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Christoph Schwindt
Jürgen Zimmermann *Editors*

# Handbook on Project Management and Scheduling Vol.1

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# Handbook on Project Management and Scheduling Vol. 1

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# 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

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# 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 |
| $\mathcal{NP}$ | Set of decision problems that can be solved in polynomial time by a non-deterministic Turing machine |

| | |
|---|---|
| $\mathscr{O}$ | Landau's symbol: for $f, g : \mathbb{N} \rightarrow \mathbb{R}_{\geq 0}$ 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

| | |
|---|---|
| $\delta_{ij}$ | 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 $\delta$ |
| $p_i$ | 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 $N$;<br>Set of activities in an activity-on-node network |
| $V^a$ | Set of real activities in an activity-on-node network |

## Resources and Skills

| | |
|---|---|
| $\Pi_k$ | Set of periods associated with partially renewable resource $k$ |
| $k$ | Single (renewable, nonrenewable, partially renewable, or storage) resource |
| $K = \|\mathscr{R}\|$ | Number of renewable resources |
| $l \in \mathscr{L}$ | Single skill |
| $L = \|\mathscr{L}\|$ | Number of skills |
| $L_i = \|\mathscr{L}_i\|$ | 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 $i$ |
| $M_i = \|\mathscr{M}_i\|$ | 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

| | |
|---|---|
| $\alpha_q$ | Dummy start activity of project $q$ |
| $\omega_q$ | 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

| | |
|---|---|
| $\lambda$ | Arrival rate of projects |
| $\mu_{\hat{z}}(z)$ | Membership function of fuzzy set $\hat{z}$ |
| $\pi_\sigma$ | Probability of scenario $\sigma$ ($\sum_{\sigma \in \Sigma} \pi_\sigma = 1$) |
| $\sigma \in \Sigma$ | Single scenario |
| $\Sigma$ | Set of scenarios |
| $\Sigma_i$ | 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 |
| $x_\alpha$ | $\alpha$-quantile ($F_{\tilde{x}}(x_\alpha) = \alpha$) |
| $z$ | (Crisp) Element from set $Z$ |
| $\hat{z}$ | General fuzzy set |

## Objective Functions

| | |
|---|---|
| $\alpha$ | 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 $x$ |
| $f_\mu$ | 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

| | |
|---|---|
| $\phi_{ij}^k$ | Amount of resource $k$ transferred from activity $i$ to activity $j$ |
| $\rho_{mut}$ | Mutation rate |
| $\sigma_{pop}$ | Population size |
| $\ell$ | Activity list $(i_1, i_2, \dots, i_n)$ |
| $\mathscr{C}$ | 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 |
| $\Delta_{LB}^{max}$ | Maximum relative deviation from lower bound |
| $\Delta_{opt}^{\varnothing}$ | Average relative deviation from optimum value |
| $\Delta_{opt}^{max}$ | Maximum relative deviation from optimum value |
| $\Delta_{UB}^{\varnothing}$ | Average relative deviation from upper bound |
| $\Delta_{UB}^{max}$ | 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 |
| $PS\infty$ | 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 |
| $PSS\infty$ | 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 $\sigma$ and $\mu$ nonrenewable resources |
| $MPS$ | Multi-mode project scheduling problem with limited renewable and nonrenewable resources |
| $MPS\infty$ | 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.

| | |
|---|---|
| $\beta_1 : mult$ | Multi-project problem |
| $\beta_1 : \circ$ | Single-project problem |
| $\beta_2 : prec$ | 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 $\gamma$: 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)."

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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

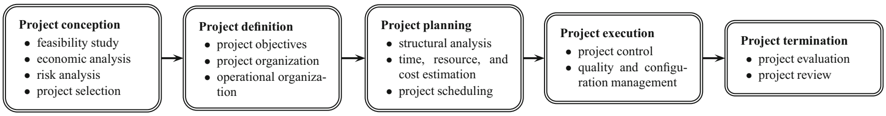


**Fig. 1** Project life cycle

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.