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Handbook on Project Management and Scheduling Vol. 1

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Editors
Christoph Schwindt
Institute of Management and Economics
Clausthal University of Technology
Clausthal-Zellerfeld
Germany

Jürgen Zimmermann
Institute of Management and Economics
Clausthal University of Technology
Clausthal-Zellerfeld
Germany

ISBN 978-3-319-05442-1 ISBN 978-3-319-05443-8 (eBook)
DOI 10.1007/978-3-319-05443-8
Springer Cham Heidelberg New York Dordrecht London

Library of Congress Control Number: 2014957172

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

This handbook is devoted to scientific approaches to the management and scheduling of projects. Due to their practical relevance, project management and scheduling have been important subjects of inquiry since the early days of Management Science and Operations Research and remain an active and vibrant field of study. The handbook is meant to provide an overview of some of the most active current areas of research. Each chapter has been written by well-recognized scholars, who have made original contributions to their topic. The handbook covers both theoretical concepts and a wide range of applications. For our general readers, we give a brief introduction to elements of project management and scheduling in the first chapter, where we also survey the contents of this book. We believe that the handbook will be a valuable and comprehensive reference to researchers and practitioners in project management and scheduling and hope that it might stimulate further research in this exciting and practically important field.

Short-listing and selecting the contributions to this handbook and working with more than one hundred authors have been a challenging and rewarding experience for us. We are grateful to Günter Schmidt, who invited us to edit these volumes. Our deep thanks go to all authors involved in this project, who have invested their time and expertise in presenting their perspectives on project management and scheduling topics. Moreover, we express our gratitude to our collaborators Tobias Paetz, Carsten Ehrenberg, Alexander Franz, Anja Heßler, Isabel Holzberger, Michael Krause, Stefan Kreter, Marco Schulze, Matthias Walter, and Illa Weiss, who helped us to review the chapters and to unify the notations. Finally, we are pleased to offer special thanks to our publisher Springer and the Senior Editor Business, Operations Research & Information Systems Christian Rauscher for their patience and continuing support.

Clausthal-Zellerfeld, Germany

Christoph Schwindt
Jürgen Zimmermann

Contents

Part VI Multi-Criteria Objectives in Project Scheduling

Part VII Multi-Mode Project Scheduling Problems

Part VIII Project Staffing and Scheduling Problems

Contents of Volume 2

Part XVI Project Risk Management

Part XVII Project Scheduling Applications

Part XVIII Case Studies in Project Scheduling

List of Symbols

Miscellaneous

$:=$	Equal by definition, assignment
$\square$	End of proof
$\lceil z \rceil$	Smallest integer greater than or equal to z
$\lfloor z \rfloor$	Greatest integer smaller than or equal to z
$(z)^+$	Maximum of 0 and z

Sets

$\emptyset$	Empty set
$]a, b[$	Open interval $\{x \in \mathbb{R} \mid a < x < b\}$
$[a, b[$	Half open interval $\{x \in \mathbb{R} \mid a \leq x < b\}$
$]a, b]$	Half open interval $\{x \in \mathbb{R} \mid a < x \leq b\}$
$[a, b]$	Closed interval $\{x \in \mathbb{R} \mid a \leq x \leq b\}$
$\|A\|$	Number of elements of finite set A
$A \subset B$	A is proper subset of B
$A \subseteq B$	A is subset of B
$A \setminus B$	Difference of sets A and B
$A \cap B$	Intersection of sets A and B
$A \cup B$	Union of sets A and B
$conv(A)$	Convex hull of set A
$f : A \to B$	Mapping (function) of A into B
$\mathbb{N}$	Set of positive integers
$\mathscr{NP}$	Set of decision problems that can be solved in polynomial time by a non-deterministic Turing machine

$\mathscr{O}$	Landau's symbol: for $f, g : \mathbb{N} \to \mathbb{R}_{\geq 0}$ it holds that $g \in \mathscr{O}(f)$ if there are a constant $c > 0$ and a positive integer n_0 such that $g(n) \leq c\, f(n)$ for all $n \geq n_0$
$\mathbb{R}$	Set of real numbers
$\mathbb{R}^n$	Set of n-tuples of real numbers
$\mathbb{R}_{\geq 0}$	Set of nonnegative real numbers
$\mathbb{Z}$	Set of integers
$\mathbb{Z}_{\geq 0}$	Set of nonnegative integers

Projects, Activities, and Project Networks

δ_{ij}	Weight of arc (i, j), start-to-start minimum time lag between activities i and j
$\mathscr{A}$	Set of all maximal feasible antichains of the precedence order (non-dominated feasible subsets)
$\overline{\mathscr{A}}$	Set of all feasible antichains of the precedence order (feasible subsets)
$A \in \overline{\mathscr{A}}$	Feasible antichain (feasible subset)
$\mathscr{A}(S, t)$	Set of activities in execution at time t given schedule S
d_{ij}	Longest path length from node i to node j in project network N
d_{ij}^{max}	Maximum time lag between the starts of activities i and j
d_{ij}^{min}	Minimum time lag between the starts of activities i and j
$\overline{d}$	Prescribed maximum project duration
E	Arc set of directed graph G or project network N
E_i^-	Set of arcs leading to node i
E_i^+	Set of arcs emanating from node i
$\mathscr{F}$	Set of all minimal forbidden sets
$F \in \mathscr{F}$	Minimal forbidden set
$G = (V, E)$	Directed graph with node set V and arc set E (precedence graph)
i, j	Activities or events of the project
(i, j)	Arc with initial node i and terminal node j
n	Number of activities of the project, without project beginning 0 and project completion $n + 1$
$N = (V, E, \delta)$	Project network with node set V, arc set E, and arc weights δ
p_i	Duration (processing time) of activity i
$Pred(i)$	Set of immediate predecessors of activity i in project network N
$\overline{Pred}(i)$	Set of all immediate and transitive predecessors of activity i in project network N
$Succ(i)$	Set of all immediate successors of activity i in project network N
$\overline{Succ}(i)$	Set of all immediate and transitive successors of activity i in project network N
TE	Transitive closure of the arc set

V	Node set of direct graph G or project network N; Set of activities in an activity-on-node network
V^a	Set of real activities in an activity-on-node network

Resources and Skills

Π_k	Set of periods associated with partially renewable resource k
k	Single (renewable, nonrenewable, partially renewable, or storage) resource
$K = \lvert\mathscr{R}\rvert$	Number of renewable resources
$l \in \mathscr{L}$	Single skill
$L = \lvert\mathscr{L}\rvert$	Number of skills
$L_i = \lvert\mathscr{L}_i\rvert$	Number of skills required by activity i
$\mathscr{L}$	Set of skills
$\mathscr{L}_i$	Set of skills required by activity i
$\mathscr{L}_k$	Set of skills that can be performed by resource k
r_{ik}	Amount of resource k used by activity i
$r_{ik}(t)$	Amount of resource k used by activity i in the t-th period of its execution
r_{il}	Number of resource units with skill l required by activity i
$r_k(S,t)$	Amount of resource k used at time t given schedule S
R_k	Capacity or availability of resource k
$R_k(t)$	Capacity of renewable resource k in period t
$\mathscr{R}$	Set of (discrete) renewable resources (e.g., workers)
$\mathscr{R}_l$	Set of workers possessing skill l
$\mathscr{R}^n$	Set of nonrenewable resources
$\mathscr{R}^p$	Set of partially renewable resources
$\mathscr{R}^s$	Set of storage resources
wc_i	Work content of activity i
$wl_{ik} = p_i \cdot r_{ik}$	Workload of renewable resource k incurred by activity i
$WL_k = R_k \cdot \overline{d}$	Workload capacity of renewable resource k

Multi-Modal Project Scheduling

m	Execution mode
$\mathscr{M}_i$	Set of alternative execution modes for activity i
$M_i = \lvert\mathscr{M}_i\rvert$	Number of modes of activity i
p_{im}	Duration of activity i in execution mode m
r_{ikm}	Amount of resource k used by activity i in execution mode m
x	Mode assignment with $x_{im} = 1$, if activity i is processed in execution mode $m \in \mathscr{M}_i$

	Staff assignment with $x_{ikl} = 1$, if a worker of resource k performs activity i with skill l

Discrete Time-Cost Tradeoff

b	Budget for activity processing
$c_i(p_i)$	Cost for processing activity i with duration p_i $(= c_{im}$ with $p_i = p_{im})$
c_{im}	Cost of executing activity i in mode m
p_{im}	Duration of activity i in mode m

Multi-Project Problems

α_q	Dummy start activity of project q
ω_q	Dummy end activity of project q
d_q	Due date for completion of project q
$\overline{d}_q$	Deadline for completion of project q
n_q	Number of real activities of project q
$q \in Q$	Single project
Q	Set of projects
V_q	Set of activities of project q

Project Scheduling Under Uncertainty and Vagueness

λ	Arrival rate of projects
$\mu_{\hat{z}}(z)$	Membership function of fuzzy set $\hat{z}$
π_σ	Probability of scenario σ $(\sum_{\sigma \in \Sigma} \pi_\sigma = 1)$
$\sigma \in \Sigma$	Single scenario
Σ	Set of scenarios
Σ_i	Set of scenarios for activity i
$E(\tilde{x})$	Expected value of $\tilde{x}$
$f_{\tilde{x}}(x)$	Probability density function (pdf) of random variable $\tilde{x}$ $(= \frac{dF_{\tilde{x}}}{dx}(x))$
$F_{\tilde{x}}(x)$	Cumulative probability distribution function (cdf) of random variable $\tilde{x}$ $(= P(\tilde{x} \leq x))$
$\tilde{p}_i$	Random duration of activity i
$P(A)$	Probability of event A
p_i^{min}, p_i^{max}	Minimum and maximum duration of activity i
$\hat{p}_i$	Fuzzy duration of activity i
$var(\tilde{x})$	Variance of $\tilde{x}$

$\tilde{x}, \tilde{\xi}$	General random variables
x_α	α-quantile $(F_{\tilde{x}}(x_\alpha) = \alpha)$
z	(Crisp) Element from set Z
$\hat{z}$	General fuzzy set

