

## 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.

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.

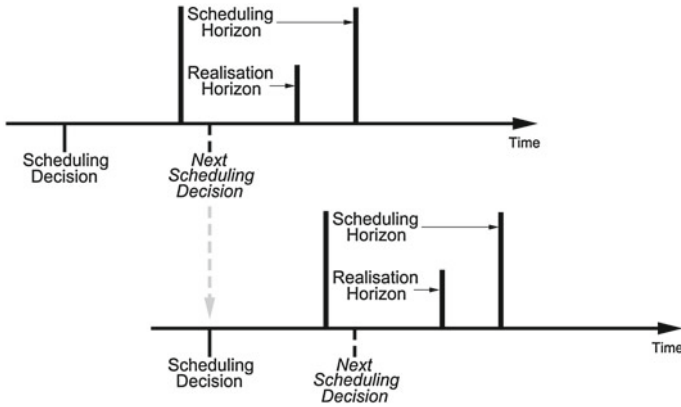
### 2.3.1 Time

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 suboptimality.

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

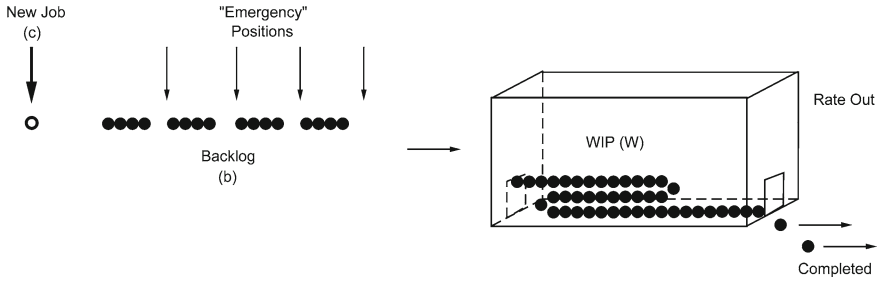
its performance, e.g. by adequate maintenance strategies and/or allocating qualitatively and quantitatively sufficient manpower, will be main approaches to increase or to maximise the performance of the system. On the short run, and immediately related to manufacturing scheduling decisions, apart from 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.

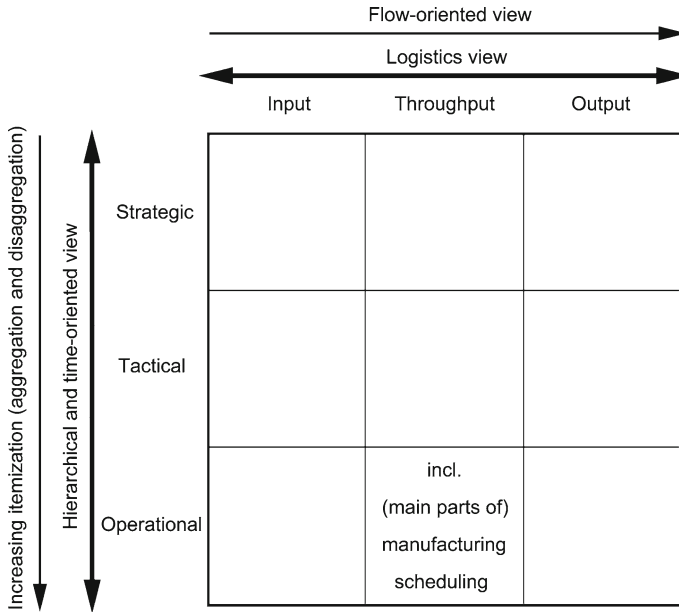
The second dimension refers to the logistics of the manufacturing activity, which is the generation of marketable or intermediate goods (or, for the sake of completeness, also the elimination of bads, such as in waste combustion; we will not address this aspect further here) that constitute the products/services 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



