases are denoted as resumable or semi-resumable operations, respectively). There are manufacturing examples of both preemptive and non preemptive operations. Heat/Chemical treatments are basically non preemptive operations, as they correspond to gradually changing the physical or chemical properties of the material under treatment, a process that, in general, cannot be reversed to the original properties of the material. On the other hand, some assembly operations are preemptive, at least from a technological viewpoint, although there may be managerial/economic considerations deterring or impeding the preemption of such operations.

As stated, these are just a fraction of the jobs/machines/operations characteristics that should be taking into accoung in the scheduling decision process. As a consequence, not every schedule that we may think of can take into account all these characteristics. In such case, this schedule is denoted as *unfeasible schedule*, as it cannot be directly translated into commands for the shop floor. Obviously, the primary goal in a scheduling process is to find at least one feasible schedule. Provided that more than one feasible schedule exists, the goal is to select (at least) one feasible schedule among the set of feasible schedules available.

Therefore, manufacturing scheduling can be viewed as a *decision-making problem*, i.e. a process to select a course of action (i.e. a schedule) among several alternative options. To do so, one or more metrics (or *criteria*) have to be defined to characterise the desired features of the schedules. Once the criterion is established, it is (at least technically) possible to compare different schedules, and to select one yielding the best value (maximum or minimum) for this criterion among all feasible schedules (*optimal schedule*).

In manufacturing, metrics are usually classified into the categories of costs (sometimes profit), time, quality and flexibility. As it will be discussed in Chap. 5, in scheduling decision-making these categories are associated with criteria related to the *completion time* of the jobs. Loosely speaking, the completion time of a job in a specific schedule is the time spent by the job in the shop floor—according to the schedule—before all its corresponding operations have been performed. Note that the completion times of the jobs in a schedule serve to know whether executing this schedule would result in delays on the delivery of the jobs with respect their committed due date, or the average time required, according to this schedule, to process the whole set of jobs.

If the criterion employed is a non-decreasing function of the completion times of the jobs, then this criterion is named *regular*. One obvious example of a regular criterion is the average completion time of the jobs, while the average delay of the jobs with respect to their due dates is an example of a non-regular criterion. Finally, note that more than one criteria can be of interest, and that there might be conflicts between them. An exhaustive discussion and classification of the different criteria employed in scheduling is given in Chap. 5, while multicriteria scheduling is discussed in Chap. 10.

In order to highlight the main issues related to scheduling decision-making, we map in Fig. 1.2 the well-known flow of a decision-making process, at least for quantifiable decision problems: Starting at the real-world problem, for which a decision is required, a formal model is derived by means of simplification and formalisation. By using some formal procedure or *algorithm* (see Sect. 7.2.1 for a more precise definition of algorithm), this formal model is solved, i.e. a formal solution for this problem is derived. Afterwards, within implementation this formal solution is transferred to a real-world solution which is implemented for solving the real-world decision problem.

The scheme presented in Fig. 1.2 is rather basic and superficial, and it can be complexified to almost every level. We just refer to this simplification because it depicts the basic issues related to manufacturing scheduling decision-making. We will go back to this figure in Chap. 6 (when discussing the transfer of real-world relations into a formal, mathematical decision model and the techniques to set up a respective formal model), and in Sect. 7.1 (when addressing the adequacy of the formal solutions found by the algorithms to the real-world problem).

Since it has been established that obtaining (one or several) schedules is the main goal of the manufacturing scheduling decision problem, in the next sections we will present ways to represent schedules (Sect. 1.5.1), their main types (Sect. 1.5.2), and the number of existing schedules (Sect. 1.5.3).

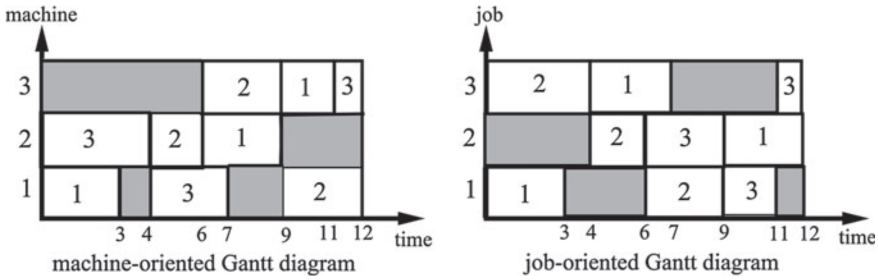

Fig. 1.3 Machine-oriented and job-oriented Gantt diagrams (Domschke et al. 1997)

1.5.1 Representation of Schedules

A schedule is traditionally represented by the so-called Gantt diagrams. While always horizontally mapping the time scale, with respect to the vertical axis Gantt diagrams can be machine-oriented or job-oriented. Figure 1.3 shows these two types of diagrams for the same schedule. The length of each box represents the length of the operation in the job or machine, depending on the diagram.

Note that the first of the two diagrams indicates the sequence in which jobs are processed on each machine, i.e. the first machine processes job 1, then job 3, and finally job 2. In the following, we will denote this sequence of jobs using a vector, i.e. the previous job sequence is denoted as $(1, 3, 2)$. This is an important notation since, as we will discuss later, there are occasions in which a full specific schedule can be obtained just by giving these sequences of jobs (or sequences for short) on each machine.

A modern and perhaps more adequate way of representing schedules is the disjunctive graph presentation which will be shortly described below. A disjunctive graph is a graph $G = (V, C \cup D)$ where V denotes a set of vertices corresponding to the operations of jobs. C is a set of conjunctive arcs connecting every two consecutive operations of the same job. The undirected edges of set D connect mutually unordered operations which require the same machine for their execution. Each vertex is weighted with the processing time of the operation at its start. The edges have weight 0. In the disjunctive graph representation, obtaining one schedule is equivalent to select one arc in each disjunction, i.e. to turn each undirected disjunctive edge into a directed conjunctive arc. By fixing directions of all disjunctive edges, the execution order of all conflicting operations requiring the same machine is determined and a complete schedule is obtained. Moreover, the resulting graph has to be acyclic.

An example of a disjunctive graph is given in Fig. 1.4 In this example there are three machines $M = \{M_1, M_2, M_3\}$ and a set of three jobs $J = \{J_1, J_2, J_3\}$ which are described by the following sequences of operations: J_1: $T_1 \rightarrow T_2 \rightarrow T_3$, J_2 : $T_4 \rightarrow T_5$, $J_3 : T_6 \rightarrow T_7 \rightarrow T_8$. For any operation T_i the required machine $M(T_i)$ and the processing time p_i are assumed to be known.

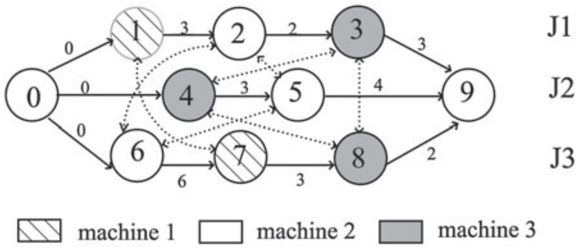

Fig. 1.4 An example for a disjunctive graph (Błażewicz et al. 2000)

1.5.2 Classes of Schedules

For non-preemptive scheduling problems, several classes (or types) of schedules can be identified. As we will see, these classes are used

1. to reduce the number of possible schedules which reduces the search effort for good or optimal solutions as compared with a continuum of solutions, and
2. to identify properties of the solution space and/or good or optimal solutions to adjust solution procedures accordingly.

The classes of schedules that can be considered are:

- *Non-delay schedules:* A schedule having no unforced idle time on any machine is called a non-delay schedule, i.e. a feasible schedule belongs to the class of non-delay schedules if and only if no operation is kept waiting while the machine assigned to this operation is available to process it.
- *Active schedules:* A schedule is said to be active if no operation can start earlier without delaying at least one other operation in this schedule. Obviously, non-delay schedules are active whereas the opposite does not hold.
  It can be shown that for scheduling decision problems with a regular criterion there is an active schedule which is optimal. Note that this does not hold for non-regular criteria.
- *Semi-active schedule:* A feasible schedule is called semi-active if no operation can be completed earlier without changing the order of processing on any one of the machines. Obviously, an active schedule has to be semi-active. However, the reverse is not necessarily true. Intuitively, semi-active schedules are characterised by the fact that every operation is left-shifted as much as possible, i.e. given the current sequence of operations on every machine, every operation is started as soon as possible.

