

Mario Vanhoucke

Project Management with Dynamic Scheduling

Baseline Scheduling, Risk Analysis
and Project Control

2nd Edition

 Springer

Mario Vanhoucke

Project Management with Dynamic Scheduling

Baseline Scheduling, Risk Analysis
and Project Control

Second Edition



Springer

Mario Vanhoucke
Ghent University
Fac. Economics and Business Administration
Ghent
Belgium

ISBN 978-3-642-40437-5 ISBN 978-3-642-40438-2 (eBook)
DOI 10.1007/978-3-642-40438-2
Springer Heidelberg New York Dordrecht London

Library of Congress Control Number: 2013956213

© Springer-Verlag Berlin Heidelberg 2013, 2012

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

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

Preface

Project scheduling began as a research track within the mathematical field of Operations Research in order to determine start and finish times of project activities subject to precedence and resource constraints while optimizing a certain project objective (such as lead-time minimization, cash-flow optimization, etc.). The initial research done in the late 1950s mainly focused on network based techniques such as CPM (Critical Path Method) and PERT (Program Evaluation and Review Technique), which are still widely recognized as important project management tools and techniques.

From this moment on, a substantial amount of research has been carried out covering various areas of project scheduling (e.g. time scheduling, resource scheduling, cost scheduling). Today, project scheduling research continues to grow in the variety of its theoretical models, in its magnitude and in its applications. While the focus of decennia of research was mainly on the static development of algorithms to deal with the complex scheduling problems, the recent research activities gradually started to focus on the development of dynamic scheduling tools that are able to respond to a higher uncertainty during the project's progress.

The topic of this book is known as *dynamic scheduling* and is used to refer to three dimensions of project management and scheduling: the construction of a *baseline schedule* and the analysis of a project *schedule's risk* as preparation for the *project control* phase during the progress of the project. This dynamic scheduling point of view implicitly assumes that the usability of a project's baseline schedule is rather limited and only acts as a point of reference in the project life cycle. Consequently, a project schedule should especially be considered as nothing more than a predictive model that can be used for resource efficiency calculations, time and cost risk analyses, project control and performance measurement. In all upcoming chapters, the project control phase will also be called project *tracking* or project *monitoring*.

In this book, the three dimensions of dynamic scheduling are highlighted in detail and are based on and inspired by a combination of academic research studies at Ghent University (www.ugent.be), in-company trainings at Vlerick Business School (www.vlerick.com) and consultancy projects at OR-AS (www.or-as.be).

First, the construction of a project baseline schedule is a central theme throughout the various chapters of the book. This theme is discussed from a complexity point of view with and without the presence of project resources. Second, the creation of an awareness of the weak parts in a baseline schedule is highlighted, known as schedule risk analysis techniques that can be applied on top of the baseline schedule. Third, the baseline schedule and its risk analyses can be used as guidelines during the project control step where actual deviations can be corrected within the margins of the project's time and cost reserves.

Scope

The goal of this book is not to compete with excellent handbooks on general project management principles nor to give an extensive overview of all project management aspects that might contribute to the overall success of a project. Instead, the aim is to bring a clear and strong focus on the preparatory phases, the project baseline scheduling and the schedule risk analysis phases, to support the project control phase where project performance measurement is a key issue for a project's success. The intention is to hold the middle between a research handbook and a practical guide for project schedulers or project management software users. To that purpose, the content of this book is brought in such a way that it is able to inform a wide audience about the current state-of-the-art principles in dynamic project scheduling. The target audience can consist of undergraduate or MBA students following a project management course, participants of company trainings with a focus on scheduling or software users who search for added value when using software tools.

Book Overview

Chapter 1 gives a short introduction to the central theme of the book and highlights the three components of dynamic project scheduling: project scheduling, risk analysis and project control. The chapter gives a brief overview of the project life cycle and makes a distinction between project complexity and uncertainty using a *project mapping* matrix. The *complexity* dimension is related to the absence or presence of project resources under limited availability, as discussed in Parts I (low complexity) and II (high complexity) of the book. The *uncertainty* dimension is related to the need of a project's schedule risk analysis and is discussed in individual Chaps. 5 and 10 of both parts. Example files and more information can be downloaded from www.or-as.be/books.

Part I. Scheduling Without Resources

Part I is devoted to dynamic scheduling principles for projects without resources. It is assumed that project resources are not limited in availability, which leads to simple and straightforward scheduling tools and techniques that can be considered as basic techniques for the more complex resource-constrained scheduling methods of Part II.

Chapter 2 gives an overview of the basic scheduling principles without using resources and thereby lays the foundation for all future chapters to predict the timing and cost outline of a project. The basic critical path calculations of project scheduling are highlighted and the fundamental concept of an activity network is presented. Moreover, the Program Evaluation and Review Technique (PERT) is discussed as an easy yet effective scheduling tool for projects with (low) variability in the activity duration estimates.

Chapter 3 presents an interactive game that acts as a training tool to help practitioners and project management students to gain insight in the basic project scheduling techniques. The game involves the iterative re-scheduling of a project within the presence of uncertainty. Each project activity can be executed under different duration and cost combinations, which is known as the critical path method (CPM). The game is set up to highlight the importance of a thorough knowledge of baseline scheduling techniques and to create an awareness of the need for schedule risk analyses (discussed in Chap. 5).

Chapter 4 serves as an illustrative chapter based on a case study of a capacity expansion project at a water production center in the northern part of Belgium. It shows that the clever use of basic critical path scheduling algorithms can lead to a realistic baseline schedule once the scheduling objective is clearly defined. It will be shown that scheduling the project with certain techniques will improve the financial status of the project, as measured by its net present value.

Chapter 5 highlights the importance of a schedule risk analysis (SRA) once the baseline schedule has been constructed. This second dimension of dynamic scheduling connects the risk information of project activities to the baseline schedule and provides sensitivity information of individual project activities as a way to assess the potential impact of uncertainty on the final project duration and cost. When management has a certain feeling of the relative sensitivity of the project activities on the project objective, a better management focus and a more accurate response during project control should positively contribute to the overall performance of the project.

Chapter 6 describes the first part of a series of three case exercises (Parts II and III can be found in Chaps. 11 and 14). Each case description is an integrated exercise to get acquainted with the scheduling principles discussed in the previous chapters. The case of Chap. 6 assumes the construction of a baseline schedule and knowledge of basic critical path scheduling principles and allows the extension to basic calculations of risk in order to take protective actions. The solution and the educational approach depend on the wishes and needs of the students who solve the

case and the teacher who can act as the moderator during the case teaching session. A teaching session should allow enough freedom to extend the original topic to various other dynamic scheduling related issues.

