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Part I

Background

1 Introduction

This chapter provides an overview of scheduling and its role within a manufacturing organization, with special focus on the process industries. Section 1.1 introduces some preliminary concepts, including a definition of scheduling, some simple problems, the role of scheduling in a manufacturing supply chain, and a general problem statement for chemical production scheduling. The different chemical production environments, which play a key role in the definition of the different classes of problems, are introduced in Section 1.2. Section 1.3 presents the different classes of problem, and Section 1.4 outlines the different approaches to scheduling. Finally, an outline of the book is presented in Section 1.5.

1.1 Preliminaries

1.1.1 Scheduling: Applications and Definition

Scheduling finds applications in a wide variety of sectors: educational institutions, government organizations, manufacturing, sports, transportation, etc. In the manufacturing sector, scheduling has been practiced for more than a century, though, surprisingly, the first systematic methods appeared in the 1950s.[1] Since then, the field has seen the development of theoretical results regarding the complexity of different scheduling problems and a variety of modeling and solution methods. The aforementioned developments coupled with advances in computing power have enabled the use of optimization-based methods for a number of scheduling problems.

Scheduling is a *decision-making process that concerns the allocation of limited resources to competing tasks over time with the goal of optimizing one or more objectives*. A typical example would be the allocation of (limited) classrooms to a set of (competing) classes with the goal of meeting instruction needs and instructor preferences. In terms of manufacturing, the first methods were developed for discrete manufacturing. Consequently, most books focus on this type of problem, where scheduling and sequencing are viewed as two different types of decision. In this book, we will use the term *scheduling* to describe a more broad decision-making process where,

[1] Interestingly, the widely used Gantt chart was introduced by Henry Gantt in the 1910s (e.g., *Organizing for Work*, pp. 45, 89, and 95), but as a visualization tool. Gantt did not present a method to find schedules.

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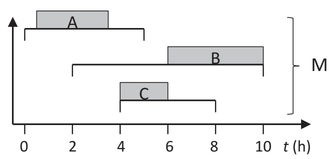
A

Job	τ_i	ρ_i	ε_i
A	3	0	5
B	4	2	10
C	2	4	8



B

Job	$\tau_{i,j}$ M1/M2	ρ_i	ε_i
A	3/3	0	5
B	4/4	2	10
C	2/2	4	8
D	2/4	2	8
E	3/3	4	9

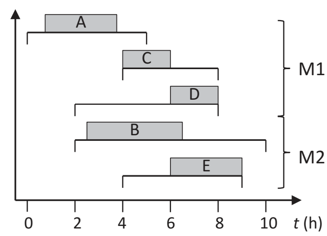


Figure 1.1 Single-machine (A) and parallel-machine (B) problems. Processing times, τ_{ij}, and release/due times, ρ_i/ε_i, are given in the tables. The ordinate of the charts represent time; width of rectangles, representing jobs, is proportional to processing times; and the placement of the rectangles shows the timing of jobs.

among others, we decide (1) what and how many tasks need to be carried out to meet given constraints; (2) what resources will be allocated to the selected tasks; and (3) when the selected tasks will be carried out. Also, as we will discuss in the next section, the necessity to model the amounts of (mostly fluid) materials involved in chemical production is a key feature that distinguishes discrete from chemical manufacturing scheduling.

1.1.2 Some Simple Problems

In this subsection, we discuss simple problems in order to introduce the three basic decisions that need to be made when solving a scheduling problem: (1) The decision on the number of jobs to be scheduled, (2) the assignment of jobs to machines, and (3) the sequencing of jobs assigned to a particular machine. For now, we will use the terms *jobs* and *machines* from discrete manufacturing.

The simplest scheduling problem is the single-machine problem, where N jobs $i \in \mathbf{I} = \{1, 2, \ldots N\}$ subject to release, ρ_i, and due, ε_i, times[2] and processing times, τ_i, have to be scheduled on one machine. Note that, as stated, this is a feasibility problem: Find a schedule that satisfies all constraints. An instance of this problem and a solution to it are shown in Figure 1.1A. Potential objective functions for this problem are (1) minimization of makespan and (2) minimization of lateness (if due times are not hard).

