# Preface

Scheduling theory, born in the middle of the 1950s, has become an established area of operations research, with numerous widely quoted books and influential surveys that cover various stages of development in scheduling or addressing a particular range of its models. Journals are published, and regular conferences are held with scheduling as the main topic. Hundreds of researchers around the world work on further advancing this branch of knowledge, and thousands of students of all levels study its aspects either as a full course or as a part of more general courses related to operations research, operations management, industrial engineering, and logistics.

As with most areas of operations research, scheduling is motivated by practical needs and its achievements are fed back into various areas of industry, service, transport, etc. Whatever the motivation or application, scheduling problems are normally formulated in terms of processing jobs on machines, with a purpose of optimizing a certain objective function. In classical deterministic machine scheduling, it is assumed that for a given job, its processing times on the machines are known and remain unchanged during the planning horizon. Although the classical scheduling models form a solid theoretical background, due to their too ideal nature, their immediate practical applications are very rare. It is not by chance that a major current trend of scheduling calls for studies of more realistic models that combine scheduling decisions with logistics decisions such as batching, transportation, and maintenance.

The models of classical scheduling are too static and do not respond to possible changes of processing conditions. In reality, actual processing times of a job may be affected by the fact that either these conditions get worse, or they may improve, or undergo some changes which affect the processing time in a less predictable, not necessarily monotone way. One aspect addressed in this book is related to the study of such time-changing effects.

The studies of scheduling problems with time-changing effects were originated by O.I. Melnikov and Y.M. Shafransky (both from Minsk, Belarus) in the late 1970s. By the mid-1990s, such studies had become a noticeable part of scheduling research, and currently, the total number of publications exceeds several thousands.

There has been a need for summarizing the obtained results, identifying most influential ones and presenting them from a unified position. Partly, such a purpose was achieved by the book “Time-Dependent Scheduling” written by S. Gawiejnowicz (Poznan, Poland) and published by Springer in 2008. The book, however, gives a systematic treatment of only one particular type of time-changing effect, under which the actual processing times of jobs depend on their start times in a schedule. There are other effects, still not covered in the monographic scheduling literature, including positional effects (the actual processing times of jobs are affected by their position in a sequence on a machine), cumulative effects (times are affected by the total value of some parameter of previously scheduled jobs), or combined effects, where a combination of the “pure” effects mentioned above are applied together.

Another reason that has motivated us to undertake the task of writing this book is a need for studying the possibility of including certain activities in a schedule that alter the processing conditions. As a simple example, imagine process jobs using a cutting tool which gradually loses its sharpness, so it takes longer to process a later scheduled job. The decision-maker may decide to stop and sharpen the tool or replace it by a new tool, and such a maintenance activity may appear to be beneficial for the overall performance. We hope that this example, simple as it is, demonstrates the need for studying the scheduling problems with time-changing effects and rate-modifying activities; the reader will find these words in the title of our book.

Our personal interest in the models that we study in this book does not have a long history. Vitaly Strusevich, among his other scheduling-related studies, was involved in several papers on scheduling with changing times, jointly written with the late V.S. Gordon (Minsk, Belarus), and C.N. Potts and J.D. Whitehead (both from Southampton, UK). Kabir Rustogi, who pursued his PhD at the University of Greenwich, London, UK, wrote his PhD thesis on this topic, with Vitaly Strusevich as the first supervisor. The thesis was awarded the Best PhD Prize of the Operational Research Society (2013). The content of that thesis along with several joint papers, some additionally co authored by H. Kellerer (Graz, Austria), has determined the content of this book to a very large extent.

It would be impossible to include into a one-volume book all relevant major results, known and new, for all scheduling systems and all objectives. We have, therefore, decided to be selective and to limit our consideration only to those models and solution methods that are sufficiently representative to be of interest to the reader and, at the same time, fall within the scope of our own research interests to reflect our own contributions to the area.

In this book, we focus on two-machine environments. Most of the presented results address scheduling problems on a single machine; however, we also consider problems on parallel machines (identical, uniform, or unrelated). Scheduling systems that involve multi stage processing, such as the flow shop, appear to be outside the scope of this book.

We also have decided to limit our consideration to two objective functions: the maximum completion time, known as the makespan, and the total completion time, in both unweighted and weighted forms. We do not discuss scheduling problems with the objective functions related to due dates, such as the maximum lateness or the total tardiness. We also do not include the models that involve assignments of due dates or due windows to jobs.

From a methodological point of view, our main goal has been to systematically present the results related to the computational complexity and approximability of the chosen range of problems. Mainly, we explore how the classical and simple scheduling models can be extended to incorporate more features related to practical needs but still remain polynomially solvable by an appropriate adaptation of the classical solution methods. For those problems that are NP-hard, so that the existence of a polynomial-time solution algorithm is unlikely, we present approximation algorithms and schemes with provable running times and accuracy. Exact methods of guided enumeration, such as branch-and-bound techniques, and heuristic procedures, e.g., local search or evolutionary algorithms, are left beyond the content of this book.