Objective Functions

α	Continuous interest rate
$\beta = e^{-\alpha}$	Discount rate per unit time
c_i^F	Cash flow associated with the start or completion of activity i
$c_i^{F-} > 0$	Disbursement $-c_i^F > 0$ associated with activity or event i
$c_i^{F+} > 0$	Payment $c_i^F > 0$ associated with activity or event i
c_k	Cost for resource k per unit
$C_{max} = S_{n+1}$	Project duration (project makespan)
$f(S)$	Objective function value of schedule S (single-criterion problem); Vector $(f_1(S), \ldots, f_\nu(S))$ of objective function values (multi-criteria problem)
$f(S, x)$	Objective function value of schedule S and mode assignment x
f_μ	Single objective function in multi-criteria project scheduling
LB	Lower bound on minimum objective function value
npv	Net present value of the project
$\mathscr{PF}$	Pareto front of multi-criteria project scheduling problem
UB	Upper bound on minimum objective function value
w_i	Arbitrary weight of activity i

Temporal Scheduling

C_i	Completion time of activity i
EC_i	Earliest completion time of activity i
ES	Earliest schedule
ES_i	Earliest start time of activity i
LC_i	Latest completion time of activity i
LS	Latest schedule
LS_i	Latest start time of activity i
S	Schedule
S_i	Start time of activity i or occurrence time of event i
TF_i	Total float of activity i

Models and Solution Methods

ϕ_{ij}^k	Amount of resource k transferred from activity i to activity j
ρ_{mut}	Mutation rate
σ_{pop}	Population size
ℓ	Activity list $(i_1, i_2, \ldots, i_n)$
$\mathscr{C}$	Set of activities already scheduled (completed set)
$\mathscr{D}$	Decision set containing all activities eligible for being scheduled
$S^{\mathscr{C}}$	Partial schedule of activities $i \in \mathscr{C}$
t	Time period, start of period $t+1$
T	Last period, end of planning horizon

Computational Results

$\Delta_{LB}^{\varnothing}$	Average relative deviation from lower bound
Δ_{LB}^{max}	Maximum relative deviation from lower bound
$\Delta_{opt}^{\varnothing}$	Average relative deviation from optimum value
Δ_{opt}^{max}	Maximum relative deviation from optimum value
$\Delta_{UB}^{\varnothing}$	Average relative deviation from upper bound
Δ_{UB}^{max}	Maximum relative deviation from upper bound
LB_0	Critical-path based lower bound on project duration
LB^*	Maximum lower bound
n_{best}	Number of best solutions found
$n_{iter}^{\varnothing}$	Average number of iterations
n_{iter}^{max}	Maximum number of iterations
n_{opt}	Number of optimal solutions found
OS	Order strength of project network
p_{feas}	Percentage of instances for which a feasible solution was found
p_{inf}	Percentage of instances for which the infeasibility was proven
p_{opt}	Percentage of instances for which an optimal solution was found
p_{unk}	Percentage of instances for which it is unknown whether there exists a feasible solution
RF	Resource factor of project
RS	Resource strength of project
t_{cpu}^{lim}	CPU time limit
$t_{cpu}^{\varnothing}$	Average CPU time
t_{cpu}^{max}	Maximum CPU time

Three-Field Classification $\alpha \mid \beta \mid \gamma$ for Project Scheduling Problems[1]

Field α: Resource Environment

PS	Project scheduling problem with limited (discrete) renewable resources
PS∞	Project scheduling problem without resource constraints (time-constrained project scheduling problem)
PSc	Project scheduling problem with limited continuous and discrete renewable resources
PSf	Project scheduling problem with limited renewable resources and flexible resource requirements (problem with work-content constraints)
PSS	Project staffing and scheduling problem with multi-skilled resources of limited workload capacity
PSS∞	Project staffing and scheduling problem with limited multi-skilled resources of unlimited workload capacity
PSp	Project scheduling problem with limited partially renewable resources
PSs	Project scheduling problem with limited storage resources
PSt	Project scheduling problem with limited (discrete) time-varying renewable resources
$MPSm, \sigma, \mu$	Multi-mode project scheduling problem with m limited (discrete) renewable resources of capacity σ and μ nonrenewable resources
MPS	Multi-mode project scheduling problem with limited renewable and nonrenewable resources
MPS∞	Multi-mode project scheduling without resource constraints (time-constrained project scheduling problem)

Field β: Project and Activity Characteristics

The second field $\beta \subseteq \{\beta_1, \beta_2, \ldots, \beta_{13}\}$ specifies a number of project and activity characteristics; $\circ$ denotes the empty symbol.

β_1 : *mult*	Multi-project problem
$\beta_1 : \circ$	Single-project problem
β_2 : *prec*	Ordinary precedence relations between activities

[1]The classification is a modified version of the classification scheme introduced in Brucker P, Drexl A, Möhring R, Neumann K, Pesch E (1999) Resource-constrained project scheduling: notation, classification, models, and methods. Eur J Oper Res 112:3–41.

$\beta_2 : temp$	Generalized precedence relations between activities (minimum and maximum time lags between start or completion times of activities)
$\beta_2 : feed$	Feeding precedence relations between activities
$\beta_3 : \overline{d}$	Prescribed deadline $\overline{d}$ for project duration
$\beta_3 : \circ$	No prescribed maximum project duration
$\beta_4 : bud$	Limited budget for activity processing
$\beta_4 : \circ$	No limited budget for activity processing
$\beta_5 : p_i = sto$	Stochastic activity durations
$\beta_5 : p_i = unc$	Uncertain activity durations from given intervals
$\beta_5 : p_i = fuz$	Fuzzy activity durations
$\beta_5 : \circ$	Deterministic/crisp activity durations
$\beta_6 : c_i = sto$	Stochastic activity cost
$\beta_6 : c_i = unc$	Uncertain activity cost from given intervals
$\beta_6 : c_i = fuz$	Fuzzy activity cost
$\beta_6 : \circ$	Deterministic/crisp activity cost
$\beta_7 : Poi$	Stochastic arrival of projects with identical project network according to Poisson process
$\beta_7 : \circ$	Immediate availability of project(s)
$\beta_8 : act = sto$	Set of activities to be executed is stochastic
$\beta_8 : \circ$	Set of activities to be executed is prescribed
$\beta_9 : pmtn$	Preemptive problem, activities can be interrupted at any point in time
$\beta_9 : pmtn/int$	Preemptive problem, activities can be interrupted at integral points in time only
$\beta_9 : l\text{-}pmtn/int$	Preemptive problem, activities can be interrupted at integral points in time, the numbers of interruptions per activity are limited by given upper bounds
$\beta_9 : \circ$	Non-preemptive problem (activities cannot be interrupted)
$\beta_{10} : r_{il} = 1$	Each activity requires at most one resource unit with skill l for execution
$\beta_{10} : \circ$	Each activity i requires an arbitrary number of resource units with skill l for execution
$\beta_{11} : cal$	Activities can only be processed during certain time periods specified by activity calendars
$\beta_{11} : \circ$	No activity calendars have to be taken into account
$\beta_{12} : s_{ij}$	Sequence-dependent setup/changeover times of resources between activities i and j
$\beta_{12} : \circ$	No sequence-dependent changeover times
$\beta_{13} : nestedAlt$	The project network is given by a nested temporal network with alternatives, where only a subset of the activities must be executed
$\beta_{13} : \circ$	No alternative activities have to be taken into account

Field γ: Objective Function

f	General (regular or nonregular) objective function
reg	Regular objective function
mac	General mode assignment cost
$staff$	General project staffing cost (project staffing and scheduling)
rob	Robustness measure
$mult$	General multi-criteria problem
$f_1/f_2/\ldots$	Multi-criteria problem with objective functions $f_1, f_2, \ldots$
C_{max}	Project duration
$\Sigma c_i^F \beta^{C_i}$	Net present value of project
$\Sigma c_k \max r_{kt}$	Total availability cost (resource investment problem)
$\Sigma c_k \Sigma r_{kt}^2$	Total squared utilization cost (resource leveling)
$\Sigma c_k \Sigma o_{kt}$	Total overload cost (resource leveling)
$\Sigma c_k \Sigma \Delta r_{kt}$	Total adjustment cost (resource leveling)
$\Sigma c_i(p_i)$	Total cost of activity processing (time-cost tradeoff problem)
wT	Weighted project tardiness

Examples

$PS \mid prec \mid C_{max}$	Basic resource-constrained project scheduling problem (RCPSP)
$PS \mid temp, pmtn \mid C_{max}$	Preemptive resource-constrained project scheduling problem with generalized precedence relations
$MPS\infty \mid prec, \overline{d} \mid \Sigma c_i(p_i)$	Discrete time-cost tradeoff problem (deadline version)
$MPS \mid temp \mid \Sigma c_i^F \beta^{C_i}$	Multi-mode resource-constrained net present value problem with generalized precedence relations
$PS \mid prec \mid C_{max}/\Sigma r_{kt}^2$	Bi-criteria resource-constrained project scheduling problem (project duration, total squared utilization cost)
$PS \mid prec, p_i = sto \mid C_{max}$	Stochastic resource-constrained project scheduling problem

Project Management and Scheduling

Christoph Schwindt and Jürgen Zimmermann

1 Projects, Project Management, and Project Scheduling

Nowadays, *projects* are omnipresent. These unique and temporary undertakings have permeated almost all spheres of life, be it work or leisure, be it business or social activities. Most frequently, projects are encountered in private and public enterprizes. Due to product differentiation and collapsing product life cycles, a growing part of value adding activities in industry and services is organized as projects. In some branches, virtually all revenues are generated through projects. The temporary nature of projects stands in contrast with more traditional forms of business, which consist of repetitive, permanent, or semi-permanent activities to produce physical goods or services (Dinsmore and Cooke-Davies 2005, p. 35).

Projects share common characteristics, although they appear in many forms. Some projects take considerable time and consume a large amount of resources, while other projects can be completed in short time without great effort. To get a clear understanding of the general characteristics of a project, we consider the following two definitions of a project, which are taken from Kerzner (2013, p. 2) and PMI (2013, p. 4).