A due time is meant to be a *preferred* delivery time; it can be violated at a cost. If a due time is hard, that is, cannot be violated, then the term *deadline* is used instead. Note that this problem involves only sequencing and timing decisions: the sequence in which jobs are processed and the (exact) time they start. Note that there are infinite timing solutions for a given sequence. In the example shown in Figure 1.1A, the sequencing and timing are A (starting at $t = 1$) → C (starting at $t = 4$) → B (starting at $t = 6$).

[2] In this book, we will use the terms release/due *time*, instead of the more commonly used release/due *date*. This is because the horizons in the instances we will use to illustrate the basic concepts are short, typically less than 24 hours. Also, we will assume that the orders are due at a granularity finer than one day.

An extension of this problem is the *parallel machines* problem, where N jobs $i \in \mathbf{I} = \{1, 2, \ldots N\}$ subject to release, ρ_i, and due, ε_i, times have to be scheduled on M machines $j \in \mathbf{J} = \{1, 2, \ldots M\}$. The processing times of job i on machine j is τ_{ij}. This problem can also be a feasibility problem or have a time-related objective function. A solution to an instance of this problem is shown in Figure 1.1B. In addition, if the processing costs, γ_{ij}, of job i on the various machines are different, then a minimization of processing cost can be an alternative objective function. Note that there are two decision types to be made in this case: (1) assignment of jobs to machines and (2) sequencing and timing of jobs on each machine. In the instance shown in Figure 1.1B, jobs A, C, and D are assigned to machine M1, and jobs B and E are assigned to machine M2. However, as in the *single-machine* problem, the tasks (jobs) to be scheduled are known prior to optimization.

The natural extension of the previous problem is when the conversion of (external) orders to (internal to the problem) jobs is part of the optimization (scheduling). Consider the case where N orders $i \in \mathbf{I} = \{1, 2, \ldots N\}$ with release/due times, ρ_i/ε_i, and amounts due, φ_i, have to be met. Each order has to be converted into jobs to be processed on exactly one of M parallel machines $j \in \mathbf{J} = \{1, 2, \ldots, M\}$. Each order is for a specific product, so processing times can be expressed in terms of orders, that is, the processing times of (all jobs for) order i on machine j is τ_{ij}. In addition, each machine has capacity β_j, that is, all jobs executed on machine j will have size β_j. Unlike the previous two problems, the number of jobs is unknown – it is essentially an optimization decision.

1.1.3 Scheduling in the Supply Chain

A manufacturing supply chain (SC) is a network of facilities and distribution options that performs the following functions: procurement of raw materials, transformation of raw material into intermediate and finished products, and distribution of finished products to customers. The goal of SC optimization is to maintain high customer satisfaction levels at the minimum total cost. To achieve this goal, SC managers have to optimize material, monetary, and information flows, and in order to do so have to consider a number of *planning functions*. The *supply chain planning matrix* in Figure 1.2 shows the main planning functions, which, in general, can be categorized in terms of (1) the timescale of the planning horizon and the frequency at which the associated decisions are made and (2) the business functions.

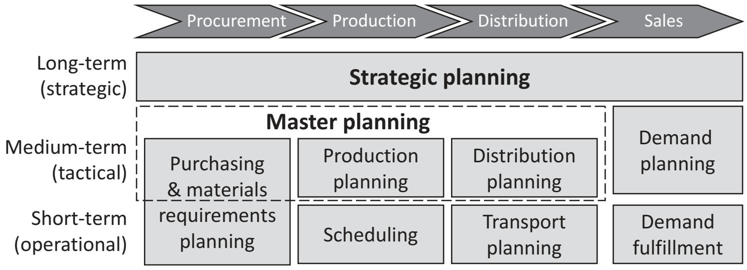


Figure 1.2 Supply chain matrix.

Long-term (strategic) planning decisions concern mostly the structure (design) of the supply chain, for example, location of production sites and warehouses, and facility capacity. The planning horizon is multiple years. The goal of medium-term (tactical) planning is to meet customer demand over a medium-term horizon (3–12 months) at the minimum cost given the current SC structure. Medium-term decisions include, for example, the calculation of monthly production targets and the allocation of these targets to different production sites. Finally, short-term (operational) planning concerns *day-to-day* decisions, for example, the assignment of production tasks to specific equipment units and the timing of the execution of these tasks. The planning horizon can be anywhere between a few days and a few months.