Part II. Scheduling with Resources

Part II extends the previously discussed dynamic scheduling principles to projects with resources that have a limited availability. In these complex scheduling settings, activities are executed by resources that are restricted in availability over time. This resource restriction leads to an increase in scheduling complexity, as will be shown in the various chapters of this part.

Chapter 7 gives an extensive overview of tools and techniques for resource-constrained project scheduling. It is shown that the introduction of resources in project scheduling leads to an increase in scheduling complexity. The importance of the choice of a scheduling objective is highlighted in detail by showing various resource-constrained scheduling models. The ability to assess the quality of the resource feasible schedule as well as a basic knowledge about scheduling software functionalities are discussed throughout the sections of this chapter.

Chapter 8 further elaborates on the resource-constrained project scheduling topics of the previous chapter and presents some advanced results obtained by various research projects. This chapter extends the resource models to other scheduling objectives, studies the effect of activity splitting and setup times and introduces learning effects in a resource-constrained project environment. These topics are brought together in a separate chapter such that the reader can skip these advanced topics without losing overview of the general dynamic scheduling theme.

Chapter 9 presents, similar to Chap. 4, an illustrative case study of a practical project scheduling study. The project to construct a tunnel to connect the two sides of the Westerschelde in the Netherlands is used to illustrate the importance of the scheduling objective as discussed intensively in the previous chapters. More precisely, it will be shown that the minimization of a bottleneck resource's idle time during the scheduling phase can lead to important cost savings.

Chapter 10 elaborates on the construction of a resource feasible project schedule as discussed in the previous chapter, but extends this scheduling approach to a more flexible baseline schedule protected against unexpected events. The Critical Chain/Buffer Management (CC/BM) approach incorporates a certain degree of flexibility in the activity start times in order to easily monitor schedule deviations and quickly respond by taking corrective actions to keep the whole project on schedule. The technique is initiated by E. M. Goldratt in his groundbreaking book "Critical Chain" as a practical translation of the so-called *Theory of Constraints* in a project scheduling environment.

Chapter 11 presents the second part of a fictitious case exercise introduced in Chap. 6 that aims at the construction of a resource feasible project schedule using project scheduling software tools. The goal of the student is to go further

than submitting software print-outs to the project team. Instead, the purpose is the integration of the resource-constrained scheduling principles of the previous chapters within the features of a project scheduling tool in order to provide an easy and understandable information sheet on the predicted project execution to the various members of a project team. It allows the integration of CC/BM techniques of the previous chapter to highlight the advantages and potential weaknesses.

Part III. Project Control

Part III uses the schedules constructed in the previous chapters as inputs for the project execution phase where project's progress needs to be measured and monitored in order to take corrective actions when the project runs into trouble. This third dimension of dynamic scheduling completely relies on the quality of the two other dimensions (baseline scheduling and risk analysis) discussed in the previous chapters. The construction of a baseline schedule based on a sound methodology as well as the knowledge of the sensitivity of each project activity on the project's time and cost dimensions act as inputs during the project control step to better support corrective actions in case the project is in danger.

Chapter 12 gives an overview of the Earned Value Management (EVM) method to measure a project's time and cost performance. It gives an overview of all EVM metrics and performance measures to monitor the time and cost dimension of a project's current progress to date. Moreover, it also illustrates how this performance information can be used to predict the expected remaining time and cost to finalize the project that serve as triggers to take corrective actions to bring the project back on track, when needed.

Chapter 13 is a summary chapter of a large simulation study to predict the final duration of a project in progress using EVM forecasting methods. The chapter briefly discusses results that give an idea of the accuracy of different EVM forecasting methods along the life cycle of the project. It also presents an extension to the classical use of EVM to measure the adherence of a project in progress to the original baseline schedule. The main results of this chapter have been awarded by the International Project Management Association (www.ipma.ch) with the IPMA 2008 Research Award.

Chapter 14 is a third fictitious case exercise that allows the integration of EVM reports in the project control phase in order to get acquainted with the terminology and characteristics of EVM. It assumes a dynamic multi-project setting where three projects are executed in parallel. The purpose is the clever use of EVM methods and metrics and the critical review of these methods as a dynamic time/cost performance measurement system.

Part IV. Scheduling with Software

Part IV presents the main features of a software tool that integrates the three dynamic scheduling dimensions (scheduling, risk analysis and control) discussed in the previous sections.

Chapter 15 gives a brief overview of the main features of the software tool ProTrack (acronym for *Project Tracking*). Although ProTrack is a commercial software tool and is therefore not free of charge, a student friendly version with time-limited functionalities can be freely downloaded from www.protrack.be such that the main dynamic scheduling principles discussed in this book can be easily tested in a fictitious project environment.

Part V. Conclusions

Part V contains Chap. 16 and provides overall conclusions on dynamic scheduling. It provides an overall summary of all chapters and gives directions for practical use of software tools and suggestions for further actions on research and practical applications.

Acknowledgements

This book is the result of several research projects, consultancy tasks and fruitful discussions with both academics and practitioners. I am therefore indebted to many people who have helped me in writing this book.

I would like to thank my father, Robert Vanhoucke, for the fruitful discussions while writing Chap. 4 during the final stages of my PhD period. He helped me with the technical details of the project at a water production center (Vlaamse Maatschappij voor Watervoorziening) and provided me with useful information about it. I am also grateful to Dr. Stan Beernaert, chief executive at the Vlaamse Maatschappij voor Watervoorziening at the time of the project scheduling phase, for giving me the permission to use the data of the project. Last but not least, I would like to thank ir. Paul Suenens, project leader for the project, for providing me with a detailed description of the project by means of a Microsoft Project file.

I would like to thank Iris Vodderie for drawing my attention to the construction project in the Netherlands as described in Chap. 9. I am also grateful to Karel De Bel, Senior consultant Plancon and Theun Steinfort, projectmanager “Ontwerp en Voorbereiding”, for giving me the permission to use the data of the project and for providing me with a detailed description of the project. I want to especially thank Koen Van Osselaer for the nice and pleasant collaboration during this project.

I am also thankful to Prof. Dr. Bert De Reyck from London Business School (UK) and University College London (UK) who allowed me to use the project description

that was used during the writing of the Chaps. 6, 11 and 14. Although the case exercises of these chapters go far beyond the original purpose of his bridge project example, the general project characteristics of this bridge example were used as the foundation to describe the three case exercises.