1. "A project can be considered to be any series of activities and tasks that:
    - have a specific objective to be completed within certain specifications,
    - have defined start and end dates,
    - have funding limits (if applicable),
    - consume human and nonhuman resources (i.e., people, money, equipment),
    - are multifunctional (i.e., cut across several functional lines)."

C. Schwindt (✉) • J. Zimmermann
Institute of Management and Economics, Clausthal University of Technology, Clausthal-Zellerfeld, Germany
e-mail: christoph.schwindt@tu-clausthal.de; juergen.zimmermann@tu-clausthal.de

2. "A project is a temporary endeavor undertaken to create a unique product, service, or result."

According to these definitions, we understand a project as a one-time endeavor that consists of a set of activities, whose executions take time, require resources, and incur costs or induce cash flows. Precedence relations may exist between activities; these relations express technical or organizational requirements with respect to the order in which activities must be processed or with respect to their timing relative to each other. Moreover, the scarcity of the resources allocated to the project generally gives rise to implicit dependencies among the activities sharing the same resources, which may necessitate the definition of additional precedence relations between certain activities when the project is scheduled. A project is carried out by a project team, has a deadline, i.e., is limited in time, and is associated with one or several goals whose attainment can be monitored.

Typical examples for projects are:

- construction of a building, road, or bridge,
- development of a new product,
- reorganization in a firm,
- implementation of a new business process or software system,
- procurement and roll-out of an information system,
- design of a new pharmaceutical active ingredient, or
- conducting an election campaign.

Project management deals with the coordination of all initiating, planning, decision, execution, monitoring, control, and closing processes in the course of a project. In other words, it is the application of knowledge, skills, tools, and techniques to project tasks to meet all project interests. According to the Project Management Institute standard definition (PMI 2013, p. 8), managing a project includes

- identifying requirements,
- establishing clearly understandable and viable objectives,
- balancing the competing demands for time, quality, scope, and cost, and
- customizing the specifications, plans, and approach to the concerns and expectations of the different stakeholders.

Consequently, successful project management means to perform the project within time and cost estimates at the desired performance level in accordance with the client, while utilizing the required resources effectively and efficiently.

From a project management point of view, the life cycle of a project consists of five consecutive phases, each of which involves specific managerial tasks (cf., e.g., Klein 2000; Lewis 1997). At the beginning of the first phase, called *project conception*, there is only a vague idea of the project at hand. By means of some feasibility studies as well as economic and risk analyses it is decided whether or not a project should be performed. In the *project definition phase* the project objectives and the organization form of the project are specified. In addition, the

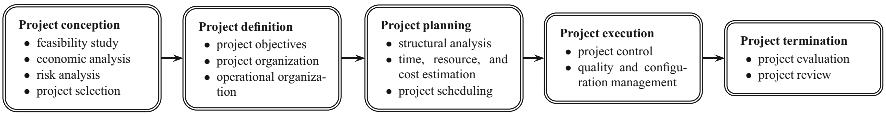

Fig. 1 Project life cycle

operational organization in the form of a roadmap (milestone plan) is conceived. In the *project planning phase* the project is decomposed into precedence-related activities. Then, for each activity the duration, the required resources, and the cost associated with the execution of that activity are estimated. Furthermore, the precedence relations among the activities are specified. Finally, a project schedule is determined by some appropriate planning approach (project scheduling). After these three phases the project is ready for implementation and the *project execution phase* starts. By monitoring the project progress, project management continuously evaluates whether or not the project is performed according to the established baseline schedule. If significant deviations are detected, the plan has to be revised or an execution strategy defined in the planning phase is used to bring the project back to course. Moreover, quality and configuration management are performed in this phase (PMI 2013; Turner 2009). The final *project termination phase* evaluates and documents the project execution after its completion. Figure 1 summarizes the five phases of the project life cycle. Next, we will consider the project scheduling part of the planning phase in more detail.

Project scheduling is mainly concerned with selecting execution modes and fixing execution time intervals for the activities of a project. One may distinguish between time-constrained and resource-constrained project scheduling problems, depending on the type of constraints that are taken into account when scheduling the project. In time-constrained problems it is supposed that the activities are to be scheduled subject to precedence relations and that the required resources can be provided in any desired amounts, possibly at the price of higher execution cost or unbalanced resource usage. In the setting of a resource-constrained project scheduling problem, the availability of resources is necessarily assumed to be limited; consequently, in addition to the precedence relations, resource constraints have to be taken into account. Time-cost tradeoff and resource leveling problems are examples of time-constrained project scheduling problems. These examples show that time-constrained problems also may include a resource allocation problem, which consists in assigning resource units to the execution of the activities over time.

Different types of precedence relations are investigated in this handbook. An ordinary precedence relation establishes a predefined sequence between two activities, the second activity not being allowed to start before the first has been completed. Generalized precedence relations express general minimum and maximum time lags between the start times of two activities. Feeding precedence relations require that an activity can only start when a given minimum percentage of its predecessor activity has been completed. The difference between generalized and feeding precedence relations becomes apparent when the activity durations are not fixed in advance or when activities can be interrupted during their execution.

Throughout this handbook, the term “resource” designates a pool of identical resource units, and the number of resource units available is referred to as the capacity or availability of the resource. In project scheduling, several kinds of resources have been introduced to model input factors of different types. Renewable resources represent inputs like manpower or machinery that are used, but not consumed when performing the project. In contrast, nonrenewable resources comprise factors like a budget or raw materials, which are consumed in the course of the project. Renewable and nonrenewable resources can be generalized to storage resources, which are depleted and replenished over time by the activities of the project. Storage resources can be used to model intermediate products or the cash balance of a project with disbursements and progress payments. Resources like electric power or a paged virtual memory of a computer system, which can be allotted to activities in continuously divisible amounts, are called continuous resources. Partially renewable resources refer to unions of time intervals and can be used to model labor requirements arising, e.g., in staff scheduling problems.

A common assumption in project scheduling is that activities must not be interrupted when being processed. There exist, however, applications for which activity splitting may be advantageous or even necessary. Examples of such applications are the aggregate mid-term planning of project portfolios composed of subprojects or working packages and the scheduling of projects in which certain resources cannot be operated during scheduled downtimes. The preemptive scheduling problems can be further differentiated according to the time points when an activity can be interrupted or resumed. Integer preemption problems assume that an activity can only be split into parts of integral duration, whereas continuous preemption problems consider the general case in which activities may be interrupted and resumed at any point in time.

An important attribute of a project scheduling problem concerns the number of execution modes that can be selected for individual activities. The setting of a single-modal problem premises that there is only one manner to execute an activity or that an appropriate execution mode has been selected for each activity before the scheduling process is started. A multi-modal problem always comprises a mode selection problem, the number of alternative modes for an activity being finite or infinite. Multiple execution modes allow to express resource-resource, resource-time, and resource-cost tradeoffs, which frequently arise in practical project scheduling applications.

With respect to the scheduling objectives, one may first distinguish between single-criterion and multi-criteria problems. A problem of the latter type includes several conflicting goals and its solution requires concepts of multi-criteria decision making like goal programming or goal attainment models. Second, objective functions can be classified as being regular or non-regular. Regular objective functions are defined to be componentwise nondecreasing in the start or completion times of the activities. Obviously, a feasible instance of a problem with a regular objective function always admits a solution for which no activity can be scheduled earlier without delaying the processing of some other activity. Since in this case, the search for an optimal schedule can be limited to such "active" schedules, problems with regular objective functions are generally more tractable than problems involving a non-regular objective function.

A further attribute of project scheduling problems refers to the level of available information. The overwhelming part of the project scheduling literature addresses deterministic problem settings, in which it is implicitly assumed that all input data of the problem are precisely known in advance and no disruptions will occur when the schedule is implemented. In practice, however, projects are carried out in stochastic and dynamic environments. Hence, it seems reasonable to account for uncertainty when deciding on the project schedule. This observation leads to stochastic project scheduling problems or project scheduling problems under interval uncertainty, depending on whether or not estimates of probability distributions for the uncertain parameters are supposed to be available. Fuzzy project scheduling problems arise in a context in which certain input data are vague and cannot be specified on a cardinal scale, like assessments by means of linguistic variables.

Finally, project scheduling problems may be categorized according to the distribution of information or the number of decision makers involved. Most work on project scheduling tacitly presumes that the projects under consideration can be scheduled centrally under a symmetric information setting, in which there is a single decision maker or all decision makers pursue the same goals and are provided access to the same information. However, in a multi-project environment, decentralized decision making may be the organization form of choice, generally leading to an asymmetric information distribution and decision makers having their own objectives. In this case, a central coordination mechanism is needed to resolve conflicts and to achieve a satisfying overall project performance.

Table 1 summarizes the classification of project scheduling problems considered in this handbook. For further reading on basic elements and more advanced concepts of project scheduling we refer to the surveys and handbooks by Artigues et al. (2008), Demeulemeester and Herroelen (2002), Hartmann and Briskorn (2010), and Józefowska and Węglarz (2006).

2 Scope and Organization of the Handbook

Given the long history and practical relevance of project management and scheduling, one might be tempted to suppose that all important issues have been addressed and all significant problems have been solved. The large body of research papers, however, that have appeared in the last decade and the success of international project management and scheduling conferences prove that the field remains a very active and attractive research area, in which major and exciting developments are still to come.

Table 1 Classification of project scheduling problems

Attributes	Characteristics
Type of constraints	Time-constrained problem
	Resource-constrained problem
Type of precedence relations	Ordinary precedence relations
	Generalized precedence relations
	Feeding precedence relations
Type of resources	Renewable resources
	Nonrenewable resources
	Storage resources
	Continuous resources
	Partially renewable resources
Type of activity splitting	Non-preemptive problem
	Integer preemption problem
	Continuous preemption problem
Number of execution modes	Single-modal problem
	Multi-modal problem
Number of objectives	Single-criterion problem
	Multi-criteria problem
Type of objective function	Regular function
	Non-regular function
Level of information	Deterministic problem
	Stochastic problem
	Problem under interval uncertainty
	Problem under vagueness
Distribution of information	Centralized problem (symmetric distribution)
	Decentralized problem (asymmetric distribution)

This handbook is a collection of 62 chapters presenting a broad survey on key issues and recent developments in project management and scheduling. Each chapter has been contributed by recognized experts in the respective domain. The two volumes comprise contributions from seven project management and scheduling areas, which are organized in 19 parts. The first three areas are covered by Vol. 1 of the handbook, the remaining four areas being treated in Vol. 2. The covered topics range from basic project scheduling problems and their generalizations through multi-project planning, project scheduling under uncertainty and vagueness, recent developments in general project management and project risk management to applications, case studies, and project management information systems. The following list provides an overview of the handbook's contents.