In terms of business functions, planning can be divided into procurement, production, distribution, and sales, though the importance and complexity of the associated problems vary greatly by sector. For instance, in industrial gases, the distribution of liquid gases using trailers under a vendor-managed inventory policy is significantly more complex than the associated production scheduling problem (of air separation units), whereas in specialty products the production of multiple low-volume, high-value products in multi-product batch facilities is more complex than the associated distribution problem.

It is important to note that the planning functions are not independent from each other. They interact because decisions made by one function become inputs to another, for example, production targets, determined at the master planning level, become inputs to the scheduling function. In fact, in some ways, the goal of SC optimization is to effectively integrate organizational units so as to coordinate material, information, and financial flows. However, solving the integrated problem is intractable and business units have different decision-makers and/or different objectives. Thus, decisions have to be made based on the solution of smaller, *local* planning functions.

Chemical production scheduling deals with the short-term planning for the production business function, in the chemicals sector, broadly defined. As it will be discussed in the next subsection, the interactions of the scheduling function with the other planning functions have important implications.

1.1.4 Interactions with Other Planning Functions

In addition to the planning functions shown in Figure 1.2, scheduling also interacts with shop-floor management, or in the case of high-volume (typically continuous) manufacturing, with real-time optimization (RTO) and process control. While the specifics of these interactions are not unique across industrial sectors, not even across plants of the same company, the general structure is similar to the one shown in Figure 1.3. There are four ways in which these interactions shape the scheduling problem at hand.

First, the interaction of scheduling with production planning in particular determines what type of decisions are made by the scheduler. For example, if production targets (orders), but not batches, are determined by production planning, then scheduling encompasses all three major decisions (batching, assignment, sequencing/timing); otherwise, if production targets are converted into batches at the production planning level, then scheduling involves only assignment and sequencing decisions.

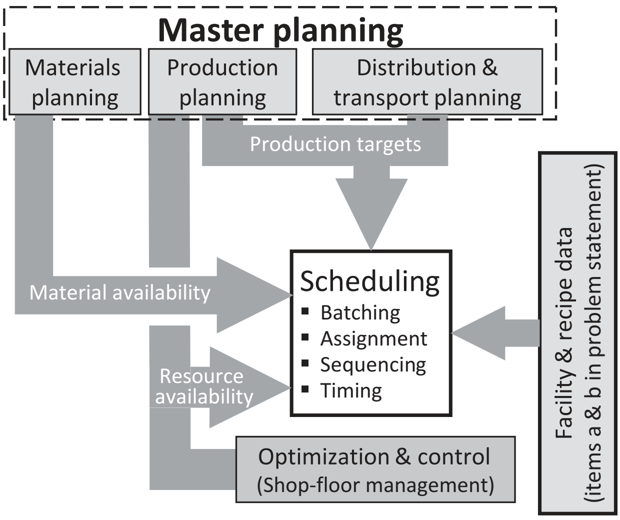


Figure 1.3 Interactions of scheduling with other planning functions.

Second, market considerations (including demand planning) combined with capacity constraints determine the production goal. For example, in a capacity-constrained environment, the production goal, and therefore the objective function of an optimization-based approach, would be the maximization of throughput or profit; otherwise, if excess capacity is available, then the objective function will most likely be the minimization of total cost. As we will see in Section 1.3, the objective function is one of the features determining the class of a problem.

Third, master and demand planning determine the production pattern. The production of high-volume products with relatively constant demand often leads to periodic production (production wheel) that requires periodic scheduling. If the demand is time varying but there are good quality forecasts available, then short-term scheduling is required in order to maintain a *target inventory position* (TIP) for a *make-to-stock* (*push*) policy. Yet, when the demand is time varying and good forecasts are not available (typically for low-volume specialty products), then a *make-to-order* (*pull*) inventory policy is typically adopted, which means that short-term scheduling should be used frequently to react to new orders.