I also would like to thank Prof. Dr. Roel Leus from the Katholieke Universiteit Leuven (Belgium) for the co-writing of parts of Chap. 10 as a foundation article used in the Project Management course at Ghent University.

I am obviously very much indebted to Tom Van Acker, partner at OR-AS, for the co-development of our software tool ProTrack as described in Chap. 15. Obviously, without his help, this book was not what it is now. The close relation between the various chapters of the book and the features and characteristics of the software tool is the results of years of work, both at the programming side of our software tool as at the consultancy side when dealing with real project schedules and all corresponding difficulties related to that. Both the software and the book is therefore the result of joint efforts of all OR-AS customers, a team of volunteers (both researchers as people from practice) and PhD students in project scheduling who all contributed in one way or another. A special thank you goes to Stephan Vandevoorde, who always supported and motivated the OR-AS team when our activities progressed slower than expected. A special word of thank goes to Sylvain Beernaert, Vincent Van Peteghem, Broos Maenhout, Veronique Sels, Thomas De Jonghe, Jeroen Colin, Christophe Van Huele and Mathieu Wauters for their careful attention during proofreading the final manuscripts. Thank you, all.

I acknowledge the support by the Research collaboration fund of PMI Belgium received in Brussels in 2007 at the Belgian Chapter meeting, the support for a research project funding by the Flemish Government (2008), Belgium, the research support of the National Bank of Belgium (NBB) as well as the support given by the “Fonds voor Wetenschappelijk Onderzoek (FWO), Vlaanderen, Belgium” and the “Bijzonder Onderzoeksfonds (BOF)” at Ghent University. Parts of the research topics in this book have been awarded by the IPMA Research award in 2008 during the 22nd world congress in Rome (Italy) with the study “Measuring Time – An Earned Value Simulation Study”. Thanks to this support and these financial sources, I was able to write parts of Chap. 12 based on data from various real-life consultancy projects.

It goes without saying that all of this took a lot of time, both during the weeks and the weekend. I am therefore especially thankful to Gaëtane for the many hours of proofreading and editing and the kids, Joyce and Thierry, for their never-ending patience when I was working on the software tool often 7 days a week.

London, UK
Ghent, Belgium

Mario Vanhoucke

Contents

1	Introduction	1
1.1	Introduction	1
1.2	The Project Life Cycle (PLC)	2
1.2.1	Project Phases	3
1.2.2	The PLC in PMBOK	3
1.2.3	The PLC Used in This Book	4
1.3	Dynamic Scheduling Methodology	6
1.3.1	Project Mapping	6
1.3.2	Complexity	7
1.3.3	Uncertainty	7
1.3.4	Control	8
1.4	Conclusions	8

Part I Scheduling Without Resources

2	The PERT/CPM Technique	11
2.1	Introduction	11
2.2	Project Definition Phase	12
2.2.1	WBS and OBS	12
2.2.2	Network Analysis	14
2.2.3	Generalized Precedence Relations	18
2.2.4	Other Constraint Types	22
2.3	Project Scheduling Phase	23
2.3.1	Introduction to Scheduling	24
2.3.2	Critical Path Calculations	25
2.4	Program Evaluation and Review Technique (PERT)	30
2.4.1	Three Activity Duration Estimates	31
2.4.2	Probability of Project Completion	32
2.4.3	Beyond PERT	34
2.5	Conclusion	34

3	The Critical Path Method	37
3.1	Introduction to Literature	37
3.2	Time/Cost Scheduling Trade-Offs	38
3.2.1	Linear Time/Cost Relations	38
3.2.2	Discrete Time/Cost Relations	41
3.3	The Project Scheduling Game	42
3.3.1	Why Do Managers Need This Game?	42
3.3.2	The Project Data of PSG	44
3.3.3	Simulation Process of PSG	46
3.3.4	Access to PSG Using ProTrack	52
3.4	Educational Approach	52
3.4.1	Simulation Seminar and Target Group	52
3.4.2	Teaching Process	53
3.4.3	Performance Evaluation	54
3.4.4	Game Discussion	54
3.4.5	PSG as a Research Tool	55
3.5	Conclusions	56
4	The VMW Project	59
4.1	Introduction	59
4.2	Description of the Project	61
4.2.1	Subproject 1: Extension of the Storage Capacity of Treated Water	61
4.2.2	Subproject 2: Increase of the Production Capacity	64
4.2.3	Work Breakdown Structure	71
4.3	Analysis of the Project	71
4.3.1	Features of the Project	71
4.3.2	Earliest Start Schedule	73
4.3.3	Maximizing the Net Present Value	75
4.3.4	Robust Schedule	76
4.4	Conclusions	78
4.5	Appendix	78
5	Schedule Risk Analysis	81
5.1	Introduction	81
5.2	Schedule Risk Analysis	82
5.2.1	Step 1. Baseline Scheduling	83
5.2.2	Step 2. Risk and Uncertainty	84
5.2.3	Step 3. Monte-Carlo Simulation	86
5.2.4	Step 4. Results	87
5.3	Sensitivity Measures	87
5.3.1	Criticality Index CI	88
5.3.2	Significance Index SI	89
5.3.3	Cruciality Index CRI	90
5.3.4	Schedule Sensitivity Index SSI	91

- 5.4 Sensitivity Examples 91
 - 5.4.1 A Fictitious Project Example 91
 - 5.4.2 Counterintuitive Examples 94
- 5.5 Schedule Risk Analysis in Action 95
 - 5.5.1 Project Tracking 96
 - 5.5.2 Network Topology 96
- 5.6 Conclusion 99
- 6 The Mutum-Paraná II Bridge Project (A) 101**
 - 6.1 Introduction 101
 - 6.2 The Team Meeting 102
 - 6.3 The Project 102
 - 6.4 The Team Proposals 105
- Part II Scheduling with Resources**
- 7 Resource-Constrained Project Scheduling 109**
 - 7.1 Introduction 109
 - 7.2 Resources 110
 - 7.3 Scheduling Objective 111
 - 7.3.1 Regular and Nonregular Objectives 111
 - 7.3.2 Time Minimization 113
 - 7.3.3 Net Present Value Maximization 117
 - 7.3.4 Resource Leveling 122
 - 7.4 Scheduling Methods 124
 - 7.4.1 Constructive Heuristics 125
 - 7.4.2 Lower Bounds 128
 - 7.4.3 Assessing Schedule Quality 130
 - 7.4.4 Other Scheduling Methods 131
 - 7.5 Scheduling Extensions 134
 - 7.5.1 Variable Resource Availability 134
 - 7.5.2 Multi-mode: A Time/Resource Trade-Off 135
 - 7.5.3 Others 135
 - 7.6 Resource Cost 136
 - 7.6.1 Types of Costs 136
 - 7.6.2 Cost Sensitivity 138
 - 7.7 Conclusions 139
- 8 Resource-Constrained Scheduling Extensions 141**
 - 8.1 Introduction 141
 - 8.2 Other Scheduling Objectives 142
 - 8.2.1 Work Continuity Optimization 142
 - 8.2.2 Quality Dependent Time Slots 150
 - 8.2.3 Resource Availability Cost Problem 155