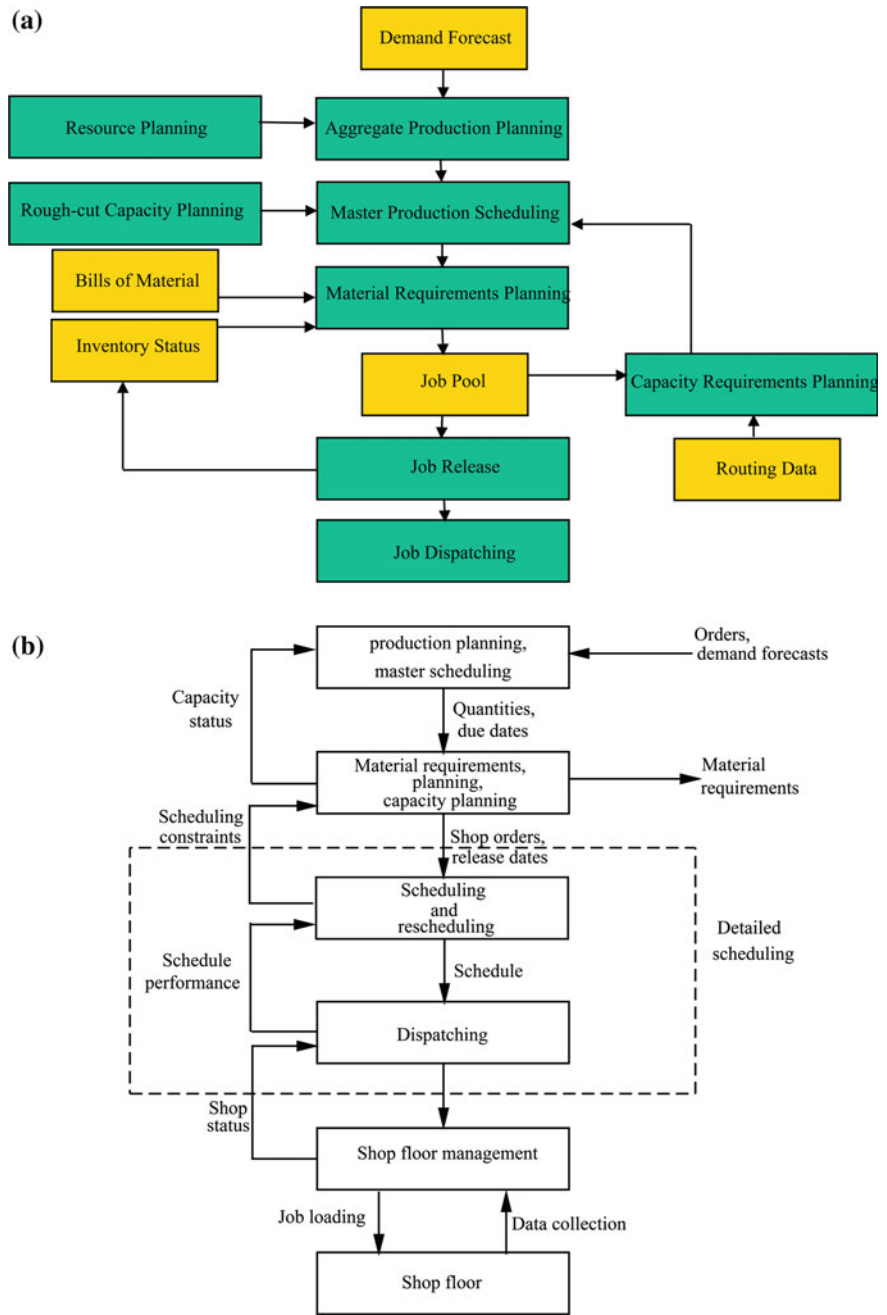


Fig. 2.6 Multi-level scheme of PPC. **a** Hopp and Spearman (2008), **b** Pinedo (2012)

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.