The classes of schedules are further detailed in Fig. 1.5. Note that, in order to take advantage of restricting the search of the optimal solution to a certain class of schedules, it has to be checked in advance whether all optimal solutions (or at least one of them) fulfil the respective property. In this case, the effort to find an adequate

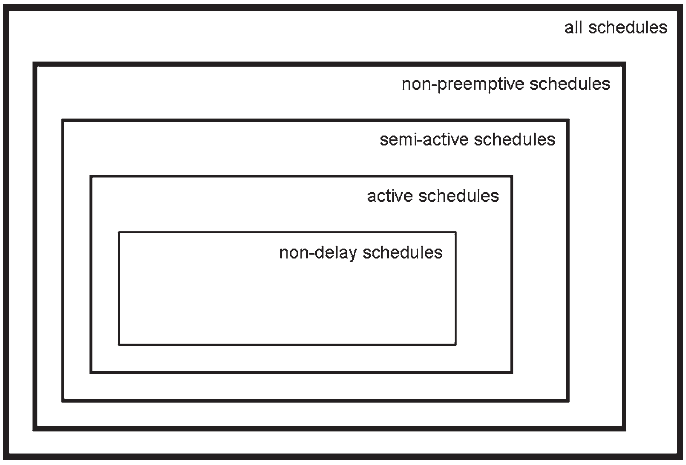

Fig. 1.5 Classes of non-preemptive schedules for job shop problems (similar to Pinedo 2012; T'Kindt and Billaut 2006)

(possibly optimal) solution might be reduced significantly as compared with the evaluation of all possible solutions.

1.5.3 Combinatorial Nature of Manufacturing Scheduling

Although the expressions schedule and sequence are often used synonymously in the literature, one schedule uniquely defines a sequence but not vice versa. Often, especially in a multi-stage context, (at least non-critical) operations will have some time buffer within a given sequence. These time buffers will open ranges for the assignment of these operations to the time-scale. Operations might be assigned 'left-shifted' to their earliest possible processing period (as is often supposed in scheduling procedures), 'right-shifted' to their latest possible processing period (as might make sense from a profitability point of view, i.e. to minimise tied-up capital), or somewhere in between (e.g. if externally specified due dates should be reached and neither early nor late completion of operations or jobs, respectively, is intended).

In general, the number of feasible schedules for most manufacturing scheduling problems will be infinite while the number of sequences will be countable and even finite, however possibly rather large. I.e. although the number of sequences on every single machine and in combination over all machines will be finite, a single operation might often be shifted continuously on the time scale, at least within some time limits. However, if we can prove, as holds in many scheduling settings, that an optimal solution will always be active (at least in some non-preemptive scheduling problems, see Sect. 1.5.2), no matter whether left-shifted or right-shifted, the number of solutions to be considered for the determination of an optimal solution will be finite.

As a consequence, manufacturing scheduling problems are usually classified as combinatorial problems since the number of solutions to be considered in the optimisation process can be limited to a finite number. Therefore, procedures to generate feasible and optimal solutions can be basically enumerative. However, as we shall see in Sect. 2.3.2.1, (complete) enumeration will usually require too much of time and of other computational resources. Consequently, other maybe approximate methods will be more appropriate.

1.6 Conclusions and Further Readings

During the last decades, manufacturing scheduling has been identified to be one of the most important decisions in planning and control of industrial plant operations, both in science and in practice. Scheduling is seen as a decision-making process that is used in manufacturing industries as well as in service industries.

In this chapter we have introduced the conceptual framework which we will use throughout this book. We have given a definition of manufacturing scheduling and (even if only in a coarse manner) delineated which aspects are within the scope of the book, and which are not. A framework for studying and connecting the different topics involved in manufacturing scheduling (models, methods and tools under human guidance) has been presented, and the basic scheduling concepts have been introduced.

The remainder of the book follows the structure summarised in Fig. 1.1. First, in Chap. 2 we finalize Part I, which has been devoted to analysing the manufacturing context in which scheduling takes place. We then discuss the issues related to the different parts in a scheduling system as depicted in Fig. 1.1 one by one: Part II of the book (Chaps. 3, 4, 5 and 6) is devoted to scheduling models, Part III (7, 8, 9, and 10) to scheduling methods, and Part IV (Chaps. 11 and 12) to scheduling tools. Finally, Part V (Chaps. 13, 14, and 15) relinks all these elements into the concept of a scheduling system by discussing its relations with its organisational (i.e. human) environment, and the process of developing such systems. This part concludes by presenting a real implementation in which the main concepts and issues discussed in the book are presented.

As scheduling is an area of utmost importance in Operations Research and Management Science, there is a wealth of books dealing with specific aspects of scheduling. We omit those books of wider scope (e.g. in Operations Management) that partially cover scheduling decisions in one or two chapters. Among these, we would like to cite the book by Hopp and Spearman (Hopp and Spearman 2008), although there are other excellent books on Operations Management. Interestingly, the reader would detect that, in some of these books, the authors do not seem to feel very comfortable placing scheduling in the context of production management and the tone and content of the chapter(s) devoted to scheduling are quite different than that of the rest of the chapters.

Regarding the scheduling topic itself, the book acknowledged to be the first book devoted to scheduling is Conway et al. (1967). This book, and most pre-dated to 1995, seems today a bit outdated as the scheduling field has almost unrecognisably changed since, and the contents would be entirely different even if the topics addressed were identical. Regarding introductory readings on the topic of manufacturing scheduling, there are many excellent books, although most of them lean towards one or two of the components of our framework. Among the principal books, here we mention those by Baker (1974); French (1982); Błazewicz et al. (2002); Brucker (2007); Pinedo (2012); Baker and Trietsch (2009) or Pinedo (2009). Less known but interesting references are those of Domschke et al. (1997).

The terms predictive scheduling and reactive scheduling are discussed—although in a slightly different manner than here—in Aytug et al. (2005). The last reference is also a key source regarding the use of scheduling for providing information for different business functions in the company. Specifically, the uses of scheduling for due date quoting and acceptance/rejection decisions are discussed in Framinan and Leisten (2010). An excellent book describing human performance in scheduling is MacCarthy and Wilson (2001). Brucker (2007) is devoted mostly to models and methods for scheduling problems, not confined to the manufacturing field.

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Chapter 2
The Context of Manufacturing Scheduling

2.1 Introduction

In the previous chapter, a unified view of manufacturing scheduling has been given. Furthermore, we have also outlined that manufacturing scheduling is not carried out in an isolated manner, but as part of a set of interrelated decisions—collectively known as production management—dealing with efficiently ensuring the delivery of goods provided by the company. Therefore, before analysing manufacturing scheduling decisions in detail, it is worth looking at the context in which manufacturing scheduling is embedded: i.e the company's production management and in the supply network to which the company belongs.

More specifically, in this chapter we

- present a framework for scheduling decisions (Sect. 2.2),
- analyse manufacturing scheduling as an isolated decision process and study the main aspects influencing these decisions (Sect. 2.3) and
- investigate the relationship of manufacturing scheduling with other decisions in the company and its supply chain network (Sect. 2.4).

2.2 A Framework of Manufacturing Scheduling

The basic definitions for manufacturing scheduling have been given in the previous chapter. In this section, we now discuss the decision framework of manufacturing scheduling, i.e. the main aspects influencing the scheduling decision process. We adopt a systems analysis approach: A system can be characterised by its objects and their relations and whether it is closed or open (i.e. whether it does not include relations to the off-system environment or it does). Manufacturing scheduling can be interpreted as a closed system when it is studied as an isolated decision process, and also as an open system when the focus is set on its relationship to other decision processes.

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This dual (open and closed) view will be extended in the next sections. First (Sect. 2.3), we study manufacturing scheduling as an isolated decision process and will discuss the main aspects influencing these decisions. Next (Sect. 2.4), the relationship of scheduling with other decisions is investigated. These relationships can be classified into three types:

- Relationship between manufacturing scheduling and the rest of decisions in production management (Sect. 2.4.1).
- Relationship between manufacturing scheduling and the rest of decisions (apart from those in production management) within the company (Sect. 2.4.2).
- Relationship between manufacturing scheduling and the rest of decisions in the supply network in which the company is integrated (Sect. 2.4.3).