- Area A: Project duration problems in single-modal project scheduling
  - Part I: The Resource-Constrained Project Scheduling Problem
  - Part II: The Resource-Constrained Project Scheduling Problem with Generalized Precedence Relations

  - Part III: Alternative Resource Constraints in Project Scheduling
  - Part IV: Preemptive Project Scheduling

- Area B: Alternative objectives in single-modal project scheduling
  - Part V: Non-Regular Objectives in Project Scheduling
  - Part VI: Multi-Criteria Objectives in Project Scheduling

- Area C: Multi-modal project scheduling
  - Part VII: Multi-Mode Project Scheduling Problems
  - Part VIII: Project Staffing and Scheduling Problems
  - Part IX: Discrete Time-Cost Tradeoff Problems

- Area D: Multi-project problems
  - Part X: Multi-project scheduling
  - Part XI: Project Portfolio Selection Problems

- Area E: Project scheduling under uncertainty and vagueness
  - Part XII: Stochastic Project Scheduling
  - Part XIII: Robust Project Scheduling
  - Part XIV: Project Scheduling Under Interval Uncertainty and Fuzzy Project Scheduling

- Area F: Managerial approaches
  - Part XV: General Project Management
  - Part XVI: Project Risk Management

- Area G: Applications, case studies, and information systems
  - Part XVII: Project Scheduling Applications
  - Part XVIII: Case Studies in Project Scheduling
  - Part XIX: Project Management Information Systems

The parts of Areas A to E, devoted to models and methods for project scheduling, follow a development from standard models and basic concepts to more advanced issues such as multi-criteria problems, project staffing and scheduling, decentralized decision making, or robust optimization approaches. Area F covers research opportunities and emerging issues in project management. The chapters of the last Area G report on project management and scheduling applications and case studies in various domains like production scheduling, R&D planning, make-or-buy decisions and supplier selection, scheduling in computer grids, and the management of construction projects. Moreover, three chapters address the benefits and capabilities of project management information systems.

Most chapters are meant to be accessible at an introductory level by readers with a basic background in operations research and probability calculus. The intended audience of this book includes project management professionals, graduate students in management, industrial engineering, computer science, or operations research, as well as scientists working in the fields of project management and scheduling.

3 Outline of the Handbook

Area A of this handbook is dedicated to single-modal project scheduling problems in which the activities have to be scheduled under precedence relations and resource constraints and the objective consists in minimizing the duration (or makespan) of the project. In practice, these project scheduling problems have a large range of applications, also beyond the field of proper project management. For example, production scheduling and staff scheduling problems can be modeled as single-modal project scheduling problems. In order to model specific practical requirements like prescribed minimum and maximum time lags between activities, availability of materials and storage capacities, or divisible tasks, project scheduling models including generalized precedence relations, new types of resource constraints, or preemptive activities have been proposed. These extensions to the basic model are also addressed in this portion of the handbook.

Part I is concerned with the classical resource-constrained project scheduling problem RCPSP. Solution methods for the RCPSP have been developed since the early 1960s and this problem is still considered the standard model in project scheduling. In Chap. 1 Rainer Kolisch reviews shifts, schedule types, and schedule-generation schemes for the RCPSP. A shift transforms a schedule into another schedule by displaying sets of activities. Based on the introduced shifts, different types of schedules, e.g., semi-active and active schedules, are defined. Furthermore, two different schedule-generation schemes are presented. The serial schedule-generation scheme schedules the activities one by one at their respective earliest feasible start times. The parallel schedule-generation scheme is time-oriented and generates the schedule by iteratively adding concurrent activities in the order of increasing activity start times. Variants of the two schemes for the resource-constrained project scheduling problem with generalized precedence relations and for the stochastic resource-constrained project scheduling problem are discussed as well. Chapter 2, written by Christian Artigues, Oumasr Koné, Pierre Lopez, and Marcel Mongeau, surveys (mixed-)integer linear programming formulations for the RCPSP. The different formulations are divided into three categories: First, time-indexed formulations are presented, in which time-indexed binary variables encode the status of an activity at the respective point in time. The second category gathers sequencing formulations including two types of variables. Continuous natural-date variables represent the start time of the activities and binary sequencing variables are used to model decisions with respect to the ordering of activities that compete for the same resources. Finally, different types of event-based formulations are considered, containing binary assignment and continuous positional-date variables. In Chap. 3 Sigrid Knust overviews models and methods for calculating lower bounds on the minimum project duration for the RCPSP. Constructive and destructive bounds are presented. The constructive lower bounds are based on the relaxation or Lagrangian dualization of the resource constraints or a disjunctive relaxation allowing for activity preemption and translating precedence relations into disjunctions of activities. Destructive lower bounds arise from disproving hypotheses on upper bounds on the minimum objective function value. Knust reviews destructive lower bounds for the RCPSP that are calculated using constraint propagation and a linear programming formulation. Chapter 4 by Anurag Agarwal, Selcuk Colak, and Selcuk Erenguc considers meta-heuristic methods for the RCPSP. Important concepts of heuristic methods as well as 12 different meta-heuristics are presented. Amongst others, genetic algorithms, simulated annealing methods, and ant-colony optimization are discussed. A neuro-genetic approach is presented in more detail. This approach is a hybrid of a neural-network based method and a genetic algorithm.

Part II deals with the resource-constrained project scheduling problem with generalized precedence relations RCPSP/max. Generalized precedence relations express minimum and maximum time lags between the activities and can be used to model, e.g., release dates and deadline of activities or specified maximum makespans for the execution of subprojects. In Chap. 5 Lucio Bianco and Massimiliano Caramia devise lower bounds and exact solution approaches for the RCPSP/max. First, a new mathematical formulation for the resource-unconstrained project scheduling problem is presented. Then, they propose a lower bound for the RCPSP/max relying on the unconstrained formulation. The branch-and-bound method is based on a mixed-integer linear programming formulation and a Lagrangian relaxation based lower bound. The mixed-integer linear program includes three types of time-indexed decision variables. The first two types are binary indicator variables for the start and the completion of activities, whereas the third type corresponds to continuous variables providing the relative progress of individual activities at the respective points in time. Chapter 6 presents a constraint satisfaction solving framework for the RCPSP/max. Amedeo Cesta, Angelo Oddi, Nicola Policella, and Stephen Smith survey the state of the art in constraint-based scheduling, before the RCPSP/max is formulated as a constraint satisfaction problem. The main idea of their approach consists in establishing precedence relations between activities that share the same resources in order to eliminate all possible resource conflicts. Extended optimizing search procedures aiming at minimizing the makespan and improving the robustness of a solution are presented. Chapter 7, written by Andreas Schutt, Thibaut Feydy, Peter Stuckey, and Mark Wallace, elaborates on a satisfiability solving approach for the RCPSP/max. First, basic concepts such as finite domain propagation, boolean satisfiability solving, and lazy clause generation are discussed. Then, a basic model for the RCPSP/max and several expansions are described. The refinements refer to the reduction of the initial domains of the start time variables and the identification of incompatible activities that cannot be in progress simultaneously. The authors propose a branch-and-bound algorithm that is based on start-time and/or conflict-driven branching strategies and report on the results of an experimental performance analysis.

Part III focuses on resource-constrained project scheduling problems with alternative types of resource constraints. The different generalizations of the renewable-resources concept allow for modeling various kinds of limited input factors arising in practical applications of project scheduling models. Chapter 8, written by Sönke Hartmann, considers the resource-constrained project scheduling problem with time-varying resource requirements and capacities RCPSP/t. After a formal description of the problem, relationships to other project scheduling problems are discussed and practical applications in the field of medical research and production scheduling are treated. The applicability of heuristics for the RCPSP to the more general RCPSP/t is analyzed and a genetic algorithm for solving the RCPSP/t is presented. In Chap. 9 Jacques Carlier and Aziz Moukrim consider project scheduling problems with storage resources. In particular, the general project scheduling problem with inventory constraints, the financing problem, and the project scheduling problem with material-availability constraints are discussed. For the general problem setting, in which for each storage resource the inventory level must be maintained between a given safety stock and the storage capacity, two exact methods from literature are reviewed. The financing problem corresponds to the single-resource case in which the occurrence times of the project events replenishing the storages are fixed and no upper limitation on the inventory levels are given. This problem can be solved by a polynomial-time shifting algorithm. Eventually, the authors explain how the general problem can be solved efficiently when the storage capacities are relaxed and a linear order on all depleting events is given. Chapter 10, written by Grzegorz Waligóra and Jan Węglarz, is concerned with the resource-constrained project scheduling problem with discrete and continuous resources DCRCPSP. First, the authors survey the main theoretical results that have been achieved for the continuous resource allocation setting. Then, the DCRCPSP with an arbitrary number of discrete resources and a single continuous resource with convex or concave processing rate, respectively, is analyzed. For the case of concave processing rates, a solution method based on feasible sequences of activity sets is presented. In Chap. 11 Ramon Alvarez-Valdes, Jose Manuel Tamarit, and Fulgencia Villa discuss the resource-constrained project scheduling problem with partially renewable resources RCPSP/π. After the definition of the problem, the authors review different types of requirements of real-world scheduling problems that can be modeled using partially renewable resources and survey the existing solution procedures for RCPSP/π. Preprocessing procedures and two heuristic approaches, a GRASP algorithm and a scatter search method, are treated in detail.