8.3	Quantitative Project Descriptions.....	158
8.3.1	Network Topology.....	158
8.3.2	Resource Scarceness.....	160
8.3.3	Relevance.....	161
8.4	Extra Scheduling Features.....	162
8.4.1	Activity Assumptions.....	162
8.4.2	Setup Times.....	165
8.4.3	Learning.....	167
8.5	Conclusions.....	173
9	The Westerschelde Tunnel Project.....	175
9.1	Introduction.....	175
9.2	The Project.....	176
9.2.1	The Project Network.....	176
9.2.2	The Project Characteristics.....	178
9.3	Project Scheduling.....	180
9.3.1	An Earliest Start Schedule.....	181
9.3.2	Minimizing Resource Idle Time.....	182
9.3.3	Various Other Scenarios.....	184
9.4	Conclusions.....	185
10	Critical Chain/Buffer Management.....	187
10.1	Introduction.....	187
10.2	Sources of Uncertainty.....	189
10.2.1	Parkinson's Law.....	190
10.2.2	The Student Syndrome.....	191
10.2.3	Multiple Parallel Paths.....	192
10.2.4	Multitasking.....	192
10.3	Critical Chain/Buffer Management.....	193
10.3.1	Theory of Constraints in Project Management.....	194
10.3.2	Working Backwards in Time.....	194
10.3.3	The Project Buffer.....	195
10.3.4	Feeding Buffers.....	197
10.3.5	The Critical Chain.....	198
10.3.6	Resource Buffers.....	199
10.4	An Illustrative Example.....	200
10.5	Project Execution and Buffer Management.....	202
10.6	A Critical Note.....	205
10.6.1	Scheduling Objective.....	205
10.6.2	Scheduling Quality.....	206
10.6.3	Critical Chain.....	206
10.6.4	Buffer Sizing.....	207
10.6.5	Buffer Management.....	207
10.7	Conclusions.....	207

- 11 The Mutum-Paraná II Bridge Project (B)**209
 - 11.1 Introduction209
 - 11.2 The Project in Detail210
 - 11.2.1 The Resources212
 - 11.2.2 The Relations212

- Part III Project Control**

- 12 Earned Value Management**217
 - 12.1 Introduction218
 - 12.2 EVM Key Parameters219
 - 12.2.1 Planned Value220
 - 12.2.2 Actual Cost220
 - 12.2.3 Earned Value221
 - 12.2.4 Earned Schedule222
 - 12.3 Performance Measurement223
 - 12.3.1 Variances223
 - 12.3.2 Indicators225
 - 12.4 Forecasting229
 - 12.4.1 Time Forecasting229
 - 12.4.2 Cost Forecasting233
 - 12.5 A Fictitious Project Example234
 - 12.6 Conclusions239

- 13 Advanced Topics**241
 - 13.1 Introduction241
 - 13.2 Schedule Adherence242
 - 13.2.1 The p-Factor Concept243
 - 13.2.2 Effective Earned Value246
 - 13.3 If Time Is Money, Accuracy Pays!247
 - 13.3.1 Research Scope247
 - 13.3.2 Research Methodology248
 - 13.3.3 Drivers of Forecast Accuracy251
 - 13.4 Project Tracking Efficiency255
 - 13.4.1 Top-Down Project Tracking Using EVM256
 - 13.4.2 Bottom-Up Project Tracking Using SRA256
 - 13.4.3 Project Tracking Efficiency257
 - 13.5 Conclusions259

- 14 The Mutum-Paraná II Bridge Project (C)**261
 - 14.1 Introduction261
 - 14.2 The Project Portfolio262
 - 14.3 The Management Committee Meeting265
 - 14.4 The Agenda267
 - 14.5 Appendix267

Part IV Scheduling with Software

15 Dynamic Scheduling with ProTrack.....275

- 15.1 Introduction.....275
- 15.2 Baseline Scheduling.....277
- 15.3 Schedule Risk Analysis.....277
- 15.4 Project Control.....278
- 15.5 ProTrack’s Advanced Features.....279
 - 15.5.1 Automatic Project Generation.....279
 - 15.5.2 Standard and Advanced EVM Features.....281
 - 15.5.3 Forecasting Accuracy Calculations.....282
 - 15.5.4 Project Control Charts.....283
- 15.6 PSG: ProTrack as a Teaching Tool.....286
 - 15.6.1 Simulating Time/Cost Trade-Offs.....286
 - 15.6.2 Submitting Project Data.....287
- 15.7 P2 Engine: ProTrack as a Research Tool.....287
 - 15.7.1 Advancing the State-of-the-Art Knowledge.....287
 - 15.7.2 Scanning a Project.....288
- 15.8 Conclusions.....289

Part V Conclusions

16 Conclusions.....293

- 16.1 Baseline Scheduling.....294
- 16.2 Schedule Risk Analysis.....296
- 16.3 Project Control.....297
- 16.4 Summary.....299
- 16.5 Future Developments.....300

References.....313

Chapter 1

Introduction

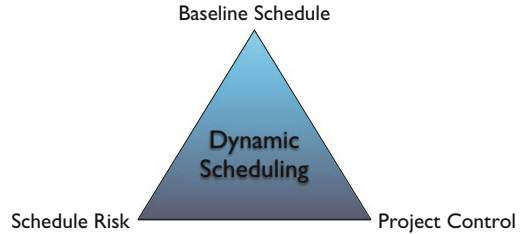
Abstract This chapter gives a short introduction to the central theme of the book and highlights the three components of dynamic project scheduling: the construction of a project baseline schedule, a risk analysis of this schedule and the project's performance measurement and control component. The chapter also gives a short introduction to the *project life cycle* to provide a guidance to the various chapters of the book. A simple and intuitive project mapping approach is briefly described and will be used to put all techniques discussed throughout the various chapters into perspective.