2.3 The Closed View of Scheduling Problems and Decisions

Manufacturing scheduling problems and decisions can be classified along different dimensions or features. Perhaps the most employed dimensions are the following:

1. Deterministic vs. stochastic. In the case where all the characteristics of the decision problem (processing time of each operation, release date, due date, etc.) are well known and single-valued, the decision problem is of deterministic type. In contrast, it is considered of stochastic type if at least one of these characteristics is not known deterministically but only with its probability distribution.
2. Static vs. dynamic. If all the relevant data of the decision problem are known in advance, i.e. at the point in time where the planning procedure starts, then the problem is classified as static. If it is taken into account that intermediately (i.e. before the realisation of the schedule is finished) appearing new information is included, the scheduling problem is called dynamic.
3. Organisation of the decision process (centralised vs. decentralised). In a centralised manufacturing environment all jobs/operations are scheduled to all machines by a central planning authority. A main task to make such systems run effectively is the provision of this institution with all relevant information. In decentralised systems, in its extreme version, one planning institution exists separately on each stage. These authorities, of course, have to interact with each other, given the reason for agent-based scheduling approaches both in practice as well as item of the scientific consideration. Carefully setting up the respective information system, therefore, is one main task when setting up decentralised scheduling systems.
4. Scope of the solution to be generated (complete vs. partial schedule). If the outcome resulting from the scheduling process is not complete, it is called a partial schedule. The incompleteness of a partial schedule can refer to many items. For example, not every machine and/or type of operation might be considered, the time horizon regarded might be limited deliberately, etc. In a well-organised

planning and control system, also for manufacturing scheduling, the effects of such a limited scope have to be anticipated and examined carefully.

We can use the above structure to classify scheduling decisions. This classification will be employed in the next subsections when we analyse the main aspects influencing manufacturing scheduling, namely time, complexity, variability and flexibility.

2.3.1 Time

As already discussed, time is the main reference point of scheduling and scheduling decisions. Apart from duration, starting and ending specification of operations and their assignment to the timescale by scheduling decisions, there are several further time-related issues in scheduling, which are graphically described in Fig. 2.1. These are:

- Point in time of scheduling. The point in time of a scheduling decision itself, its level of information with respect to the real-world scheduling problem (e.g. the degree of determination of operations duration or even operations' determination in total) or, more precisely, its time lag to the first operation to be physically executed may play an important role concerning the quality of the scheduling decision.
- Scheduling horizon. Scheduling horizon refers to the time horizon of operations or jobs considered in the scheduling process. The scheduling horizon is strongly related to the selection of jobs included in the scheduling decision problem.
- Scheduling frequency refers to the frequency and the trigger of updating of a schedule, by including new information arrived meanwhile into the new scheduling decision can be controlled. This updating process might be rhythmic or event-based, e.g. if a new job arrives or a machine becomes (un-)available.
- Realisation horizon. Closely connected to scheduling horizon and scheduling rhythm is the determination of the realisation horizon, i.e. those part of the scheduling horizon which is implemented, usually at least until updating by the next (possibly re-)scheduling decision takes place. This happens because scheduling is often performed on the well-known *rolling horizon* basis, i.e. a schedule is constructed for the scheduling horizon, but it is executed only for the first few periods of this horizon (i.e. its realisation horizon) before it is updated by a new plan using updated input data.

Additionally, it should be mentioned that the grid of the time scale might influence the quality of the scheduling decision as well. However, usually, the time grid assumed for the process, may it be minutes, hours, shifts or days, will be 'adequately' detailed, i.e. will not contribute to significant infeasibilities and/or suboptimalities.

Closely related to time aspects in manufacturing scheduling is the consideration whether a new or updated schedule is generated from scratch as a greenfield solution or whether at least parts of it are predetermined by remaining operations from the

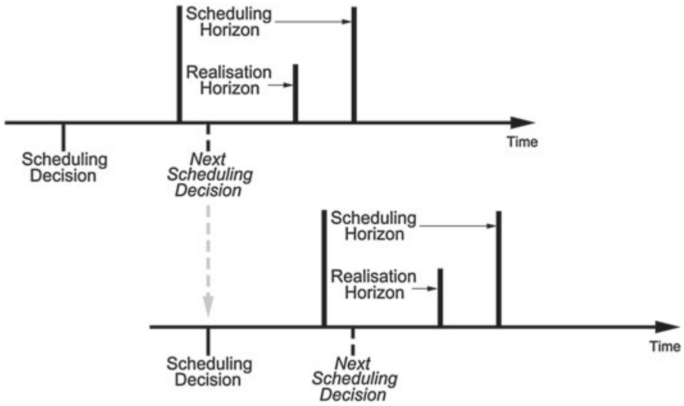

Fig. 2.1 Time aspects of manufacturing scheduling

former schedule. The latter case is, obviously, more realistic and sometimes expressed by something like 'the tails of the former schedule are the heads of the new, updated one'. However, many scheduling approaches in science as well as their software implementation in practice disregard this predetermination of the beginning of a schedule (at least on some machines) and generate the new schedule from scratch (usually including the remaining operations of the former schedule) into the planning process of the new iteration, not as fixed in the beginning of the new schedule.

In order to avoid nervousness consequences already mentioned in Sect. 1.2, plan revisions in this update might be intended to be avoided or at least be minimised from a planning point of view, and only new jobs should be appended to the old plan. However, the relevance of this update has to be interpreted at least two-fold: On one hand, jobs (or at least operations) already started should be more or less fixed and their schedule might be, therefore, fixed as input data for the new schedule. The time period covering such jobs/operations is denoted as *frozen period*. On the other hand, if previously scheduled jobs have not yet been started or physically prepared in the shop floor, respectively, their preliminary schedule might be known only to the planner while shop floor people possibly got no information on these scheduled but not yet released jobs/operations up to the replanning point in time. Therefore, these latter jobs/operations may be very well considered anew in the replanning procedure of the rolling horizon approach—without causing much additional nervousness to the shop floor level.

A further approach to reduce nervousness in the shop floor is to expand the frozen periods to more than the plan revision point in time, so plan revisions enter the shop floor more 'smoothly'. However, this advantage with respect to reduced nervousness is balanced by a reduced reaction speed of the shop floor.

Another way of updating schedules is *event-oriented scheduling*. Predefined types of events, such as newly arriving and/or cancelled jobs, machine failures or unavailability of material, tools and/or staff, processing times different from the planned ones (a very common situation), etc. give reason for updating the schedule. Sometimes, not a single modification but a certain amount (number) of modifications is awaited before a plan update is initiated. The modifications might be just added to the old schedule or a more or less complete replanning is executed while avoiding nervousness, if possible, as mentioned above with respect to the rolling horizon approach. It should be pointed out that event-oriented scheduling requires more or less permanent observation (and availability) of all relevant actual data.

As already mentioned, the scheduling process itself might be *static* or *dynamic*. Static in this context does not necessarily mean the absence of intermediate updating, e.g. in a rolling horizon context. And dynamic does not include only simply more than one planning period. Recall that static scheduling is separated from dynamic scheduling by the fact that static scheduling derive a plan/schedule always from scratch without taking explicitly into account that till the end of the execution of the plan changes might and will appear. The explicit provision of resources (time, capacity, etc.) for these changes and or scheduling with the explicit inclusion of these possible changes (e.g. by applying scenario techniques and/or techniques of flexible planning) characterise dynamic scheduling.

Within the dynamic context above mentioned, at least four different types of scheduling approaches can be identified:

- Completely reactive scheduling. This type of scheduling is defined more or less as online scheduling. Assuming the poor quality of centrally determined schedules as a drawback, it is supposed that quick and local reaction yields better scheduling results. Therefore, simple scheduling approaches (known as scheduling policies and described in Sect. 7.4), are locally applied on the shop floor level, possibly in real time to determine the next job to be processed on a specific machine. This approach is flexible and is able to include most recent information from the very detailed shop floor level. However, because of its myopic perspective, the overall performance of this approach is questionable since it usually includes an inherent lack of coordination.
- Predictive-reactive scheduling. The most common dynamic scheduling approach in manufacturing systems is called predictive-reactive scheduling. It combines static-deterministic scheduling as a first step with event-based reactive, possibly real-time updating of schedules in the meantime as second step until a new static-deterministic schedule is generated. Apart from its time coordination effect between the two steps, this approach is also intended to coordinate the broader view of the overall system to be scheduled in the first step with the myopic perspective of rescheduling in the second. However, as often confirmed empirically, large tolerances in the second step often significantly reduce the overall performance of the system since the finally implemented schedule may deviate significantly from the original schedule—and the deviations are a result of local, myopic considerations exclusively.
- Robust predictive-reactive scheduling. Taking into account the problems of predictive-reactive scheduling, additional robustness considerations should be included, both with respect to the robustness of the first step's overall schedule

and the limitation of the second step's tolerances. The focus of robust predictive-reactive scheduling is building predictive-reactive schedules which minimise or at least limit the effects of disruption on the performance measure values of the realised schedule.