Fourth, input parameters to scheduling (e.g., order data) are determined by other functions. For example, production planning determines production targets; procurement planning determines the availability of feedstocks (or the release date of orders); and process control determines the availability of resources. Conversely, scheduling decisions become inputs to other functions. The flow of information from other planning functions to scheduling is shown in Figure 1.3.

In general, the integration of planning functions and/or organizational units improves the competitiveness of the SC as a whole through the coordination of material, information, and financial flows. The integration with planning has the potential to lead to better solutions, especially when the overall economics are governed by planning decisions, but the ability to meet specific targets depends on scheduling decisions. The integration with control is critical when inputs to scheduling depend on control actions, for example, when changeover times and costs in continuous processes depend on the transition between steady states. The integration with control is not critical when production tasks have processing times (and costs) that do not depend on control decisions, for example, batch processes with fixed processing times and temperature/pH profiles. The integration with design, though the latter is not a planning function, can also lead to better designs because the capacity of a facility often depends on the mix of products it produces, which means that better decisions regarding the capacity of the units can be made when the schedule for the nominal production of the facility is considered. The integration of scheduling with process control and medium-term planning will be discussed in Chapters 14 and 15, respectively. Finally, we note that there are two challenges that may prevent such integration: (1) organization challenges (e.g., multiple decision-makers with conflicting objectives) and (2) challenges pertaining to the formulation and solution of optimization models (e.g., the models cannot be generated due to lack of data or are computationally intractable).

1.1.5 Scheduling in the Process Industries

In the process industries, scheduling problems arise in multiple sectors, such as (1) the petroleum industry (e.g., transportation and unloading of crude oil from ships and pipelines, crude oil distillation column charging schedule); (2) pharmaceutical, nutraceutical, and food manufacturing (e.g., scheduling of small-scale multiproduct batch processes); (3) specialty chemical manufacturing (e.g., batch scheduling); (4) mining; (5) metals processing; and (6) energy generation, etc.

The importance of scheduling has increased due to the recent trend toward product customization and diversification. To produce multiple low-volume products, chemical companies employ multiproduct facilities with often complex process networks and multiple shared resources. To utilize these capital-intensive assets efficiently and at the same time respond to demand fluctuations, manufacturing facilities have to be utilized close to their capacity, which leads to a challenging scheduling problem: Production targets close to system limits have to be met at the minimum cost subject to constraints resulting from the complex nature of these facilities. Another important driver, in high-volume production environments, is cost reduction and maximization of production efficiency.

To address these problems, researchers in the area of process systems engineering (PSE) have developed various approaches. Most of the early papers, in the late 1970s and early 1980s, considered the scheduling of batch processes in what we will later define as *sequential* production environments, that is, problems where batches have to be processed in consecutive stages (with no intermediate mixing or splitting). These problems are in some ways similar to the problems arising in discrete manufacturing. The scope of chemical production scheduling was expanded in the early 1990s to include facilities of arbitrary structure with no material handling (i.e., mixing and splitting) restrictions, additional resource constraints, and various processing restrictions. Since then, numerous modeling and solution methods have been proposed to address an ever-widening set of problems and applications. As a result, chemical production scheduling has become an important research subarea of process operations.

1.1.6 General Problem Statement

The term *scheduling* has been traditionally used to describe only the allocation of tasks to resources over time, that is, it considers only the timing of tasks. In this book, we consider a broader problem that includes the determination of the number and type of tasks to be performed, the assignment of tasks to resources, and the sequencing and/or timing of tasks. Accordingly, the general problem statement is as follows.

Given are the following:

(a) Production facility data (e.g., processing unit, storage vessel capacities)
(b) Production recipes (e.g., processing times/rates, resource requirements)
(c) Production costs (e.g., materials and utilities costs)
(d) Material and resource availability and compatibility with tasks
(e) Production targets or orders with due dates

Note that inputs to scheduling include parameters that can be considered *fixed* (e.g., facility-related or product-related data) as well as parameters defined by other planning functions and thus can be time varying (e.g., material and resource availability, production targets).

The goal is to find the *optimal* schedule that meets production targets while satisfying all resource constraints. The optimization objective is typically the minimization of total cost (raw materials + production + inventory + utilities), though other time-related objective functions (e.g., makespan and lateness minimization) as well as profit or throughput maximization can also be used (see Section 1.3.3 for a detailed discussion of objective functions).