1.1 Introduction

Project management is the discipline of planning, organizing and managing resources to bring about the successful completion of specific project goals and objectives. The project management discipline can be highlighted from various angles and sub-disciplines and contains important issues such as project objective and scope management, human resource management and setting the roles and responsibilities of all participants and stakeholders of a project, planning principles and resource allocation models, etc. The current book does not aim at providing a general overview on project management, but instead has a clear focus on the planning aspect of projects. The topic of the book could be best described as *dynamic project scheduling* to illustrate that project scheduling is a dynamic process that involves a continuous stream of changes and that it is a never ending process to support decisions that need to be made along the life of the project. The focus of the book lies on three crucial dimensions of dynamic scheduling, which can be briefly summarized along the following lines:

- Scheduling: Construct a timetable to provide a start and end date for each project activity, taking activity relations, resource constraints and other project characteristics into account and aiming at reaching a certain scheduling objective.

Fig. 1.1 The three components of dynamic project scheduling



- Risk Analysis: Analyze the strengths and weaknesses of the project schedule in order to obtain information about the schedule sensitivity and the impact of unexpected changes that undoubtedly occur during project progress on the project objective.
- Control: Measure the (time and cost) performance of a project during its progress and use the information obtained during the scheduling and risk analysis steps to monitor and update the project and to take corrective actions in case of problems.

The scope and purpose of the book is to bring a mixed message trying to combine theoretical principles from literature with practical examples and case exercises. To that purpose, the reader should take a step back from the buttons and looks of the project management software tools and/or the daily practice of project management to see what the dynamic scheduling principles have to offer. Rather than solely focusing on the latest state-of-the-art scheduling techniques from the academic literature, the reader will be drowned into a wide variety of scheduling and control principles and an often pragmatic project scheduling and monitoring approach, each time illustrated by means of short examples, practical case examples or fictitious integrated exercises. Figure 1.1 highlights the three basic components of dynamic scheduling.

Each of these three dimensions of dynamic scheduling plays an important role in the project life of a project. In the next section, the so-called project life cycle is briefly discussed from different angles and the link with dynamic scheduling is shown.

1.2 The Project Life Cycle (PLC)

Typically, a project goes through a number of different phases, which is often referred to as the project life cycle. In this book “Managing high-technology programs and projects”, Archibald (1976) describes the project life cycle as follows:

The project life cycle has identifiable start and end points, which can be associated with a time scale. A project passes through several distinct phases as it matures. The life cycle includes all phases from point of inception to final termination of the project. The interfaces between phases are rarely clearly separated, except in cases where proposal acceptance of formal authorization to proceed separates the two phases.

Consequently, the PLC is defined by the time window between the initial start of the project and the final termination and consists of a number of phases, separated by major milestones. The number of phases and their corresponding titles differ from industry to industry and from project to project. The next two subsections elaborate on the project life cycle with a number of examples, without having the intention to provide a full literature review.

1.2.1 Project Phases

A project consists of sequential phases. These phases are extremely useful in planning a project since they provide a framework for budgeting, manpower and resource allocation and for scheduling project milestones and project reviews. The method of dividing a project into phases may differ somewhat from industry to industry and from product to product and it can be summarized as follows:

- Concept (initiation, identification, selection).
- Definition (feasibility, development, demonstration, design prototype).
- Execution (implementation, production, design/construct/commission, install and test).
- Closeout (termination and post completion evaluation).

Archibald (1976) argues that the number of phases and the titles are so generic that they are of little value in describing the project life cycle process. Although the construction and presentation of a generic project life cycle seems to be difficult, if not impossible, each PLC shares a number of common characteristics.

- The major milestones between the phases represent high-level decision points.
- The phases may, and frequently will, overlap.

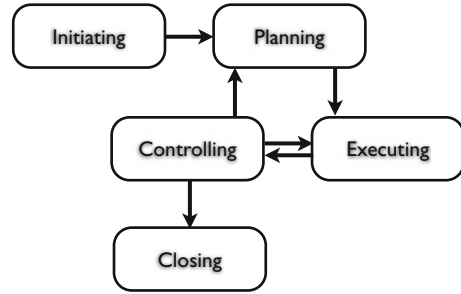
Between the various phases are decision points, at which an explicit decision is made concerning whether the next phase should be undertaken. A major review of the entire project occurs at the end of each phase, resulting in authorization to proceed with the next phase, cancellation of the project, or repetition of a previous phase.

1.2.2 The PLC in PMBOK

In the first edition of PMBOK,¹ the project life cycle concept was not mentioned at all. In the later editions, PMI realized the importance of the “divide and conquer”

¹The Project Management Body of Knowledge, published by the Project Management Institute (PMI) – www.pmi.org.

Fig. 1.2 Accomplishment of a project through the integration of five project management processes (PMBOK)



principle as the complexity and the size of the project increase and included the PLC concept in the book. More precisely, PMBOK describes the project life cycle as follows:

Because projects are unique undertakings, they involve a degree of uncertainty. Organizations performing projects will usually divide each into several project phases to improve management control and provide for links to the ongoing operations of the performing organization. Collectively, the project phases are known as the project life cycle.

Each project is marked by the completion of one or more deliverables, such as a feasibility study or a detail design. These deliverables, and hence the phases, are part of a generally sequential logic designed to ensure proper definition of the project. The conclusion of each phase is generally marked by a review. These reviews, often called milestones, phase exits, stage gates or kill points, are necessary to:

- Determine if the project should continue to the next phase.
- Detect and correct errors cost effectively.

Although PMBOK presents a sample generic life cycle as shown in Fig. 1.2, they argue that many project life cycles have similar phase names with similar deliverables required but few are identical. The next section presents a similar generic project life cycle that will be used throughout all chapters of this book.

1.2.3 The PLC Used in This Book

Figure 1.3 shows an illustrative project life cycle that will be used throughout the remaining chapters of this book. This generic project life cycle was initially constructed and used for a consultancy study summarized in Chap. 4 and serves as an ideal tool to illustrate the dynamic scheduling approach taken in this book.

This generic project life cycle is based on a life cycle description by Klein (2000) and consists of a project conception phase, a project definition phase, a phase in which the project has to be scheduled, the execution of the project, the project control phase and the termination of the project.

At the beginning, in the so-called conceptual phase, an organization identifies the need for a project or receives a request from a customer.