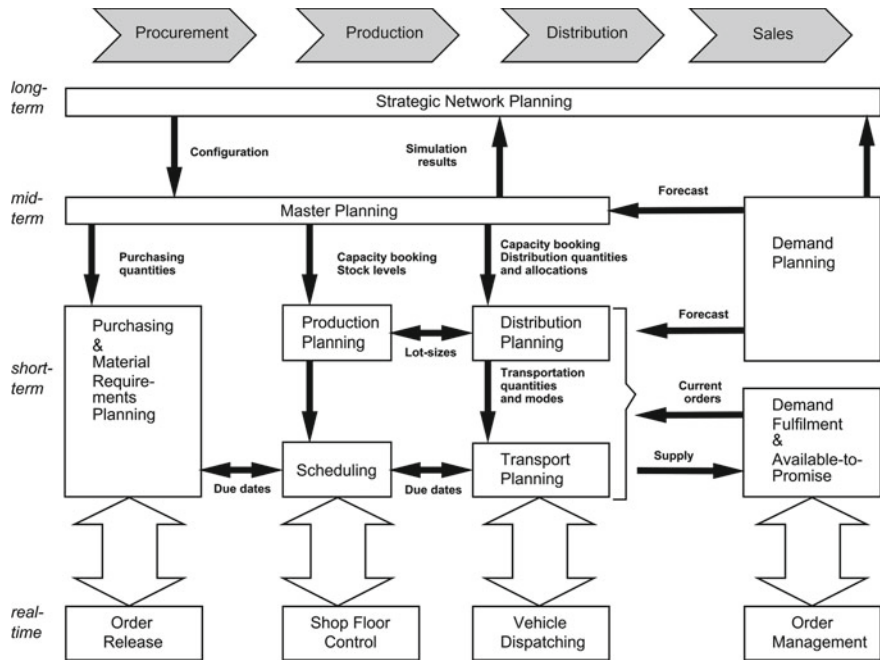


Fig. 2.7 APS modules from a logistics (supply chain) perspective (Reuter and Rohde 2008, p. 249)

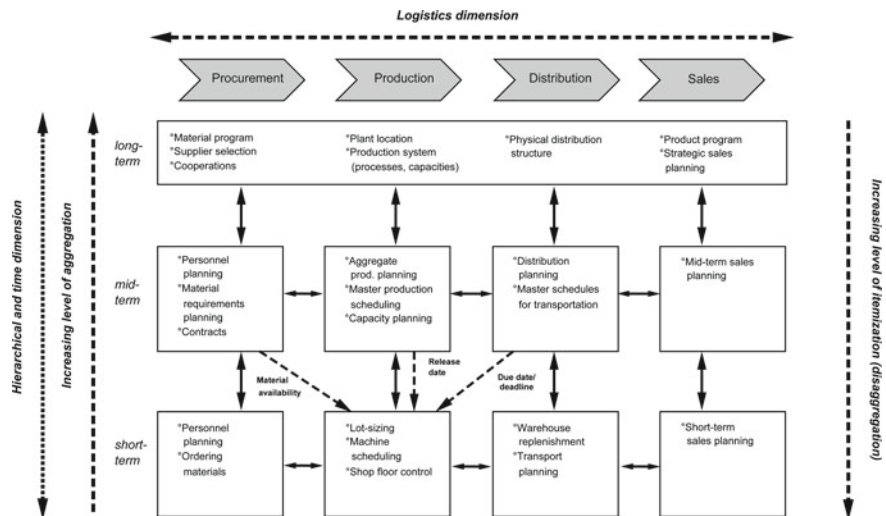


Fig. 2.8 (Supply chain) planning tasks in APS systems (modified from Fleischmann et al. 2008)

### ***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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Manufacturing Scheduling Systems

An Integrated View on Models, Methods and Tools

Framinan, J.M.; Leisten, R.; Ruiz García, R.

2014, XVIII, 400 p. 106 illus., 51 illus. in color.,

Hardcover

ISBN: 978-1-4471-6271-1