- Robust proactive scheduling. Robust proactive scheduling intends to immunise the predictive schedule in advance against possible stochastic disruptions. Usually, specific time buffers are included to cope with this kind of uncertainty and to make the predictive schedule robust. Determination of the predictability measures is the main difficulty of this approach.

Predictive scheduling is an integral part of manufacturing systems planning. Predictive schedules are often produced in advance in order to direct production operations and to support other planning activities. Since most manufacturing systems operate in dynamic environments subject to various real-time events, this may render the predictive optimal schedule neither feasible nor optimal. Therefore, dynamic scheduling is of great importance for the successful implementation of approaches to real-world scheduling systems.

Rolling horizon approaches and reactive scheduling can be interpreted as manifestations of *rescheduling* approaches. These rescheduling approaches may be triggered externally, e.g. by newly arriving orders or by reaching the next planning point in time. They might be induced, however, also internally, i.e. by every significant deviation from the planned, predictive schedule derived earlier. The reasons for these deviations might be multifaceted as is well known. They can refer to resource availability, stochasticity of processing times, etc. The decision whether a deviation is significant (i.e. it initiates an update of the schedule) or not, depends on the assessment of the decision maker(s). In case of large deviations and subsequent adjustment requirements, the existing schedule can be updated, repaired or rejected/stopped. In the latter case, a completely new schedule will be determined.

The 'core' rescheduling approaches include updating and repairing of a schedule. Rescheduling in this perception is said to be 'the process of updating an existing production schedule in response to disruptions or other changes. This includes the arrival of new jobs, machine failures, and machine repairs.' (Vieira et al. 2003). Reasons for rescheduling may also be due date changes, job cancellations, delay in the arrival or shortage of materials, change in job priorities, rework or quality problems, overestimation or underestimation of processing times, operator absenteeism, etc. Reaction to rescheduling requirements does not only include the modification of the schedule itself but may also refer to the modification of its preconditions, including the alternatives of overtime, assignment of utility persons, in-process subcontracting, process change or re-routing, machine substitution, etc. These arrangements represent means to augment the manufacturing capacity as basis of a (re-)scheduling decision while opposite arrangements will reduce it.

Vieira et al. (2003) present a framework for rescheduling which includes rescheduling environments, rescheduling strategies (including rescheduling policies) and rescheduling methods as categories of classification. This framework is outlined in Fig. 2.2.

Rescheduling environments				
Static (finite set of jobs)		Dynamic (infinite set of jobs)		
Deterministic (all information given)	Stochastic (some information uncertain)	No arrival variability (cyclic production)	Arrival variability (flow shop)	Process flow variability (job shop)

Rescheduling strategies				
Dynamic (no schedule)		Predictive-reactive (generate and update)		
Dispatching rules	Control-theoretic	Rescheduling policies		
		Periodic	Event-driven	Hybrid

Rescheduling methods				
Schedule generation		Schedule repair		
Nominal schedules	Robust schedules	Right-shift rescheduling	Partial rescheduling	Complete regeneration

Fig. 2.2 Rescheduling framework (Vieira et al. 2003)

Since the rescheduling environment can be either static or dynamic (see classification above), in the static environment, a given set of jobs/orders/operations have to be scheduled while in a dynamic setting, jobs may arrive after the scheduling decision has been taken. Therefore, in principle, the set of jobs might be interpreted as infinite.

The static situation can be further separated into a deterministic and a stochastic setting. Note that a deterministic setting, either needs no rescheduling because it represents the 'true' situation, or an update is performed from scratch. In contrast, a dynamic environment might be (a) deterministic with respect to job arrivals (i.e. production cycles which are repeated again and again), (b) stochastic with respect to jobs' arrival times but with same flow of every job through the system (flow shop setting), (c) or dynamic with respect to arrival times and varying with respect to jobs' routes through the system (job shop setting).

Rescheduling strategies for simply adapting the current schedule or modifying it myopically then may use (mostly myopic) dispatching rules (see Sect. 7.4) or some control-theoretic approach which basically tries to keep the system in balance and initiates adaptations if the system under consideration runs the risk of getting imbalanced. Otherwise, the combination of predictive and reactive schemes which have been described above can be applied, periodically, event-driven or in some way hybrid. Finally, the possible rescheduling methods are obvious from Fig. 2.2, namely separating schedule generation from schedule repair approaches.

2.3.2 Complexity

Complexity, in many contexts, often is used as a rather nebulous expression or concept. References dealing with the definition and the discussion of the expression 'complexity' are as numerous as confusing. In systems theory, complexity of a system is given by the number and diversity of objects in the system as well as by the number and the diversity of the relations between the objects.

In parallel to Fig. 1.2 in Sect 1.5, complexity in manufacturing scheduling can be restricted either to the formal sphere on one hand, or can also be addressed more generally and then be extended to the real-world sphere. These two types of complexity are discussed in the next subsections.

2.3.2.1 Computational Complexity

Complexity on the formal sphere refers to the complexity of the formal problem and the corresponding algorithms for solving the formal problem. We refer to this type of complexity to as *computational complexity* and it will be treated in detail in Chap. 7. Roughly speaking, this concept of complexity serves to separate algorithms whose computational effort can be bounded by some polynomial function of some characteristics of the formal problem from those where such a polynomial limit has not been derived yet and where it will probably never be found. This separation is justified by the fact that polynomial approaches can be usually accomplished within reasonable computational effort while non-polynomial algorithms cannot.

In particular, algorithms performing an explicit or implicit enumeration of each feasible solution are of this non-polynomial type. Since, as we have discussed in Sect. 1.5.3, procedures to generate feasible and optimal schedules are basically enumerative, we can conclude that manufacturing scheduling is complex from this formal perspective.

A final remark is that the polynomial/non-polynomial behaviour of the algorithms refers to its worst case performance and does not give any insight in its average behaviour. In contrast, from a real-world application point of view, a non-polynomial algorithm might reach a good or even the optimal solution in reasonable time. However, the proof of this optimality might be the additional and very time-consuming step. This, from a practical point of view, gives reason to prematurely stop an optimising algorithm, especially if an available bound indicates that the maximum deviation of the current solution from the optimal solution is acceptable.

2.3.2.2 Real-World Complexity in Manufacturing Scheduling

It is a commonplace that real-world problems are complex and their respective formal problems are complex as well—no matter how complexity is defined. Here we just intend to structure real-world complexity and thereby to provide starting points for handling (including reducing) complexity.

Real-world decision problems usually include complexity imposed by a complex decision framework. This may include among others

- different, maybe even not clearly specified objectives,
- a large variety of sometimes not even clearly pre-specified constraints,
- a large, maybe even not clearly pre-specified number of possible actions,
- a possibly hierarchical or even not clearly specified system of planning and decision-making and decision-makers,
- complexity which is induced by dynamics and uncertainty,
- the interaction of all aspects mentioned above, within their category and between the categories.

As already indicated earlier, there is no clear definition of complexity. However, there is a shirt sleeve classification of complexity by Reiss (1993a, b) which can easily serve at least as a first approach to clarify complexity issues of a decision problem, and particularly manufacturing scheduling. Reiss classifies complexity aspects into

- *Mass aspects*, further divided into
  - Multiplicity, i.e. number of elements and interactions in the system, and
  - Variance, i.e. number of *different* elements and interactions in the system, and
- *Chaos aspects*, further divided into
  - Ambiguity, i.e. degree of uncertainty about the characteristics of the elements and interactions in the system, and
  - Changeability, i.e. the change of the characteristics of the elements and interactions over time (thus closely related to dynamics).

We point on the fact that classifying (manufacturing scheduling) decision problems by means of this scheme not only provides a systematisation but also gives hints on how to treat the complexity of a decision problem, may it be by simplification, by identifying the relevant issues, by indicating basic solution strategies, etc.

By applying this scheme of complexity classification to manufacturing scheduling, the multiplicity of a manufacturing system is determined, e.g. by the number of jobs, the number of stages etc. Diversity might, e.g. refer to the (non-)homogeneity of jobs processing times, the diversity of job routes in the system, etc. Replacing small jobs by a larger one, replacing single products by product types, ignoring possibly sequence-dependent setup times or replacing several machines on one (hopefully non-bottleneck) stage by one 'formal' machine with added up capacity on this stage are examples for strategies regarding the mass aspect of complexity in manufacturing scheduling. As is well known, these aspects are intensively dealt with in scheduling science and practice, however mostly, if at all, they are only implicitly seen within a complexity context.