The material of this book contains 20 chapters split into three parts. We have tried to make each chapter to be a self-sufficient document, complete with its individual bibliography. Chapters 1, 6, and 12 are introductory chapters to each part; they are of a bibliographic nature, so that unlike the other chapters, the corresponding literature references are placed within the body of each of these chapters. All other chapters are accompanied with a section entitled "Bibliographic Notes," which is essentially a review that points out the sources of the material in the main body of a chapter and provides references to further reading on the relevant topic.

Part I introduces all required concepts of the classical scheduling theory and delivers reviews of methods and techniques widely used in the remaining part of this book. In all scheduling problems of this part, no time-changing effects are assumed; i.e., the processing times remain constant. Chapter 1 describes the main notions of scheduling theory, introduces notation, and gives a brief informal introduction to issues of computational complexity and approximability. Chapter 2 gives a description of the pairwise interchange argument, presents a matching algorithm for minimizing a linear form over permutations, introduces the concept of a 1-priority rule, and shows how the interchange techniques can be used to solve various classical scheduling problems. Chapter 3 reviews the techniques of solving problems under precedence constraints, in particular of minimizing a priority-generating function under series-parallel precedence constraints. Many scheduling problems reduce to solving problems of Boolean linear and nonlinear programming, and Chap. 4 gives an overview of the relevant issues. It includes algorithms for the linear assignment problem with square and rectangular cost matrices and approximation schemes for the linear knapsack problem and problems related to minimizing a non-separable quadratic function known as the half-product. Chapter 5 discusses the issues of convexity and $V$-shapeness of finite sequences, as well as presents useful facts on combinatorial counting. Thus, Part I produces a toolkit to handle enhanced scheduling models in the forthcoming parts of the book.

Part II is devoted to scheduling problems with time-changing effects. A review of all studied effects, including rationales and illustrative examples, is given in Chap. 6. The remaining chapters of Part II address single machine problems under an effect of a particular type, except the last chapter of the part, Chap. 11, which handles models with parallel machines. Positional effects are studied in Chap. 7. Start-time-dependent effects, both pure and combined with a positional effect, are analyzed in Chap. 8 (for an additive form of the effect) and in Chap. 9 (for a multiplicative form of the effect). Chapter 10 addresses single machine problems with both pure and combined cumulative effects. Most of the results on single machine models under time-changing effects are polynomial-time algorithms based on adaptation of the matching approach, priority rules, and reductions to the linear assignment problem. The respective problems with series-parallel precedence constraints are also analyzed, where appropriate. For the parallel machine models in Chap. 11, the issues of complexity and approximability are additionally considered.

The most advanced scheduling models are studied in Part III. In the most general case, we not only allow time-changing effects to affect the actual durations of the jobs, but also present the decision-maker with a range of rate-modifying activities, including but not limited to maintenance, that alter the processing conditions. A review of the relevant issues, including a generic procedure for solving most general single machine problems of the described range, is given in Chap. 12. Similar to Part II, the remaining chapters of Part III deal with a single machine environment, except the last chapter of the part, Chap. 20, which addresses the parallel machine environment. We start with simple models with compulsory maintenance activities to be introduced in a schedule that do not alter the processing conditions and either are placed in fixed time intervals (in Chap. 14) or start no later than a given deadline (in Chap. 13). For problems considered in these two chapters, along with polynomial-time algorithms, we discuss the issues of complexity and approximability. Scheduling problems with no time-changing effects but with rate-modifying periods (RMPs) to be included in a schedule are studied in Chap. 15. Fully enhanced models that allow both RMP introduction and time-changing effects are addressed in Chap. 16 (for positional effects), in Chap. 17 (for start-time-dependent effects), and in Chap. 18 (for combined effects). The main focus of these four chapters is on the adaptation of the generic procedure described in Chap. 12 for the respective problems. Single machine problems that combine a cumulative effect and a maintenance activity are considered in Chap. 19 with a purpose of developing fully polynomial approximation schemes by adapting the schemes known for relevant Boolean programming problems. For the parallel machine models, in Chap. 20, we present a generic procedure for solving enhanced problems and its adaptations for particular versions of the main model.

We have tried to provide detailed proofs to most of the statements presented, either by adapting the original proofs or by developing new proofs. The reader familiar with the basics of operations research should be able to follow the book without consulting external sources. We perceive that most of the readers will be research students of master or doctoral levels and researchers in operations research, industrial engineering, and logistics. We hope that the practitioners will find the collected results useful, especially on enhanced models that attempt to address the practical needs.

We have benefitted through stimulating discussions with many colleagues who have been ready to encourage us and to share their knowledge and expertise. Apart from our co authors mentioned above, we are grateful to J. Blazewicz (Poznan, Poland), B. Chen and V.I. Deineko (both from Warwick, UK), A.V. Kononov and S.V. Sevastianov (both from Novosibirsk, Russia), M.Y. Kovalyov and Y.M. Shafransky (Minsk, Belarus), D. Shabtay (Be'er Sheva, Israel), N.V. Shakhlevich (Leeds, UK), A. Shioura (Tokyo, Japan), and A.J. Soper (Greenwich, UK).

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