As it will be discussed in the next section, there are different classes of scheduling problems with different sets of optimization decisions. However, in the most general case, the following are the major decisions (see Figure 1.4A for illustration):

(a) Selection and sizing of tasks (batches or lots) to be carried out (batching/lot-sizing)
(b) Assignment of tasks to processing units
(c) Sequencing and/or timing of tasks on each unit

In most problems, these decisions fully define a schedule, that is, material inventory and resource utilization profiles can be determined when we know the number, type, size, and timing of tasks.

Figure 1.4A shows the decisions made to meet demand for four products, A (800 kg), B (500 kg), C (300 kg), and D (250 kg), in a facility with two parallel units, U1 and U2, with capacity equal to 300 and 250 kg, respectively. The batching decisions for product A lead to two batches (A1 and A2) of 300 kg each and one batch (A3) of 200 kg. In terms

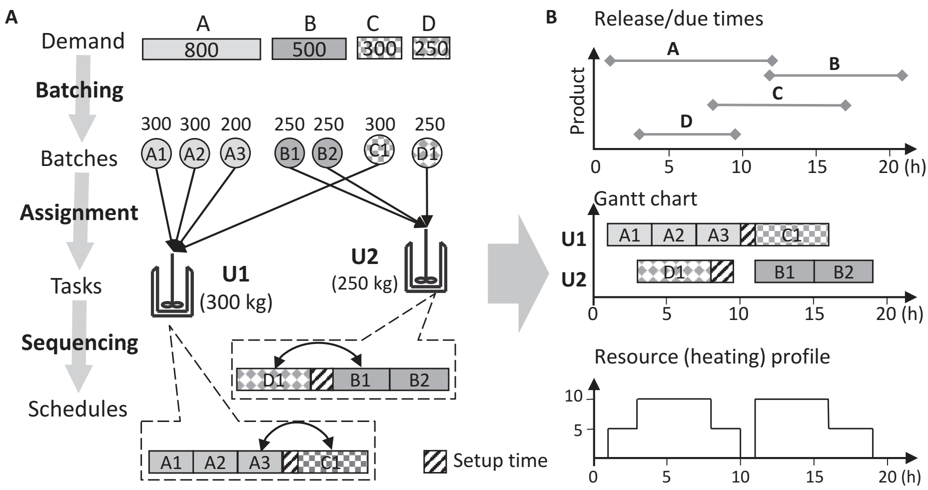


Figure 1.4 Scheduling decisions (A) and solution representation (B).

of batch-unit assignments, they are all assigned to unit U1. The demand for product C is met by one batch (C1) of size 300 kg also assigned to unit U1. The sequencing in U1 then is A1 → A2 → A3 → C1 with a changeover between A3 and C1.

A schedule is graphically represented via a Gantt chart showing the utilization of equipment over time and other auxiliary graphs. Figure 1.4B shows the windows within which batches should be executed (top panel); the Gantt charts for the two processing units (middle panel); and a utility (heating) consumption profile, assuming that all batches require five units of heating during their execution (bottom panel).

As an operational problem, scheduling is solved in a recursive manner. A schedule is generated based on the information available at the time; the early part of the schedule is implemented; and as additional information becomes available (e.g., disturbances, new orders), reoptimization is performed to dynamically adjust. This iterative procedure, in this book termed *real-time* (or *online*) *scheduling,* is discussed in Chapter 14.

1.2 Chemical Production Environments

In this section, we first present a classification of discrete manufacturing scheduling problems (Section 1.2.1) and then discuss some insights that allow us to define the major production environments for chemical manufacturing (Section 1.2.2). Finally, we discuss the main characteristics of sequential (Section 1.2.3), network (Section 1.2.4), and hybrid (Section 1.2.5) environments.

1.2.1 Discrete Manufacturing Machine Environments

The entities to be scheduled are *jobs*, $i \in \mathbf{I}$, and the shared resources are *machines*, $j \in \mathbf{J}$. A job may have to be allocated to a single *step* (*operation*) or it may require a