Part IV is devoted to preemptive project scheduling problems, in which activities can be temporarily interrupted and restarted at a later point in time. In some applications, especially if vacation or scheduled downtimes of resources are taken into account, the splitting of activities may be unavoidable. Chapter 12 by Sacramento Quintanilla, Pilar Lino, Ángeles Pérez, Francisco Ballestín, and Vicente Valls considers the resource-constrained project scheduling problem Maxnint_PRCPSP under integer activity preemption and upper bounds on the number of interruptions per activity. Existing procedures for the RCPSP are adapted to solve the Maxnint_PRCPSP, and procedures tailored to the Maxnint_PRCPSP are presented. In addition, the chapter reviews a framework for modeling different kinds of precedence relations when activity preemption is allowed. In Chap. 13 Christoph

Schwindt and Tobias Paetz first present a survey on preemptive project scheduling problems and solution methods. Next, they propose a continuous preemption resource-constrained project scheduling problem with generalized feeding precedence relations, which includes most of the preemptive project scheduling problems studied in the literature as special cases. Based on a reduction of the problem to a canonical form with nonpositive completion-to-start time lags between the activities, structural issues like feasibility conditions as well as upper bounds on the number of activity interruptions and the number of positive schedule slices are investigated. Moreover, a novel MILP problem formulation is devised, and preprocessing and lower bounding techniques are presented.

Area B of the handbook is dedicated to single-modal project scheduling problems with general objective functions, including multi-criteria problems. Non-regular objective functions motivated by real-world applications are, e.g., the net present value of the project, the resource availability cost, or different resource leveling criteria. In practice, project managers often have to pursue several conflicting goals. Traditionally, the respective scheduling problems have been tackled as single-objective optimization problems, combining the multiple criteria into a single scalar value. Recently, however, more advanced concepts of multi-criteria decision making received increasing attention in the project scheduling literature. Based on these concepts, project managers may generate a set of alternative and Pareto-optimal project schedules in a single run.

Part V treats project scheduling problems with single-criteria non-regular objective functions. These problems are generally less tractable than problems involving a regular objective function like the project duration because the set of potentially optimal solutions must be extended by non-minimal points of the feasible region. The resource-constrained project scheduling problem with discounted cash flows RCPSPDC is examined in Chap. 14. The sum of the discounted cash flows associated with expenditures and progress payments defines the net present value of the project, and the problem consists in scheduling the project in such as way that the net present value is maximized. Hanyu Gu, Andreas Schutt, Peter Stuckey, Mark Wallace, and Geoffrey Chu present an exact solution procedure relying on the lazy clause generation principle. Moreover, they propose a Lagrangian relaxation based forward-backward improvement heuristic as well as a Lagrangian method for large problem instances. Computational results on test instances from the literature and test cases obtained from a consulting firm provide evidence for the performance of the algorithms. In Chap. 15 Savio Rodrigues and Denise Yamashita present exact methods for the resource availability cost problem RACP. The RACP addresses situations in which the allocation of a resource incurs a cost that is proportional to the maximum number of resource units that are requested simultaneously at some point in time during the project execution. The resource availability cost is to be minimized subject to ordinary precedence relations between the activities and a deadline for the project termination. An exact algorithm based on minimum bounding procedures and heuristics for reducing the search space are described in detail. Particular attention is given to the search strategies and the selection of cut candidates. The authors report on computational results on a set of randomly generated test instances. Chapter 16, written by Vincent Van Peteghem and Mario Vanhoucke, considers heuristic methods for the RACP and the RACPT, i.e., the RACP with tardiness cost. In the RACPT setting, a due date for the project completion is given and payments arise when the project termination is delayed beyond this due date. Van Peteghem and Vanhoucke provide an overview of existing meta-heuristic methods and elaborate on a new search algorithm inspired by weed ecology. In Chap. 17 Julia Rieck and Jürgen Zimmermann address different resource leveling problems RLP. Resource leveling is concerned with the problem of balancing the resource requirements of a project over time. Three different resource leveling objective functions are discussed, for which structural properties and respective schedule classes are revisited. A tree-based branch-and-bound procedure that takes advantage of the structural properties is presented. In addition, several mixed-integer linear programming formulations for resource leveling problems are given and computational experience on test sets from the literature is reported. In Chap. 18 Symeon Christodoulou, Anastasia Michaelidou-Kamenou, and Georgios Ellinas present a literature review on heuristic solution procedures for different resource leveling problems. For the total squared utilization cost problem they devise a meta-heuristic method that relies on a reformulation of the problem as an entropy maximization problem. First, the minimum moment method for entropy maximization is presented. This method is then adapted to the resource leveling problem and illustrated on an example project.

Part VI covers multi-criteria project scheduling problems, placing special emphasis on structural issues and the computation of the Pareto front. Chapter 19, written by Francisco Ballestín and Rosa Blanco, addresses fundamental issues arising in the context of multi-objective project scheduling problems. General aspects of multi-objective optimization and peculiarities of multi-objective resource-constrained project scheduling are revisited, before a classification of the most important contributions from the literature is presented. Next, theoretical results for time- and resource-constrained multi-objective project scheduling are discussed. In addition, the authors provide a list of recommendations that may guide the design of heuristics for multi-objective resource-constrained project scheduling problems. Chapter 20, contributed by Belaïd Aouni, Gilles d'Avignon, and Michel Gagnon, examines goal programming approaches to multi-objective project scheduling problems. After presenting a generic goal programming model, the authors develop a goal programming formulation for the resource-constrained project scheduling problem, including the project duration, the resource allocation cost, and the quantity of the allocated resources as objective functions. In difference to the classical resource allocation cost problem, the model assumes that the availability cost refers to individual resource units and is only incurred in periods during which the respective unit is actually used.

Area C of this handbook is devoted to multi-modal project scheduling problems, in which for each activity several alternative execution modes may be available for selection. Each execution mode defines one way to process the activity, and alternative modes may differ in activity durations, cost, resource requirements, or resource usages over time. The project scheduling problem is then complemented by a mode selection problem, which consists in choosing one execution mode for each activity. Multi-modal problems typically arise from tradeoffs between certain input factors like renewable or nonrenewable resources, durations, or cost. Other types of multi-modal problems are encountered when multi-skilled personnel has to be assigned to activities with given skill requirements or when the resource requirements are specified as workloads rather than by fixed durations and fixed resource demands.

Part VII deals with multi-modal project scheduling problems in which the activity modes represent relations between activity durations and demands for renewable, nonrenewable, or financial resources. This problem setting allows for modeling resource-resource and resource-time tradeoffs, which frequently arise in practical project management. In Chap. 21 Marek Mika, Grzegorz Waligóra, and Jan Węglarz provide a comprehensive overview of the state of the art in multi-modal project scheduling. One emphasis of the survey is on the basic multi-mode resource-constrained project duration problem MRCPSP, for which they review mixed-integer linear programming formulations, exact and heuristic solution methods, as well as procedures for calculating lower bounds on the minimum project duration. Moreover, they also revisit special cases and extensions of the basic problem as well as multi-mode problems with financial and resource-based objectives. Chapter 22, written by José Coelho and Mario Vanhoucke, presents a novel solution approach to the multi-mode resource-constrained project scheduling problem MRCPSP, which solves the mode assignment problem using a satisfiability problem solver. This approach is of particular interest since it takes advantage of the specific capabilities of these solvers to implement learning mechanisms and to combine a simple mode feasibility check and a scheduling step based on a single activity list. A capital-constrained multi-mode scheduling problem is investigated in Chap. 23 by Zhengwen He, Nengmin Wang, and Renjing Liu. The problem consists in selecting activity modes and assigning payments to project events in such a way that the project's net present value is maximized and the cash balance does not go negative at any point in time. The execution modes of the activities represent combinations of activity durations and associated disbursements. In Chap. 24 Philipp Baumann, Cord-Ulrich Fündeling, and Norbert Trautmann consider a variant of the resource-constrained project scheduling problem in which the resource usage of individual activities can be varied over time. For each activity the total work content with respect to a distinguished resource is specified, and the resource usages of the remaining resources are determined by the usage of this distinguished resource. A feasible distribution of the work content over the execution time of an activity can be interpreted as an execution mode. The authors present a priority-rule based heuristic and a mixed-integer linear programming formulation, which are compared on a set of benchmark instances.

Part VIII addresses different variants of project staffing and scheduling problems. In those problem settings, the execution of a project activity may require several skills. It then becomes necessary to assign appropriate personnel to the activities and to decide on the skills with which they contribute to each activity. Isabel Correia and Francisco Saldanha-da-Gama develop a generic mixed-integer programming formulation for project staffing and scheduling problems, which is presented in Chap. 25. The formulation captures various features like unary multi-skilled resources, which contribute with at most one skill to each activity, workload capacities of the resources, multi-unit skill requirements of the activities, and generalized precedence relations. This framework is illustrated by providing MILP models for two project staffing and scheduling problems discussed in the literature, the multi-skill project scheduling problem MSPSP and the project scheduling problem with multi-purpose resources PSMPR. In Chap. 26 Carlos Montoya, Odile Bellenguez-Morineau, Eric Pinson, and David Rivreau present a heuristic method for the MSPSP, which is based on integrating column generation and Lagrangian relaxation techniques. The MSPSP consists in assigning the multi-skilled resources to the activities so as to minimize the project duration under ordinary precedence relations between the activities. The authors develop two master problem formulations, which are heuristically solved by iteratively considering restricted versions of the master problem defined on a pool of variables. In each iteration, new variables with negative reduced cost are entered into the pool, which are identified via respective pricing problems. The required dual multipliers are obtained from solving the LP relaxation of the current restricted master problem by alternating iterations of a subgradient procedure for the Lagrangian dual and simplex iterations. Project staffing and scheduling problems of type PSMPR are discussed in Chap. 27. In difference to the MSPSP, the availability of each resource is limited by a maximum workload that can be processed in the planning horizon, and a general staffing cost function is considered. The staffing cost depends on the assignment of resources to skill requirements of the activities. Haitao Li devises an exact algorithm for the general problem with convex staffing cost. The hybrid Benders decomposition method starts from hierarchically dividing the problem into a relaxed master problem covering the assignment decisions and a feasibility subproblem modeling the scheduling decisions. Both levels are linked by top-down instructions and a bottom-up feedback mechanism adding Benders cuts to the relaxed master problem when the scheduling problem is infeasible. The feasibility of the scheduling problem is checked using a constraint programming algorithm. In Chap. 28 Cheikh Dhib, Ameur Soukhal, and Emmanuel Néron address a generalization of the MSPSP in which an activity can be interpreted as a collection of concurrent subactivities requiring a single skill each and possibly differing in durations. Moreover, it is assumed that the subactivities must be started simultaneously, but may be interrupted and resumed individually at integral points in time. The authors propose a mixed-integer linear programming formulation of the problem and describe priority-rule based solution methods, which are based on the parallel schedule-generation scheme.