In contrast, chaos aspects of Reiß' complexity classification, i.e. ambiguity/ uncertainty (deterministic vs. stochastic scheduling) and/or changeability (static vs.

Complexity aspects		Some drivers of complexity in manufacturing scheduling
Mass aspects	Multiplicity	Number of jobs, stages, etc.
	Variety	Diversity of jobs' processing times, number/type of operations required, etc.
Chaos aspects	Ambiguity	Uncertainty about processing times, release times, etc.
	Changeability	Arrival of new jobs, machine breakdowns, etc.

Fig. 2.3 Summary of the classification of complexity

dynamic scheduling), are much more explicitly addressed in the scheduling literature and in applications as discussed already earlier. Replacing a dynamic problem by a 'semi-dynamic' problem with large time grid or even by a static model (without intermediate update of information) or replacing probability distributions of processing times by their expected value are simplification strategies concerning the chaotic aspects of complexity.

Figure 2.3 summarises the discussion above. It should be mentioned that complexity of the decision-making problem (in our case, manufacturing scheduling) not only refers to the structural characteristics of the planning object(s) and their relations but also to the planning procedure, including the time needed for executing the procedure. On one hand, with respect to the formal complexity discussed in the previous section, this represents at least one interface to the approach to complexity sketched out there. On the other hand, the complexity of the solution procedure is closely connected to the speed of this procedure. Taking into account that real-time solutions have come up and are required for many scheduling problems during the last years, this aspect of complexity of manufacturing scheduling becomes increasingly important. It refers not only to the 'core' algorithms applied but also to related aspects as information and/or database management both, from the input as well as from the output perspective.

Using this concept of structuring complexity and applying it to manufacturing scheduling problems, can provide valuable hints of how to make the real-world scheduling problem manageable, e.g. by well-defined simplification strategies in model building and/or model solution and removing these simplifications when deriving and implementing a solution for the real-world problem.

2.3.3 Variability

Variability, in general, is a term that roughly spoken indicates a system's behaviour with respect to its deviation from uniformity. If variability is quantifiable, it is usually expressed by the coefficient of variation of the respective context. In this section, we address the influence of variability aspects depending on the strategic, tactical, or operating decision levels already discussed in Sect. 1.2.

On the strategic (long-term) level, this includes aspects of frequency of repetition of processes. In mass production, ideally only one process is manufactured permanently. Therefore, in such a manufacturing environment, a 'true' scheduling problem will not occur. In high volume but not mass production, often a production calendar will be generated which makes further scheduling considerations superfluous. Small and medium sized lots of products with medium to large heterogeneity are the main object of shop scheduling approaches. Many approaches and publications refer to this case. Individual design of products and process sequences lead to (capacitated) project planning in (job) shop environments being also a main subject of manufacturing scheduling approaches. Therefore, with respect to the long-term level, the more product and especially process variability occurs, the more relevant become manufacturing scheduling approaches.

Looking at the tactical (mid-term) level, i.e. referring to the allocation of resources/capacities, availability and flexibility are the main drivers of manufacturing scheduling with respect to the variability perspective. Flexible machines with small and possibly sequence-independent changeover times but presumably longer processing times per part are the counterpart to inflexible machines with long and/or sequence-dependent setup times but smaller processing times per part. Availability of machines also refers to the maintenance strategy. Small, more frequent interruptions because of (preventive) maintenance make the system usually better perform as compared to long, infrequent interruptions of (probably curative) maintenance after a machine breakdown. Similar considerations take place for workforce capacity, possibly accompanied by labour regulations.

On the operating (short-term) level, where among others scheduling decisions take place, we will refer to the scheme of Figs. 2.6 and 2.7 (see Sect. 2.4.1) for considering variability aspects. Input to scheduling from the upper levels of production management (see Sect. 2.4.1) usually comprises extended demand data (including type and size of demand, processing times, due dates, release dates, etc.). In most cases/companies, these data are taken as unalterable input to the problem. However, on one hand usually these data are often not as fixed as customers, the sales department or somebody else outside the manufacturing system claims. In a make to stock environment the targets derived from the demand prognosis might be discussed just as well as customer-driven due dates in a make to order environment. This is, e.g. reflected by the discussion on due date setting which is closely related to scheduling analysis in the recent past. By introducing flexibility to due dates (e.g. by introducing due windows or re-negotiating due dates after they have been preliminary fixed, see Sect. 2.3.4) variability of the system can be reduced, uniformity can be approached and the performance of the system may be improved. Further down, additional remarks on due date setting can be found. On the other hand, if demand data shows high and/or even increasing variability (which is not unusual in a world where demand lots decrease and the degree of customer-individual requirements for specific product features increase), this variability might not be reducible. In such cases, variability usually can only be handled by introducing buffers (time, capacity and/or inventory) or by allowing worse performance (lower service level).

In addition, at all levels, with respect to variability attention has to be paid on the bottleneck's performance of the system. On the long-term level, long-term capacity considerations will take place to harmonise the long-term capacities of the system. With respect to a mid-term horizon, availability of the bottleneck and/or guaranteeing its performance, e.g. by adequate maintenance strategies and/or allocating qualitatively and quantitatively sufficient manpower, will be main approaches to increase or to maximise the performance of the system. On the short run, and immediately related to manufacturing scheduling decisions, apart from guaranteeing bottlenecks' availability, scheduling and especially shop floor control have to assure that the bottleneck(s) neither starve (because no job is available to be processed on the bottleneck) nor is blocked (because a job finished at the bottleneck is not able to leave it, may it be because of lacking transportation facilities or limited buffer space behind the bottleneck). Avoiding these drawbacks might be significantly influenced by both, adequate scheduling and applying adequate shop floor control mechanisms such as appropriate dispatching rules. With respect to transportation between different operations of a job, it can be stated that these transportation processes are often completely excluded from consideration in manufacturing scheduling approaches. However, on one hand, the variability of these transportation processes can significantly influence the overall performance of the system. On the other hand, splitting production lots into smaller transportation lots might allow overlapping processing of a job/order on consecutive machines and reduce idle time of machines as well as waiting time of jobs.

A final remark on variability in manufacturing scheduling refers to data availability and data quality and has basically been addressed already earlier. If, especially in deterministic models and respective solutions, fixed processing times, fixed release dates and fixed due dates are given, these dates, to a large extent, often will not be as deterministic in the respective real-world settings. Therefore, given degree of uncertainty (variability) of these data, in deterministic planning procedures provisions (time buffers) for this uncertainty have to be included. Another approach would be to stabilise/to standardise the system as far as possible, just to reduce the variability itself. This could be reached, e.g. by automation, standardisation (of processes as well as of labour skills), pull-based material supply etc.

2.3.4 Flexibility

Clearly, one of the aspects affecting the decision process is the degree of flexibility of the data at hand. While virtually all data under consideration are candidates to be flexibilised, here we will refer to one type of flexibility with great impact in practice, namely *due date setting/quoting*.

Although due dates are often seen as fixed input into manufacturing scheduling problems, these due dates might be flexible in one way or another which is not reflected in standard deterministic scheduling settings. Rather often, customers are flexible with respect to due dates (at least within some limits) or the manufacturing company is simply asked to propose due dates. So due date setting and/or due date quoting represent additional decision problems closely related to manufacturing scheduling which balance customer/sales needs on one hand and manufacturing

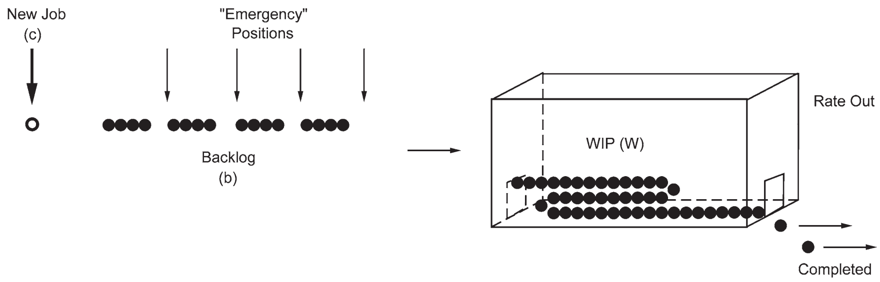

Fig. 2.4 Method for quoting lead times (Hopp and Spearman 2008)

capabilities on the other (Duenyas 1995). Thus people from the sales department and from the manufacturing department will have to agree on a due date (Fig. 2.4).