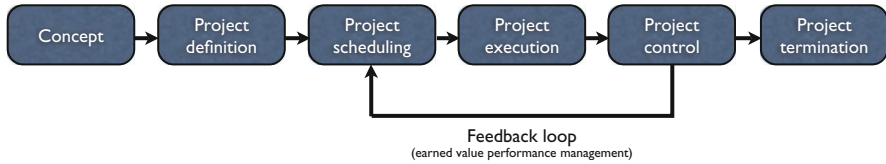


Fig. 1.3 An illustrative Project Life Cycle (PLC)

In the definition phase, the organization defines the project objectives, the project specifications and requirements and the organization of the whole project. The project objectives need to be refined and translated into a list of activities, a set of technological precedence relations and the resource availabilities and requirements. In doing so, the organization decides in detail on how it is going to achieve these objectives. The refinement of these project objectives into a final activity network containing activities and precedence relations is the subject of Chap. 2. The extension to resource availabilities and requirements is discussed from Chap. 7 onwards.

The next phase, the scheduling phase, aims at the construction of a timetable for the project activities. The construction of a precedence and/or resource feasible schedule determines a start and finish time for each activity, and hence, relies on the information obtained by the previous phase. In the following chapters of Parts I and II, a detailed overview of the scheduling principles using different techniques and aiming at reaching different targets is discussed.

During the execution and project control phases, the project has to be monitored and controlled to see whether it is performed according to the existing schedule. If deviations occur, corrective actions have to be taken. This control mechanism has been incorporated in the project life cycle by means of the feedback loop between the control phase and the scheduling phase of Fig. 1.3. This topic is the subject of Part III of this book. An update of a schedule can be done in two basic ways:

1. Reactive scheduling: This principle aims at the construction of a deterministic schedule, without taking possible risk factors or uncertainty events into account. During project execution, the project progress needs to be monitored using the information of the schedule and adaptations to the schedule need to be made when the deviations become too large. A reactive scheduling approach is the subject of Chap. 3.
2. Proactive scheduling: The uncertainty is embedded in the schedule to construct a buffered schedule. This schedule is robust and protected against possible uncertain events. In doing so, the feedback loop can be avoided within certain ranges. A proactive scheduling approach is presented in Chap. 10 of this book.

The termination phase involves the completion and a critical evaluation of the project. This information can then be used during the project life cycle of future, similar projects since the specifications of a project, the estimates of the durations, costs and resource requirements are often determined based on averages of past performance.

1.3 Dynamic Scheduling Methodology

In this section, a simple yet effective guidance is presented to classify projects along two dimensions: complexity and uncertainty. This project mapping approach will be used throughout all chapters of this book during the detailed explanation of the three dimensions of dynamic project scheduling.

1.3.1 Project Mapping

Although project scheduling is often considered to be an art more than a science, a thorough knowledge of the tools and techniques available is necessary to create a realistic project schedule. Obviously, the selection of the right tool and technique depends on the characteristics of the project and the background and knowledge of the project manager.

The approach taken along the various chapters in the book is a very pragmatic and nonscientific way of mapping projects along two dimensions as shown in Fig. 1.4: complexity and uncertainty. The advantage of this simple yet intuitive mapping approach lies in its ability to classify most project planning and scheduling techniques in one of the four quadrants. Although it is recognized that project management is more than a simple reduction to a set of scheduling tools and planning techniques, it creates awareness that techniques need to be put into perspective and need to be used only if the underlying assumptions and corresponding advantages/disadvantages are thoroughly known and understood.

The classification of scheduling techniques along the dimensions of complexity and uncertainty makes sense since dynamic scheduling is, in a way, a careful balance between dealing with complexity (mostly with the help of a commercial software tool to construct a (resource-constrained) project baseline schedule) and coping

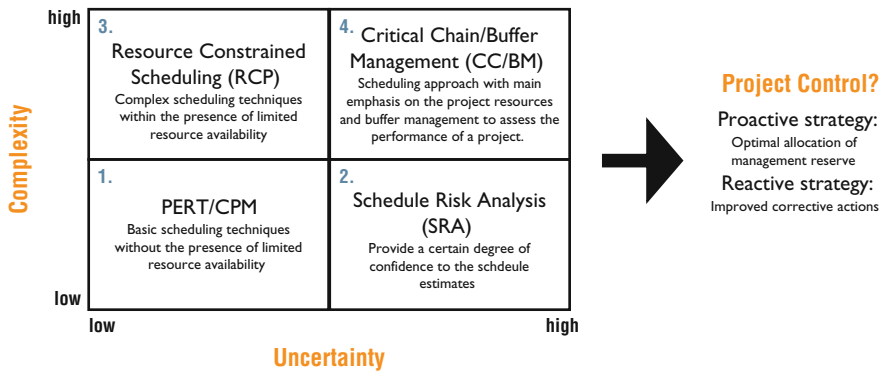


Fig. 1.4 Project mapping approach used throughout the chapters of this book

with uncertainty (realizing that a schedule obtained by a software tool will be subject to changes during the project's progress). This careful balance needs to be made by the project manager/planner and constitutes the basic starting point of this book. The ultimate goal of measuring and coping with complexity and uncertainty is to provide a basic tool to the project manager to monitor the performance of his/her project during progress. Consequently, Fig. 1.4 shows the three dimensions of dynamic scheduling: project scheduling (complexity), risk analysis (uncertainty) and project control. The complexity/uncertainty dimensions as well as their impact on the project control phase are briefly outlined in the following three subsections.

1.3.2 Complexity

The complexity dimension of Fig. 1.4 is completely related to the first dimension of dynamic scheduling: the construction of a project's baseline schedule. More precisely, it is related to the absence or presence of resources during the construction of a schedule and is used to distinguish between Parts I and II of this book.

The basic project scheduling techniques, often known under the general PERT/CPM abbreviation, assume that projects need to be done within the presence of an infinite resource capacity. Despite their simplicity, they still are considered as the basic scheduling techniques, and their principles are applicable to more advanced techniques. Due to this simplicity, their use is obviously restricted to simple and straightforward projects where resources are not assumed to be relatively highly constrained and are ignored during the scheduling process (quadrants 1 and 2 of Fig. 1.4). These resource-unconstrained project scheduling techniques are discussed in Part I of this book in Chaps. 2–6.