Discrete time-cost tradeoff problems, which are the subject of **Part IX**, represent a type of multi-modal project scheduling problems that are frequently encountered in practice. This type of problems occur when the processing of certain activities can be sped up by assigning additional resources, leading to higher execution cost. In Chap. 29 Joseph Szmerekovsky and Prahalad Venkateshan provide a literature review on the classical discrete time-cost tradeoff problem DTCTP. Furthermore, they discuss a new integer programming formulation for a version of the DTCTP with irregular start time costs of the activities. For the special case where the start time costs represent the net present value of an activity, the formulation is compared to three alternative MILP models in an extensive computational experiment. In Chap. 30 Mario Vanhoucke studies three extensions of the DTCTP and an electromagnetic meta-heuristic algorithm to solve these problems. The setting of the DTCTP with time-switch constraints presupposes that activities can only be processed in certain time periods defined by given work/rest patterns. In addition to the direct activity costs, the objective function of the DTCTP with work continuity constraints also includes costs for the supply of resources required by groups of activities; this variant of the problem can be reduced to the basic DTCTP. Finally, the DTCTP with net present value optimization is considered.

Area D of the handbook is dedicated to project planning problems involving several individual projects. We distinguish between multi-project scheduling problems, for which the set of projects to be scheduled is assumed given, and project portfolio selection problems, dealing with the choice of the projects to be actually performed. In both scenarios, there may exist dependencies between the individual projects, for example due to precedence relations between activities of different projects or due to the joint requirements for resources.

Part X deals with the first type of multi-project problems. When scheduling concurrent projects, an important question concerns the distribution of information. In the basic multi-project scheduling problem, it is assumed that all planning data are available to a single decision maker, who may centrally schedule the entire project portfolio. On the other hand, decentralized multi-project scheduling covers the situation in which information is distributed over different decision makers, who may pursue individual targets. In this case, a central coordination mechanism is needed to resolve conflicts between the individual projects. In Chap. 31 Jos Fernando Gonçalves, Jorge Jos de Magalhes Mendes, and Mauricio Resende provide a literature overview on basic multi-project scheduling problems BMPSPS. Furthermore, they develop a biased random-key genetic algorithm for the variant of the problem in which a separable polynomial function in the tardiness, the earliness, and the flow time overrun of all projects is to be minimized subject to precedence relations and the limited availability of shared resources. The decentralized multi-project scheduling problem DRCMPSP is addressed in Chap. 32. In their contribution, Andreas Fink and Jörg Homberger discuss implications of the distributed character of the problem. In addition, they provide a classification scheme of different types of DRCMPSP, categorizing problems according to the basic problem structure, the number of decision makers, the distribution of information, and the local and global objectives. The chapter also contains an extensive discussion and classification of solution approaches presented in literature, including auction and negotiation based coordination schemes.

Part XI focuses on project portfolio selection problems. Often there are more projects on offer than resources available to carry them out. In this case project management has to choose the right project portfolio for execution. In Chap. 33 Ana Fernández Carazo considers multi-criteria problems in which the performance of a portfolio is measured according to a set of conflicting goals. First she identifies a number of key factors characterizing multi-criteria project portfolio selection problems and discusses the different ways in which those factors have been modeled in the literature. Based on this analysis, a proposal for a general project portfolio selection model is developed, which synthesizes various features of previous models. Finally, a binary nonlinear multi-criteria programming formulation of the new model is provided. Walter Gutjahr in Chap. 34 surveys models for project portfolio selection problems which include learning and knowledge depreciation effects. Different types of learning curves are reviewed and it is explained how these models have been used in the context of project staffing and scheduling problems. For the integration of skill development into project portfolio selection models, a mixed-integer nonlinear programming formulation is proposed. Moreover, analytical results for continuous project portfolio investment problems under skill development are reviewed, for which it is assumed that projects can also be partially funded.

Area E of the handbook covers the realm of project scheduling under uncertainty and vagueness, an issue that is widely recognized as being highly relevant to practical project management. Stochastic scheduling problems refer to decision situations under risk, in which quantities like activity durations or activity costs are defined as random variables with known distributions and the objective consists in optimizing the expected value of some performance measure. A solution to such a stochastic problem is commonly given by a policy that is applied when the project is executed. Robust project scheduling is concerned with the problem of finding a predictive baseline schedule that still performs well in case of disruptions or adverse scenarios. Interval uncertainty designates a situation in which only lower and upper bounds can be estimated with sufficient accuracy, but no probability distributions are known. Finally, the concept of fuzzy sets allows to model situations in which vague information, which is only available on an ordinal scale, should be taken into account.

Part XII addresses different types of stochastic project scheduling problems. Chapter 35, contributed by Wolfram Wiesemann and Daniel Kuhn, deals with the stochastic time-constrained net present value problem. Both the activity durations and the cash flows associated with the activities are supposed to be independent random variables. Having discussed the relevance and challenges of stochastic net present value problems, the authors review the state of the art for two variants of the problem. If the activity durations are assumed to be exponentially distributed, the problem can be modeled as a discrete-time Markov decision process with a constant discount rate, for which different exact solution procedures are available. Alternatively, activity durations and cash flows can be represented using discrete scenarios with given probabilities. The resulting stochastic net present value problem SNPV can be formulated as a mixed-integer linear program. Several heuristic solution approaches from literature are outlined. In Chap. 36 Evelina Klerides and Eleni Hadjiconstantinou examine the stochastic discrete time-cost tradeoff problem SDTCTP. They survey the literature on static and dynamic versions of the deadline and the budget variant of this problem. For the dynamic budget variant of SDTCTP it is shown that the problem can be formulated as a multi-stage stochastic binary program with decision-dependent uncertainty. Furthermore, the authors present effective methods for computing lower bounds and good feasible solutions, which are respectively based on a two-stage relaxation and a static mode selection policy. The resource-constrained project scheduling problem with random activity durations SRCPSP is the subject of Chap. 37. Maria Elena Bruni, Patrizia Beraldi, and Francesca Guerriero give an overview of models and methods that have been proposed for different variants of this problem. They develop a heuristic based on the parallel schedule-generation scheme, which in each iteration determines the predictive completion times of the scheduled activities by solving a chance-constrained program. The presented approach is innovative in two respects. First, the use of joint probabilistic constraints allows to relax the traditional assumption that the start time of an activity can be disturbed by at most one predecessor activity at a time. Second, similar to robust project scheduling approaches, a solution to the problem is a predictive baseline schedule that is able to absorb a large part of possible disruptions. The objective, however, still consists, for given confidence level, in finding a schedule with minimum makespan. Hence, the problem to be solved can be viewed as a dual of a robust scheduling problem. The heuristic is illustrated on a real-life construction project. Chapter 38, by Saeed Yaghoubi, Siamak Noori, and Amir Azaron, tackles a multi-criteria multi-project scheduling problem in which projects arrive dynamically according to a Poisson process. Activity durations and direct costs for carrying out activities are assumed to be independent random variables. The execution of the projects is represented as a stochastic process in a queueing network with a maximum number of concurrent projects, each activity being performed at a dedicated service station. The expected values of the activity durations and the direct costs are respectively nonincreasing and nondecreasing functions of the amount of a single resource that is assigned to the service station. The problem consists in allocating the limited capacity of the resource in such a way that the mean project completion time is minimized, the utilization of the service stations is maximized, and the probability that the total direct cost exceeds the available budget is minimum. The authors apply continuous-time Markov processes and particle swarm optimization to solve this multi-objective problem using a goal attainment technique.

Part XIII comprises two chapters on robust optimization approaches to project scheduling problems under uncertainty. The basic idea of robust project scheduling consists in establishing a predictive baseline schedule with a diminished vulnerability to disturbances or adverse scenarios and good performance with respect to some genuine scheduling objective. There are many ways in defining the robustness of a schedule. For example, a schedule may be considered robust if it maximizes the probability of being implementable without modifications. Alternatively, the robustness may refer to the genuine objective instead of the feasibility; a robust schedule then typically optimizes the worst-case performance. In difference to stochastic project scheduling, robust project scheduling approaches do not necessarily presuppose information about the probability distributions of the uncertain input parameters of the problem. In Chap. 39 Öncü Hazır, Mohamed Haouari, and

Erdal Erel discuss a robust discrete time-cost tradeoff problem in which for the activity cost associated with a given mode an interval of possible realizations is specified, but no probability distribution is assumed to be known. The authors devise a mixed-integer programming formulation for this problem. The objective function is defined to be the sum of all most likely activity mode costs plus the maximum surplus cost that may be incurred if for a given number of activities, the direct cost does not assume the most likely but the highest value. The latter number of activities may be used to express the risk attitude of the decision maker. In addition, six categories of time-based robustness measures are presented and a two-phase scheduling algorithm for placing a project buffer at minimum additional cost is outlined. Based on this algorithm, the relationship between the required budget augmentation and the average delay in the project completion time can be analyzed. The robust resource-constrained project scheduling problem with uncertain activity durations is investigated in Chap. 40 by Christian Artigues, Roel Leus, and Fabrice Talla Nobibon. Like in the preceding chapter, it is assumed that no probability distributions are available; the sets of possible realizations of activity durations may form intervals or finite sets. The problem is formulated as a minimax absolute-regret model for which the objective is to find an earliest start policy that minimizes the worst-case difference between the makespan obtained when implementing the policy and the respective optimum ex-post makespan. An exact scenario-relaxation algorithm and a scenario-relaxation based heuristic are presented for this problem.