Apart from this human resources aspect, formally a due date can be determined rather easy on a coarse level. The determination of a reasonable due date has to include three time components into the calculation, i.e.

- the time required to process the current work in process, w,
- the time required to process the currently waiting jobs in front of the system and having higher priority than the job for which the due date is to be quoted, b, and
- the processing time of the job itself for which the due date is to be quoted, c.

Then the due date to be quoted is simply $d = w + b + c$. However, setting due dates in this way may turn out not to be as easy as it might look at a first glance. All 3 components include lead times which might be difficult to be calculated the more difficult/variable the manufacturing system is. Its variability might refer to jobs' flow through the system as well as to their processing times.

2.4 The Open View of Scheduling Problems and Decisions

As mentioned in Sect. 2.2, the open view of manufacturing scheduling corresponds to analysing its relationships with other (related) problems and decision-making processes. First we discuss the connection between manufacturing scheduling and the rest of decisions in production management (Sect. 2.4.1). Next, the interface between manufacturing scheduling and the rest of decisions (excluding those in production planning and control) within the company are presented in Sect. 2.4.2. Finally, we introduce the relationship between manufacturing scheduling and the rest of decisions in the supply network in which the company is integrated (Sect. 2.4.3).

2.4.1 Manufacturing Scheduling Within Production Management

In this section we investigate the relationship between manufacturing scheduling and production management. Production management decision problems are usually decomposed along two dimensions, i.e.: the scope of the decisions to be taken (briefly discussed in Sect. 1.2), and the logistic flow of the goods to be manufactured.

Once manufacturing scheduling is placed within these dimensions, we can discuss two of the most popular systems employed to conceptually describe the decisions in manufacturing, i.e. the Production Planning and Control (PPC) system, and the Advanced Planning Systems (APS) view, to study their connections with manufacturing scheduling. The two dimensions of production management decision problems are explained in Sect. 2.4.1.1, while the systems and their connections with manufacturing scheduling are discussed in Sects. 2.4.1.2 and 2.4.1.3, respectively.

2.4.1.1 The Two Dimensions of Production Management Decision Problems

The first dimension refers to the scope of the decisions in product management. In every company many different decisions have to be taken on different levels (of hierarchy and/or detail) with different importance. Usually, these decisions are not of stand-alone type but have to be coordinated with many other decisions. Depending on their relevance for the overall company, the time horizon of decisions' impact and their degree of detail of information and decision, these decisions are usually characterised as strategic, tactical and operational decisions (see Chap. 1). Strategic planning refers to long-term and conceptual decision problems to create and maintain a dynamic setting for long-term success of the company (e.g. decisions referring to locations, setting up a manufacturing hierarchy, (general and long-term) choice of process types, organisation of information flows, etc.). Tactical planning refers to mid-term and resource allocation tasks, i.e. setting up the infrastructure for a successful company (according to the strategic implications), while operational planning and control deals with short-term activities within a given infrastructure for externally specified requirements such as fulfilling orders/jobs etc.

According to this dimension, scheduling is part of planning and controlling the execution of manufacturing tasks within a given manufacturing infrastructure—and not planning of the infrastructure itself. Accordingly, many decision problems related to scheduling include a rather short-term and operational planning horizon.

The second dimension refers to the logistics of the manufacturing activity, which is the generation of marketable or intermediate goods (or, for the sake of completeness, also the elimination of bads, such as in waste combustion; we will not address this aspect further here) that constitute the products/services and are denoted as the *outputs* of the company. Manufacturing these goods requires *inputs* either procured externally or provided by own preceding production processes. This process of transforming inputs into outputs is the manufacturing or production process and, as it is the logistics stage between input and output, is sometimes called *throughput*.

Consequently, planning and control in a manufacturing system can be separated into output, input, and throughput planning and control. Throughput planning and control refers to the determination of general types of processes chosen for manufacturing down to planning and control of a physical process setting for given jobs which also includes manufacturing scheduling tasks. A main part of throughput planning and control deals with (material) flow planning and control while input planning and control refers to purchasing/procurement strategies and lot-sizing down to staging of material. Output planning and control refers to the derivation of (strategic) market strategies down to (operational) distribution.

Referring to the standard definitions and/or descriptions of logistics as an integrating, flow-oriented function which intends to optimally bridge spatial, quantitative and temporal distances between 'providers' and 'consumers', it is nearby to interpret manufacturing systems also in a logistics context: 'Providers' can be suppliers, inventories (of raw material, intermediates and/or finished goods), production sites, preceding machines, etc. Accordingly, 'consumers' can be inventories, production sites or (internal or external, referring to the system under consideration) customers. From the point of view of manufacturing, besides of the core manufacturing processes/operations, the complementary logistics operations of storing, packaging and/or transportation are linking manufacturing operations with each other and with their 'boundary' functions in procurement and distribution. These complementary operations are often not explicitly included into manufacturing scheduling. However, their influence on the overall performance of a manufacturing system should not be neglected and estimated carefully. Their influence with respect to the performance of the system as a whole might be significant.

According to the two dimensions discussed above, it is clear that most decisions in manufacturing scheduling are assigned to operational throughput planning and control (see Fig. 2.5). However, at least setting up the scheduling system itself will be part of the tactical and sometimes even of the strategic level: e.g. general choice of process type as a main framework for every scheduling approach and the decision whether centralised or decentralised scheduling systems are set up can be assigned to the strategic level. Fixing the general scheduling procedures within the strategic settings and allocation of human as well as software resources for the scheduling tasks can be interpreted as tactical decisions. Nevertheless, concrete application of decision support tools for scheduling to real-life jobs and operations will always be operational.

Figure 2.5 emphasises the necessity of *coordinating* the decisions within and across levels, both on the vertical as well as on the horizontal level: With respect to the vertical axis, strategic concepts determine the infrastructure acquired on the tactical level, and this infrastructure significantly determines the realisable alternatives on the operational level. In turn, lower levels' information and/or problems are fed back to the upper levels to possibly adjust the higher level decisions. Concerning the horizontal axis, input, throughput and output are obviously closely connected to each other, no matter whether its primal perspective is push from input to output or pull from output to input. Feedback procedures take place here as well. For the sake of brevity, we will not address diagonal influences implied by Fig. 2.5 here, although

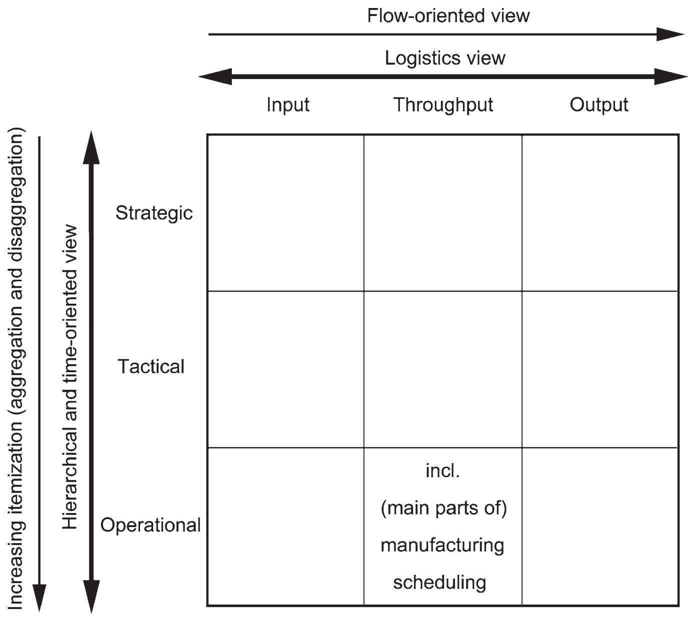

Fig. 2.5 Manufacturing scheduling in its planning and control context (see, e.g. Corsten 2009, p. 26)

these influences exist obviously. In the case of manufacturing scheduling, it has to be coordinated vertically within the multi-level structure of this field as well as with the respective horizontal 'neighbours' in input (purchasing, provision of material, etc.) and output (distribution, packaging, etc.).

Using the two dimensions, we can also classify the main decisional systems that have been employed for handling manufacturing decisions. The first one is the so-called PPC system, which basically corresponds to organising the related decisions along the vertical axis (scope of the decisions). The second view (APS) refines/extends the PPC system by introducing the logistic dimension. Both systems will be discussed in the next subsections.