However, it is generally accepted that the presence of resources under limited availability is a matter of degree in practical business projects, which results in a dramatic increase in problem complexity when constructing a project baseline schedule (quadrants 3 and 4). Therefore, Part II of this book reviews the resource-constrained project scheduling techniques. The academic literature on resource-constrained project scheduling (RCP) is rich and has a main focus on the development of algorithms and procedures to solve often very complex project models. Although it is not the intention of this book to give a summary of these algorithms, it illustrates that the presence of limited resources in projects leads to an increasing complexity. The topics are discussed in Part II in Chaps. 7–10 of this book.

1.3.3 Uncertainty

When the level of uncertainty is assumed to be high, the schedule of a project becomes more and more subject to unexpected changes during project progress, and a certain knowledge of risk is therefore often indispensable. This second dimension

of dynamic scheduling, project risk analysis, is shown by the uncertainty dimension of Fig. 1.4.

Schedule Risk Analysis (SRA) stems from the recognition that the construction of a project schedule is an uncertain art of estimating the set of activities, their network logic and their times and costs. Consequently, in order to provide a certain degree of confidence within each schedule estimate, SRA assigns distributions on top of the schedule to calculate a probability of meeting the scheduled end dates and cost targets (quadrant 2).

The Critical Chain/Buffer Management (CC/BM) approach can be seen as an extended view on schedule risk analysis, since it integrates the uncertainty of schedule estimates within the complexity view of resource scheduling principles (quadrant 4). This integrated view on resource complexity and schedule estimate uncertainty has led to a new scheduling framework that contains valuable principles applicable to practical project settings.

1.3.4 Control

It has been mentioned earlier that the project progress has to be monitored and controlled to measure whether the project is performed according to the original baseline schedule. Both a reactive and a proactive scheduling approach can be mapped into the quadrants of the project mapping approach, in order to allow taking timely corrective actions when the project is in trouble. This third dimension of dynamic scheduling, project control, is extensively discussed in Part III of this book.

1.4 Conclusions

This chapter gave a short and basic introduction to the principle of dynamic scheduling as the main topic of this book. This dynamic scheduling perspective consists of three connected sub-topics, i.e. the art and science of project scheduling, the analysis of risk and sensitivity of a project schedule's estimates and the project monitoring and control during the progress of the project. It has been shown that these three dynamic scheduling dimensions completely fit into the project life cycle concept presented in various sources in the literature.

A simple and straightforward project mapping framework has been presented as a general guidance for the various dynamic scheduling methods and techniques discussed in this book. This complexity/uncertainty framework will be used throughout the chapters of Parts I and II and aims at the construction of a feasible project schedule, which serves as a baseline point of reference for the project monitoring and control chapters discussed in Part III.

Welcome to the wonderful world of Project Management

The book has many more chapters to offer, and you will learn

- How to plan a project
- How to analyse risk
- How to allocate resources in a project
- How buffer the project
- How to monitor the progress of a project

But the book also contains live case studies such as

- Bridge construction
- Tunnel construction (Westerscheldetunnel in the Netherlands)
- Water purification (Vlaamse Maatschappij voor Watervoorziening, now called “de watergroep”)

And much more...

Take a sneak preview look at www.or-as.be.

Enjoy!
Mario Vanhoucke



List of Figures

Fig. 1.1	The three components of dynamic project scheduling	2
Fig. 1.2	Accomplishment of a project through the integration of five project management processes (PMBOK)	4
Fig. 1.3	An illustrative Project Life Cycle (PLC)	5
Fig. 1.4	Project mapping approach used throughout the chapters of this book	6
Fig. 2.1	Four levels of a Work Breakdown Structure	12
Fig. 2.2	A Responsibility Assignment Matrix (RAM)	13
Fig. 2.3	The AoA representation of the technological link between activities i and j	15
Fig. 2.4	Dummy arc for the unique identification of activities i and j	16
Fig. 2.5	Two AoA networks for the example project of Table 2.1	16
Fig. 2.6	The AoN representation of the technological link between activities i and j	17
Fig. 2.7	The AoN network for the example project of Table 2.1	18
Fig. 2.8	Four types of precedence relations between activities i and j	20
Fig. 2.9	An activity network with generalized precedence relations (Source: De Reyck 1998)	21
Fig. 2.10	The equivalence of minimal and maximal time lags	21
Fig. 2.11	The activity network of Fig. 2.9 with only minimal time lags	22
Fig. 2.12	The AoN example network of Table 2.2	26
Fig. 2.13	The ESS Gantt chart of the example project and the activity slack	29
Fig. 2.14	The modified ESS Gantt chart of the example project and the activity slack	30

List of Figures

Fig. 1.1	The three components of dynamic project scheduling	2
Fig. 1.2	Accomplishment of a project through the integration of five project management processes (PMBOK)	4
Fig. 1.3	An illustrative Project Life Cycle (PLC)	5
Fig. 1.4	Project mapping approach used throughout the chapters of this book	6
Fig. 2.1	Four levels of a Work Breakdown Structure	12
Fig. 2.2	A Responsibility Assignment Matrix (RAM)	13
Fig. 2.3	The AoA representation of the technological link between activities i and j	15
Fig. 2.4	Dummy arc for the unique identification of activities i and j	16
Fig. 2.5	Two AoA networks for the example project of Table 2.1	16
Fig. 2.6	The AoN representation of the technological link between activities i and j	17
Fig. 2.7	The AoN network for the example project of Table 2.1	18
Fig. 2.8	Four types of precedence relations between activities i and j	20
Fig. 2.9	An activity network with generalized precedence relations (Source: De Reyck 1998)	21
Fig. 2.10	The equivalence of minimal and maximal time lags	21
Fig. 2.11	The activity network of Fig. 2.9 with only minimal time lags	22
Fig. 2.12	The AoN example network of Table 2.2	26
Fig. 2.13	The ESS Gantt chart of the example project and the activity slack	29
Fig. 2.14	The modified ESS Gantt chart of the example project and the activity slack	30