Part XIV is devoted to project scheduling problems under interval uncertainty and to fuzzy project scheduling. In Chap. 41 Christian Artigues, Cyril Briand, and Thierry Garaix survey results and algorithms for the temporal analysis of projects for which the uncertain activity durations are represented as intervals. The temporal analysis computations provide minimum and maximum values for the earliest and latest start times of the activities and the total floats. Whereas the earliest start times can be calculated as longest path lengths like in the case of fixed activity durations, the computation of the latest start times is less simple. Two algorithms with polynomial time complexity are presented. Interestingly, the maximum total float of the activities can also be computed efficiently, whereas the computation of the minimum total floats constitutes an $\mathcal{NP}$-hard problem. The chapter elaborates on a recent branch-and-bound algorithm for the latter problem. Hua Ke and Weimin Ma in Chap. 42 study a fuzzy version of the linear time-cost tradeoff problem in which the normal activity durations are represented as fuzzy variables. The authors survey literature on time-cost tradeoff problems under uncertainty and vagueness. Using elements of credibility theory, the concepts of expected values, quantiles, and probabilistic constraints can be translated from random to fuzzy variables. Based on these concepts, three fuzzy time-cost tradeoff models are proposed, respectively, providing schedules with minimum α-quantile of the total cost, with minimum expected cost, and with maximum credibility of meeting the budget constraint. In addition, a hybrid method combining fuzzy simulations and a genetic algorithm for solving the three models is presented.

Area F addresses managerial approaches to support decision makers faced with increasingly complex project environments. Complex challenges arise, for example, when dealing with project portfolios, or when a project is performed on a client-contractor basis and the goals of both parties must be streamlined, or when risks arise from several sources and these risks are not independent from each other. These and further challenges are discussed in the two parts of Area F.

Part XV is concerned with general project management issues, covering project portfolio management, relational partnerships and incentive mechanisms, and specific challenges encountered in product development and engineering projects. In Chap. 43 Nicholas Hall contrasts the rapid growth of project activities in firms with the lack of trained project management professionals and research-based project management concepts. He proposes 11 areas for future research to reduce the gap between the great practical importance and the limited theoretical foundations of project management in these areas. Chapter 44 by Peerasit Patanakul addresses issues that arise in multi-project environments. These issues comprise the assignment of project managers to projects, organizational factors that enhance multi-project management, and alternative roles of a project management office. New product development constitutes a classical application area of project management procedures and tools. Nevertheless, managing product innovation is still a challenging task, due to the uncertainty associated with the development process and the strategic importance of its success. In Chap. 45 Dirk Pons provides guidelines from a systems engineering perspective, emphasizing on the management of human resources in the development process. Another traditional application area of project management is the construction industry. Construction projects involve two main parties: the contractor and the client receiving the project deliverables provided by the contractor. The concept of partnering tries to overcome the adversarial relation between contractor and client, which still tends to prevail in many construction projects. In Chap. 46 Hemanta Doloi examines key factors that are crucial for successful partnering and draws conclusions from a survey conducted in the Australian construction industry. Chapter 47, written by Xianhai Meng, deals with incentive mechanisms, which are frequently used to enhance project performance, especially in the construction industry. The author discusses different kinds of incentives and disincentives that are related to project goals such as time, cost, quality, and safety. A case study of a road construction project gives insight into the practical application of incentive mechanisms. Project complexity is a prominent cause for project failure. Hence, it is vitally important for managers to know about sources of complexity. In Chap. 48 Marian Bosch-Rekveldta, Hans Bakker, Marcel Hertogh, and Herman Mooi identify drivers of complexity. Based on a literature research and six case studies analyzing the complexity of engineering projects, they provide a framework for evaluating project complexity. The framework comprises technical, organizational, and external sources of project complexity.

Part XVI deals with project risk management. Since the importance of projects has grown and revenues from project work may constitute a considerable share of a firm's total income, managing project risk is vitally important as it helps to identify threats and to mitigate potential damage. In Chap. 49, Chao Fang and Franck Marle outline a framework for project risk management, which considers not only single risks separately but also interactions between risks. The authors show how interactions can be captured in a matrix-based risk network and provide a quantitative method to analyze such a network. Chapter 50 is concerned with risk management for software projects. Paul Bannerman reviews empirical research on the application of risk management in practice, the effectiveness of risk management, and factors that hinder or facilitate the implementation of risk management. He describes different perspectives on risk management in order to show the wide range of approaches and to identify avenues for further research. An important goal of risk management is to identify risks and to decide on the risks that should be mitigated. This decision is frequently based on a ranking of the identified risks. In Chap. 51 Stefan Creemers, Stijn Van de Vonder, and Erik Demeulemeester survey the different ranking methods that were proposed in the literature. In particular, they consider so-called ranking indices that provide a ranking of activities or risks based on their impact on the project objectives. They show that the ranking methods may differ in their outcome and evaluate their performance with a focus on the risk of project delay.

The last **Area G** proves evidence for the relevance of concepts developed in the preceding parts of this handbook to the practice of project management and scheduling. The area covers different domains beyond proper project scheduling and puts the concepts treated in the previous parts into the perspective of real-life project management. It includes chapters on project scheduling applications, case studies, and project management information systems.

Part XVII collects six industrial applications of resource-constrained project scheduling, where different models and methods presented in previous chapters are put into practice. In particular, test, production, and workflow scheduling problems are considered. Chapter 52, written by Jan-Hendrik Bartels and Jürgen Zimmermann, reports on the problem of scheduling destructive tests in automotive R&D projects. The planning objective consists in minimizing the number of required experimental vehicles. The problem is modeled as a multi-mode resource-constrained project scheduling problem with renewable and storage resources, in which the required stock must be built up before it can be consumed. In addition to different variants of a priority-rule based heuristic, an activity-list based genetic algorithm is proposed. Both heuristic approaches prove suitable for solving large-scale practical problem instances. In Chap. 53 Roman Čapek, Přemysl Šůcha, and Zdeněk Hanzálek describe a scheduling problem with alternative process plans, which arises in the production of wire harnesses. In such a production process, alternative process plans include production operations that can be performed in different ways, using fully or semi-automated machines. A mixed-integer linear programming model for a resource-constrained project scheduling problem with generalized precedence relations, sequence-dependent setup times, and alternative activities is presented. Furthermore, a heuristic schedule-construction procedure with an unscheduling step is proposed, which can be applied to large problem instances. Chapter 54 is concerned with the scheduling of jobs with large computational requirements in grid computing. An example of such jobs are workflow applications, which comprise several precedence-related computation tasks. A computer grid is a large-scale, geographically distributed, dynamically reconfigurable, and scalable hardware and software infrastructure. Marek Mika and Grzegorz Waligóra present three models for scheduling the computation and transmission tasks in grids, differing in their assumptions with respect to the workflow applications and computer networks. For the models with distributed resources and sequence-dependent setup times, resource allocation and scheduling algorithms are presented. For the model in which transmission tasks compete for scarce network resources it is shown how a feasible resource allocation can be determined. Chapter 55 by Haitao Li considers make-or-buy and supplier selection problems arising in conjunction with the scheduling of operations in make-to-order supply chains. A multi-mode resource-constrained project scheduling problem is formulated to minimize the total supply chain cost, in which synergies and interactions between sourcing and scheduling decisions are captured. The total supply chain cost involves the total fixed cost, cost of goods sold, and total pipeline stock cost and depends on the selected activity modes. The proposed solution algorithm draws on the hybrid Benders decomposition framework exposed in Chap. 27. The relaxed master problem (RMP) covers the assignment decisions, whereas the subproblem (SP) is concerned with the scheduling of the operations. The feasibility of an optimal RMP solution is checked by solving the respective SP. If the SP is feasible, an optimal solution has been found; otherwise, the algorithm identifies some cause of infeasibility and adds respective cuts to the RMP, which is then solved again. A numerical example is discussed to demonstrate the scope and depth of decision-support offered by the solutions of the model for purchasing and program managers. In Chap. 56 Arianna Alfieri and Marcello Urgo apply a project scheduling approach to make-to-order systems for special-purpose machinery like instrumental goods or power generation devices, in which products are assembled in the one-of-a-kind production mode. They present a resource-constrained project scheduling problem with feeding precedence relations and work content constraints and explain its application to a real-world case of machining center production. In Chap. 57 Matthew Colvin and Christos Maravelias apply multi-stage stochastic programming to the development process of new drugs. The problem consists in scheduling a set of drugs, each of which has to undergo three trials. If one trial fails, the development of the related drug is canceled. The required resources are limited and the objective is to maximize the expected net present value of the project. After an introduction to stochastic programming and endogenous observations of uncertainty, a mixed-integer multi-stage stochastic programming model is presented. Some structural properties of the problem are discussed and three solution methods including a branch-and-cut algorithm are developed.

Part XVIII presents two case studies in project scheduling. In Chap. 58 Maurizio Bevilacqua, Filippo Ciarapica, Giovanni Mazzuto, and Claudia Paciarotti combine concepts of robust project scheduling and multi-criteria project scheduling to tackle a construction project for an accommodation module of an oil rig in the Danish North Sea. To guarantee an efficient use of the resources, the project management identified the minimization of the project duration and the leveling of the manpower resources as primary goals. Using historical data from 15 past projects, the means and the standard deviations of the activity durations could be estimated with sufficient accuracy. To obtain a robust baseline schedule for the project, project buffers and feeding buffers were inserted in the schedule according to the lines of Goldratt's Critical Chain methodology. Compared to the traditional CPM method, the presented robust goal programming approach was able to reduce the project duration by 14 % and to improve the resource utilization by more than 40 %. In Chap. 59 Jiuping Xu and Ziqiang Zeng consider a multi-criteria version of the discrete time-cost tradeoff problem, which is called the discrete time-cost-environment-tradeoff problem DTCETP. They assume that normal activity durations are represented as triangular fuzzy numbers and that for each period there exists a limit on the total cost incurred by the processing and crashing of activities. This cash flow constraint can be modeled as a renewable resource whose capacity coincides with the cost limit. The capacity is taken up according to the requirements of alternative execution modes. In sum, the problem can be formulated as a fuzzy multi-criteria multi-mode resource-constrained project scheduling problem. Four objective functions are taken into account: the total project cost, the project duration, the total crashing costs of activities, and the quantified environmental impact of the project. Xu and Zeng develop an adaptive hybrid genetic algorithm for this problem and describe its application to the Jinping-II hydroelectric construction project on the Yalong River in the Sichuan-Chongqing region. Both the input data of the case study and the computed schedule are provided. The performance of the algorithm is evaluated based on a sensitivity analysis with respect to the objective weights and the results obtained with two benchmark heuristics.