2.4.1.2 Production Planning and Control (PPC) system

As discussed in Fig. 2.5, manufacturing scheduling is part of operational throughput planning and control. Within this cell, manufacturing scheduling is embedded usually into a multi-level production planning and control system which includes program planning, material planning, capacity and flow planning as well as scheduling. Figure 2.6 represents this classical scheme. Basically, Fig. 2.6 can be interpreted as a hierarchical itemisation of the operational/throughput cell in Fig. 2.5. This is denoted as the PPC system and, with slight differences, it has been presented in

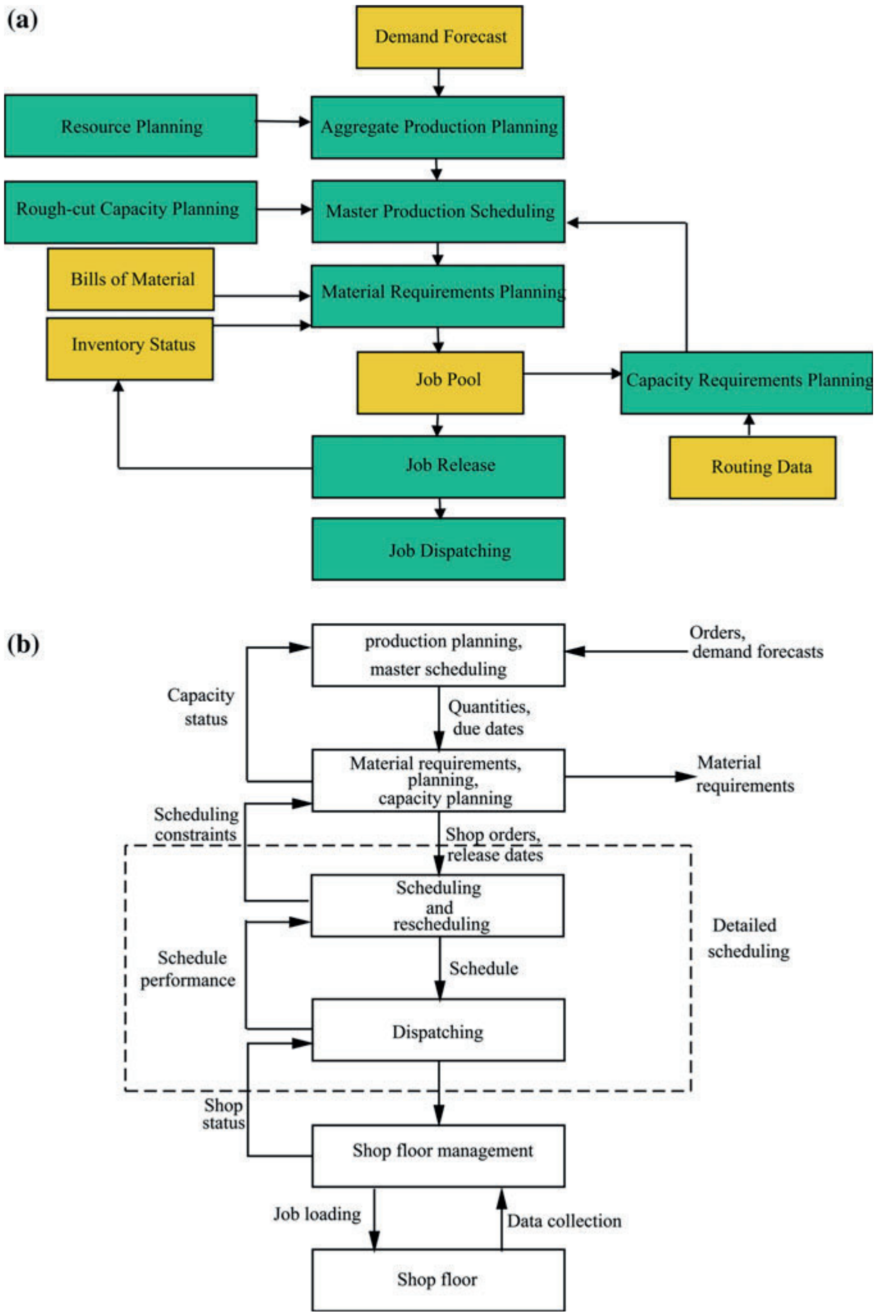

Fig. 2.6 Multi-level scheme of PPC. **a** Hopp and Spearman (2008), **b** Pinedo (2012)

many textbooks on production management. Here we show in Fig. 2.6 two of these presentations, taken from Hopp and Spearman (2008) and Pinedo (2012).

As can be seen, the wide-spread illustration scheme a includes the aggregate production planning level which is mainly used to provide adequate resources to the system on the long-term end of this overall short-term system. Manufacturing scheduling itself is only included rudimentary in this scheme, namely by the expression job dispatching.

Not as common, but to our impression reflecting the short-term aspects of manufacturing scheduling more adequately, scheme b of Fig. 2.6 represents basically the same system as in (a) (aggregate production planning might be added at top of this scheme). However, manufacturing scheduling (labelled as 'Detailed scheduling') is presented in more detail, i.e. by separating the phases of scheduling and rescheduling, dispatching and shop floor management. 'Rescheduling' here is meant to set-up a more or less completely new schedule while dispatching means to react to the shop status, e.g. by applying dispatching rules to the jobs waiting in front of a machine. Therefore, this scheme reflects the aspects of predictive and reactive scheduling addressed already in Sect. 2.3.1.

Figure 2.6b indicates that manufacturing scheduling is embedded into the classical hierarchical scheme of manufacturing by an interface with material requirements planning and capacity planning by providing implications from scheduling constraints to this level on one hand and getting information on jobs (shop orders) and their earliest release dates on the other. If scheduling/rescheduling and dispatching are seen as the level of manufacturing scheduling, then its data provides the main information with respect to job loading to the shop floor and its management as well as data collection on the jobs' current status gives feedback information for updating dispatching as well as the schedule as a whole.

Apart from this hierarchical integration of manufacturing scheduling into the planning and control context it has to be mentioned also here that the different levels of this scheme include different levels of detail (at least) with respect to products/jobs, capacities/resources and time. Because of this, horizontal (logistical) and diagonal coordination tasks occur additionally. Without getting into detail of these coordination tasks, their main components should be at least mentioned:

- decomposition and composition,
- aggregation and disaggregation,
- hierarchical coordination (including anticipation, feed-forward and feedback components),
- model building (including central and/or decentral components and their respective decision structures),
- problem solving (for the single partial problems as well as for their integration), and
- fitting the planning and control system into the organisational structure.

2.4.1.3 APS Systems and Manufacturing Scheduling

Numerous drawbacks of the classical PPC system which have been widely discussed for decades in the literature and the increasing ability to integrate different planning systems and planning levels from an IT perspective have led to the development of so-called APS systems. Additionally, the Supply Chain Management (SCM) 'movement' of the last years, may it be *intra*-organisational SCM (within one system and tending to control via hierarchical structures) or *inter*organisational (maybe crossing systems, including coordination tending to be controlled via market-based structures), promoted modified structures of PPC systems within the planning and control system of the logistics system. We only refer to some aspects of these systems which are relevant for manufacturing scheduling. More specifically, an APS system:

- gives a framework for manufacturing planning and control which includes both, the hierarchical as well as the logistics perspective,
- comprises advanced planning approaches, including 'true' optimisation approaches,
- includes state-of-the-art IT technology, i.e. among many others availability of quick (possibly real time) updated data within a network structure.

The modular structure of APS systems can be seen from Fig. 2.7. In this figure the information flows are indicated by the arrows. Manufacturing scheduling is located as short-term module within the production hierarchy which is coordinated by information flows related to production planning via lot sizes, and to procurement and distribution via due dates. It gives the main information to the shop floor control level.

Figure 2.8 presents the planning tasks in APS systems as assigned to every module. As can be seen, the scheduling module includes machine scheduling and scheduling is referring to data from the mid-term procurement, production and distribution levels using data on material availability, release dates as well as due dates/deadlines.

Finally, it should be mentioned that both, classical PPC systems as well as APS systems are integrated into standard ERP software packages. Therefore, they are applicable to real-world problems and, if they contain respective modules, they are able to perform automated manufacturing scheduling or to support respective decision problems and decision makers. However, to perform these tasks, adequate data must be available at the right time at the right place. Therefore, advanced database structures and database management are most important features of these systems. During the last years, data and model integration as well as real-time availability of data have contributed significantly to the performance of PPC and APS systems within ERP systems, including modules for manufacturing scheduling.