Project management information systems PMIS play a crucial role in the transfer of advanced project management and scheduling techniques to professional project management. **Part XIX** addresses the question of the actual contribution of PMIS on the project performance, studies the effects of PMIS on decision making in multi-project environments, and investigates the project scheduling capabilities of commercial PMIS.

Based on a PMIS success model and a survey conducted among project managers, Louis Raymond and François Bergeron in Chap. 60 empirically assess the impact of PMIS on decision makers and project success. Their model comprises five constructs: the quality of the PMIS, the quality of the PMIS information output, the use of the PMIS, the individual impacts of the PMIS, and the impacts of the PMIS on project success. Each construct is measured using several criteria. Structural equation modeling with the partial least squares method is used to analyze the relationships between the different dimensions and to test the validity of six research hypotheses. The results obtained show that the use of PMIS in professional project management significantly contributes to the efficiency and effectiveness of individual project managers and to the overall project performance. Chapter 61 presents a related study in which Marjolein Caniëls and Ralph Bakens focus on the role of PMIS in multi-project environments, where project managers handle multiple concurrent but generally less complex projects. After a survey of the literature on multi-project management and PMIS the research model is introduced, which contains six constructs: the project overload, the information overload, the PMIS information quality, the satisfaction with PMIS, the use of PMIS information,

Table 2 Overview of project scheduling problems treated in the handbook, respective acronyms used in the literature, and three-field notations of Brucker et al. (1999)

Chaps.	Project scheduling problem	Acronym	Three-field notation
1 – 4	Resource-constrained project scheduling problem	RCPSP	$PS \mid prec \mid C_{max}$
5 – 7	Resource-constrained project scheduling problem with generalized precedence relations	RCPSP/max	$PS \mid temp \mid C_{max}$
8	Resource-constrained project scheduling problem with time-varying resource requirements and capacities	RCPSP/t	$PSt \mid prec \mid C_{max}$
9	Project scheduling problems with storage resources		$PSs \mid temp \mid C_{max}$
10	Discrete-continuous resource-constrained project scheduling problem	DCRCPSP	$PSc \mid prec \mid C_{max}$
11	Resource-constrained project scheduling problem with partially renewable resources	RCPSP/π	$PSp \mid prec \mid C_{max}$
12	Integer preemptive resource-constrained project scheduling problem with limited number of interruptions per activity	Maxnint_ PRCPSP	$PS \mid prec, l\text{-}pmtn/int \mid C_{max}$
13	Continuous preemptive resource-constrained project scheduling problem with generalized precedence relations	PRCPSP/max	$PS \mid temp, pmtn \mid C_{max}$
14	Resource-constrained project scheduling problem with discounted cash flows	RCPSPDC	$PS \mid prec, \overline{d} \mid \Sigma c_i^F \beta^{C_i}$
15	Resource availability cost problem	RACP	$PS\infty \mid prec, \overline{d} \mid \Sigma c_k \max r_{kt}$
16	Resource availability cost problems	RACP, RACPT	$PS\infty \mid prec, \overline{d} \mid \Sigma c_k \max r_{kt}$, $PS\infty \mid prec \mid \Sigma c_k \max r_{kt} + wT$
17	Resource leveling problems	RLP	$PS\infty \mid temp, \overline{d} \mid \Sigma c_k \Sigma r_{kt}^2$, $PS\infty \mid temp, \overline{d} \mid \Sigma c_k \Sigma o_{kt}$, and $PS\infty \mid temp, \overline{d} \mid \Sigma c_k \Sigma \Delta r_{kt}$
18	Resource leveling problem	RLP	$PS\infty \mid prec, \overline{d} \mid \Sigma c_k \Sigma r_{kt}^2$
19	Multi-objective time- and resource-constrained project scheduling problems	MOPSPs, MORCPSPs	$PS\infty \mid prec \mid mult$, $PS \mid prec \mid mult$
20	Multi-objective resource-constrained project scheduling	MORCPSPs	$PS \mid prec \mid mult$

(continued)

Table 2 (continued)

Chaps.	Project scheduling problem	Acronym	Three-field notation
21	Multi-modal resource-constrained project scheduling problems		$MPS \mid prec \mid f$
22	Multi-mode resource-constrained project scheduling problem	MRCPSP	$MPS \mid prec \mid C_{max}$
23	Multi-mode capital-constrained net present value problem	MNPV	$MPSs \mid prec \mid \Sigma c_i^F \beta^{C_i}$
24	Project scheduling problem with work content constraints		$PSf \mid prec \mid C_{max}$
25	Project staffing and scheduling problems		$PSS \mid temp \mid f$
26	Multi-skill project scheduling problem	MSPSP	$PSS\infty \mid prec \mid C_{max}$
27	Project scheduling with multi-purpose resources	PSMPR	$PSS \mid temp \mid staff$
28	Preemptive multi-skill project scheduling problem		$PSS \mid prec, pmtn \mid C_{max}$
29	Discrete time-cost tradeoff problem (deadline version)	d-DTCTP	$MPS\infty \mid prec, \overline{d} \mid \Sigma c_i(p_i)$
	Discrete time-cost tradeoff problem with irregular starting time costs		$MPS\infty \mid prec, \overline{d} \mid f$
30	Discrete time-cost tradeoff problem with time-switch constraints	d-DTCTP-tsc	$MPS\infty \mid prec, \overline{d}, cal \mid \Sigma c_i(p_i)$
	Discrete time-cost tradeoff problem with net present value optimization	d-DTCTP-npv	$MPS\infty \mid prec, \overline{d} \mid \Sigma c_i^F \beta^{C_i}$
31	Basic multi-project scheduling problem	BMPSP	$PS \mid mult, prec \mid f$
32	Decentralized multi-project scheduling problem	DRCMPSP	
33	Multi-criteria project portfolio selection problem		
34	Project selection, scheduling, and staffing with learning problem	PSSSLP	
35	Stochastic net present value problem	SNPV	$PS \mid prec, p_i = sto \mid \Sigma c_i^F \beta^{C_i}$
36	Stochastic discrete time-cost tradeoff problem (budget version)	b-SDTCTP	$MPS\infty \mid prec, bud, p_i = sto \mid C_{max}$
37	Stochastic resource-constrained project scheduling problem	SRCPSP	$PS \mid prec, p_i = sto \mid C_{max}$
38	Markovian multi-criteria multi-project resource-constrained project scheduling problem		$MPSm, 1, 1 \mid mult, prec, bud, p_i = sto, c_i = sto, Poi \mid mult$

(continued)

Table 2 (continued)

Chaps.	Project scheduling problem	Acronym	Three-field notation
39	Robust discrete time-cost tradeoff problem		$MPS\infty \mid prec, \overline{d}, c_i = unc \mid \Sigma c_i(p_i)$
40	(Absolute regret) Robust resource-constrained project scheduling problem	AR-RCPSP	$PS \mid prec, p_i = unc \mid rob$
41	Temporal analysis under interval uncertainty		$PS\infty \mid prec, p_i = unc \mid f$ with $f \in \{ES_i, LS_i, TF_i\}$
42	Fuzzy time-cost tradeoff problem (deadline version)		$MPS\infty \mid prec, \overline{d}, p_i = fuz \mid \Sigma c_i(p_i)$
52	Multi-mode resource-constrained project scheduling problem with storage resources		$MPSs \mid temp, \overline{d} \mid \Sigma c_k \max r_{kt}$
53	Resource-constrained project scheduling problem with generalized precedence relations, sequence dependent setup times, and alternative activities	RCPSP-APP	$PS \mid temp, s_{ij}, nestedAlt \mid C_{max}$
54	Multi-mode resource-constrained project scheduling problems	MRCPSP	$MPS \mid prec \mid C_{max}$
55	Multi-mode resource-constrained project scheduling problem		$MPS \mid prec, \overline{d} \mid mac$
56	Resource constrained project scheduling problem with feeding precedence relations and work content constraints		$PSft \mid feed \mid C_{max}$
57	Stochastic net present value problem in which the set of activities to be executed is stochastic		$PS \mid prec, act = sto \mid \Sigma c_i^F \beta^{C_i}$
58	Robust multi-criteria project scheduling problem		$PS \mid prec, p_i = sto \mid C_{max}/\Sigma r_{kt}^2$
59	Fuzzy multi-criteria multi-mode project scheduling problem	DTCETP	$MPS \mid prec, \overline{d}, bud, p_i = fuz \mid mult$

and the quality of decision making. Based on the results of a survey among project managers, several hypotheses on the relationships between the constructs are tested using the partial least square method. It turns out that project and information overload are not negatively correlated with PMIS information quality and that the quality and use of PMIS information are strongly related to the quality of decision making. In the final Chap. 62, Philipp Baumann and Norbert Trautmann experimentally assess the performance of eight popular PMIS with respect to their project scheduling capabilities. Using the more than 1.500 KSD-30, KSD-60, and KSD-120 instances of the resource-constrained project scheduling problem RCPSP from the PSPLIB library, the impact of different complexity parameters and priority rules on the resulting project durations is analyzed. The results indicate that for the project duration criterion, the scheduling performances of the software packages differ significantly and that the option of selecting specific priority rules generally leads to schedules of inferior quality as compared to PMIS that do not offer this feature.

Table 2 gives an overview of the different types of project scheduling problems treated in this book. In the literature many of those problems are commonly designated by acronyms, which are provided in the third column of the table. The last column lists the respective designators of the (extended) three-field classification scheme for project scheduling problems proposed by Brucker et al. (1999). The notation introduced there and the classification scheme, which are used in different parts of this handbook, are defined in the list of symbols, which is included in the front matter of this book.

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