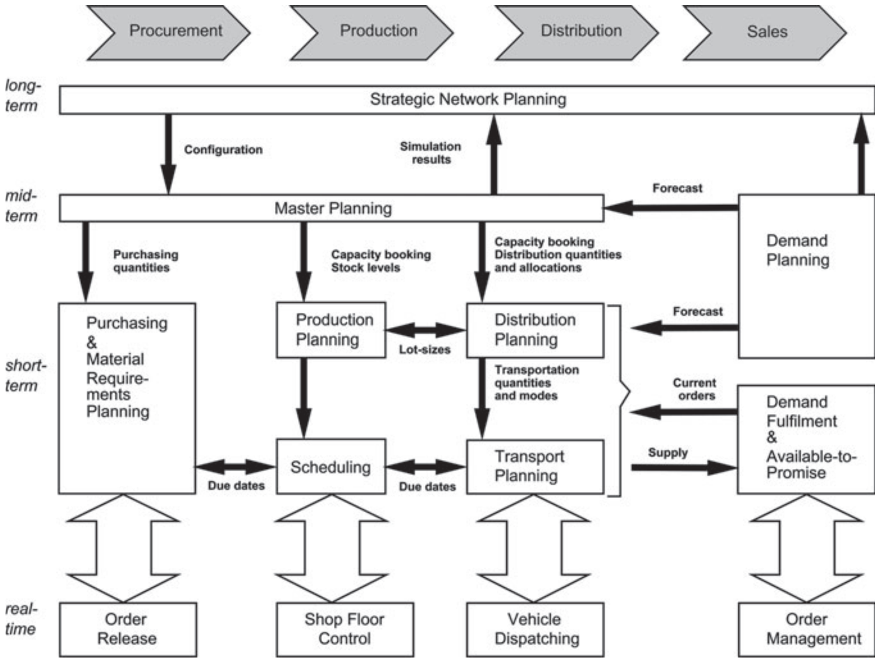

Fig. 2.7 APS modules from a logistics (supply chain) perspective (Reuter and Rohde 2008, p. 249)

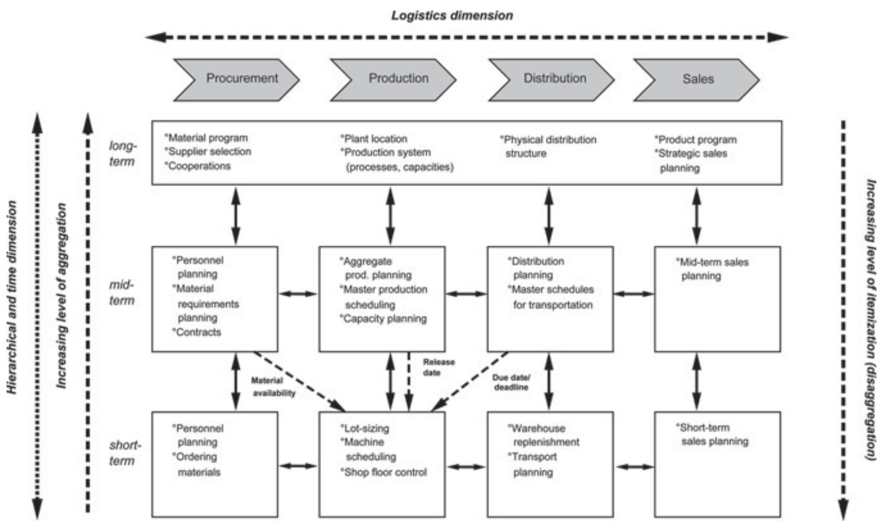

Fig. 2.8 (Supply chain) planning tasks in APS systems (modified from Fleischmann et al. 2008)

2.4.2 Interfaces of Manufacturing Scheduling with Other Decisions in Production Management

Many problems and their respective models and decisions in manufacturing combine machine scheduling aspects with other aspects in production management, such as inventory control, workforce scheduling, maintenance scheduling, capacity control or pricing. These approaches are manifold and will not be described here further. Aspects of model decomposition and solution integration are relevant here as well, however even more complicate since the objects to be planned and coordinated are even more complex than in the settings addressed earlier.

2.4.3 Manufacturing Scheduling and Intra- and Inter-Organisational Supply Networks

As already mentioned earlier, SCM (induced by movements as focus on core competences and related outsourcing), in addition to the classical and 'selfish' intra-organisational view on production, opened the view on logistics also from an inter-organisational perspective and on the combination of both, intra- and inter-organisational aspects of manufacturing.

Up to now, it can be observed that many real-world realisations of inter-organisational supply chain coordination schemes, including their IT structure, more or less simply copy the former intra-organisational information structures and transfer them to inter-organisational settings (and therewith transferring basically hierarchy-based information and coordination systems to more market-based systems–without regarding their different concepts and constraints). However, depending on the constellation of the cooperation between systems (companies) in the supply chain, every intermediate form between pure intra-organisational, hierarchically controlled coordination on one hand and pure market-based coordination on the other can appear. Although this aspect has been dealt with in science, meanwhile more or less intensively, applicable solutions to real-world systems are still missing to a large extent.

This (non-)development also alludes manufacturing scheduling. Here as well, the traditional focus on intra-organisational settings has to be supplemented by the consideration of manufacturing settings which cross borders of subsystems (e.g. plants, companies) and which are not exclusively characterised by basically hierarchical structures but also include more independent subsystems, possibly with different, maybe even conflicting objective functions. This aspect of inter-organisational manufacturing scheduling has not been dealt with very intensively so far. Instead, these inter-organisational interfaces are often seen to be determined by mid-term coordination and not by short-term scheduling. However, the closer cross-system manufacturing processes are linked, the more relevant inter-organisational approaches to manufacturing scheduling are. For example in systems including principles like

Just-in-Time or Vendor Managed Inventory, cross-system manufacturing scheduling aspects are relevant also from the short-term perspective.

As a keyword, *supply chain scheduling* occurred during the last years. For example, a hierarchy of scheduling plans can be proposed, a more aggregate master or global scheduling procedure might be linked to detailed scheduling in every subsystem, both considering predictive as well as reactive aspects of scheduling. In addition, since the manufacturing facilities in supply networks are often not located close to each other, transportation scheduling, between and within the subsystems, might become a severe issue which has to be analysed and integrated into the overall scheduling concept carefully. Further future research topics will appear with respect to these and other related topics.

Finally, it should be mentioned that, on a more abstract level, there are systematic approaches for structuring inter- and intra-organisational supply chains or supply networks. The well-known SCOR (Supply Chain Operations Reference Model) model is the reference point for these approaches. However, also in the SCOR model manufacturing scheduling aspects are not addressed explicitly and/or intensively, at least not from a model building and solution procedure point of view.

2.5 Conclusions and Further Readings

As stated in the introduction, this chapter serves to contextualise manufacturing scheduling. A framework for scheduling decisions has been presented, employing a dual view (open/closed) of manufacturing scheduling coming from systems analysis. The closed view analyses manufacturing scheduling as an isolated problem area and related decision process and the main aspects influencing these decisions (time, complexity, flexibility and variability) are discussed. In contrast, the open view emphasises the relationship of manufacturing scheduling with other decisions in the company and its supply chain network.

This chapter is conceptually demanding, and many of the ideas sketched here would deserve greater space. At the expense of rigour, these have been reduced to the minimum to give an integrated framework for understanding the context in which scheduling takes place. We believe that, in some cases, this lack of understanding is one of the causes leading to the poor design of scheduling systems and/or to under/over-estimate the importance of scheduling decisions in some manufacturing scenarios.

Regarding the presentation of the framework, most of the discussion of complexity is along the classification by Reiss (1993a, b), which is further elaborated in Gepp et al. (2013). For a comprehensive discussion of variability aspects in manufacturing, the book of Hopp and Spearman (2008) is an excellent reference. A discussion between centralised and decentralised systems can be found in Hamscher et al. (2000). Excellent places to start with the topics of rescheduling are Ouelhadj and Petrovic (2009) and Vieira et al. (2003). Holistic books about the manufacturing framework are the excellent Factory Physics books (Hopp and

Spearman 1996, 2008). This is, in any case, a very small extract of the related vast literature on scheduling topics. For a detailed discussion on planning and the PPC system, the reader is referred to Domschke et al. (1997). Aspects of horizontal (logistical) and diagonal coordination tasks within the PPC system are discussed in detail in Stadtler (2000), while a comprehensive presentation of and an overview on APS systems is given in the book chapter of Reuter and Rohde (2008). Finally, a nice presentation of the main concepts related to supply chain management is Stadtler and Kilger (2002).

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