Fig. 2.15	A beta distribution used to express activity duration variability in PERT	32
Fig. 3.1	The time/cost trade-off of an activity.....	39
Fig. 3.2	A fictitious AoA network with five nondummy activities.....	40
Fig. 3.3	A discrete time/cost trade-off for an activity.....	41
Fig. 3.4	The PSG project life cycle.....	43
Fig. 3.5	The default PSG project network.....	45
Fig. 3.6	The simulation process of the game.....	50
Fig. 3.7	The six decision moments of PSG.....	51
Fig. 3.8	The PSG Gantt chart in ProTrack.....	53
Fig. 3.9	The complete time/cost profile of the PSG project.....	54
Fig. 4.1	Graphical scheme of the production process at the WPC of Kluizen.....	60
Fig. 4.2	Graphical scheme of the production process at the WPC of Kluizen and the new storage extensions (RWK1, RWK2, HDZ' and HSC').....	62
Fig. 4.3	Network representation of the work completed at the production plant WPC Kluizen	64
Fig. 4.4	Network representation of the work completed outside the production plant WPC Kluizen.....	66
Fig. 4.5	Graphical scheme of subproject 2: Increase in capacity.....	67
Fig. 4.6	Network representation of the three steps to increase the production capacity.....	71
Fig. 4.7	The WBS for the VMW project up to the work package level.....	72
Fig. 4.8	Network representation (AoN) of the VMW project.....	74
Fig. 4.9	Three different schedules for a subpart of subproject “constructing a pump at Zelzate” (see Table 4.2). (a) Earliest start schedule (0% slack value); (b) Latest start schedule (100% slack value); (c) Robust schedule (50% slack value).....	75
Fig. 4.10	The net present values (in BEF) for different schedules with different degrees of the %Slack.....	77
Fig. 5.1	The four steps of a schedule risk analysis	83
Fig. 5.2	Monte-Carlo simulation principle	86
Fig. 5.3	Cumulative project duration graph	88
Fig. 5.4	An example project (Source: Vanhoucke 2010a)	92
Fig. 5.5	A parallel two nondummy activity example network (SP = 0) (Source: Williams 1992)	95
Fig. 5.6	A serial two nondummy activity example network (SP = 1) (Source: Williams 1992)	95
Fig. 5.7	Action thresholds during project tracking using SRA activity information	97

Fig. 5.8	Two projects with serial (<i>left</i>) and/or parallel (<i>right</i>) activities	98
Fig. 6.1	The highway bridge – profile	103
Fig. 6.2	The highway bridge – cross section	103
Fig. 6.3	The project network for the Mutum-Paraná II bridge project (A)	105
Fig. 7.1	The AoN example network of Table 7.1	114
Fig. 7.2	Resource graph for earliest start schedule (ESS)	115
Fig. 7.3	Feasible resource graph with minimal time	116
Fig. 7.4	Feasible resource graphs with four renewable resources	118
Fig. 7.5	Independent activity cash flows can be represented by a single cash flow value using discount rates	119
Fig. 7.6	Feasible resource graph with maximal <i>npv</i>	121
Fig. 7.7	Feasible resource graph with leveled resource use	124
Fig. 7.8	A feasible project schedule obtained using the SPT rule with the serial and parallel schedule generation schemes	127
Fig. 7.9	The critical path of the example project and the time window for all noncritical activities	129
Fig. 7.10	Assessment of the project schedule quality	131
Fig. 7.11	Multi-mode resource-constrained project schedule	135
Fig. 8.1	Feasible resource graph with work continuity optimization	144
Fig. 8.2	An example project with six repeating activities (Source: Harris and Ioannou (1998))	146
Fig. 8.3	The repetitive project network of Fig. 8.2 with six units	147
Fig. 8.4	RSM diagram for a six units project of Fig. 8.2	147
Fig. 8.5	An example project with ten repeating activities	148
Fig. 8.6	Trade-off between work continuity and project deadline	149
Fig. 8.7	An example project with quality-dependent time slots	154
Fig. 8.8	The RCPSP schedule with minimal time (<i>top</i>) and quality-dependent time slots (<i>bottom</i>)	155
Fig. 8.9	The efficient cost curves for two resource types and the search for the best resource availabilities	158
Fig. 8.10	Resource-constrained project scheduling under various activity assumptions	163
Fig. 8.11	Resource-constrained project scheduling with setup times	165
Fig. 8.12	Different schedules for an example project (Source: Van Peteghem and Vanhoucke (2010b)).....	169

Fig. 8.13	Comparison of three project baseline schedules to measure the influence of activity learning.....	171
Fig. 9.1	The transverse link subproject: section in the area of a cross passage (Source: KMW).....	177
Fig. 9.2	The unit project network of the “Transverse Links” subproject.....	177
Fig. 9.3	Gantt chart obtained by the ESS of the project (units 4 and 5).....	179
Fig. 10.1	A typical right skewed probability density function	189
Fig. 10.2	50% time estimate and 90%-percentile	190
Fig. 10.3	An assembly activity can only start when multiple predecessors are finished	192
Fig. 10.4	Multitasking versus no multitasking	193
Fig. 10.5	A serial project network with safety time for each individual activity	195
Fig. 10.6	Inserting a project buffer	197
Fig. 10.7	A project with a feeding chain	198
Fig. 10.8	Inserting a feeding buffer	198
Fig. 10.9	An unbuffered resource feasible schedule (CC = 1-2-4)	199
Fig. 10.10	A buffered resource feasible schedule	199
Fig. 10.11	An example project network with 11 nondummy activities	200
Fig. 10.12	A resource feasible latest start schedule	201
Fig. 10.13	The buffered network of Fig. 10.11	202
Fig. 10.14	Insertion of the buffers into the baseline schedule	203
Fig. 10.15	Buffer management thresholds as a function of proportion of project completed	204
Fig. 12.1	Earned Value Management: key parameters, performance measures and forecasting indicators	218
Fig. 12.2	Planned Value of a 5-activity project with BAC = €100,000 and PD = 5 weeks	220
Fig. 12.3	The planned value, actual cost and earned value at week 3	221
Fig. 12.4	Linear interpolation between PV_i and PV_{i+1}	222
Fig. 12.5	The EVM key parameters PV, AC and EV for a project under four scenarios	224
Fig. 12.6	The SV and CV graph for the 5-activity example project	225
Fig. 12.7	The ES metric for a late (<i>left</i>) and early (<i>right</i>) project	226
Fig. 12.8	The SPI and SPI(t) graph for the 5-activity example project	227

Fig. 12.9 The SPI and SV versus SPI(t) and SV(t) performance measures..... 228

Fig. 12.10 Expected cost and time performance 230

Fig. 12.11 The example project of Fig. 5.4 with activity cash flows 235

Fig. 12.12 The baseline schedule for the project of Fig. 12.11 235

Fig. 12.13 The actual project execution Gantt chart of the example project 235

Fig. 12.14 The traditional S-curves for the example project..... 238

Fig. 12.15 The nine duration forecasts along the life of the project..... 239

Fig. 13.1 A fictitious four-activity project network 244

Fig. 13.2 A fictitious four-activity project under three progress scenarios..... 245

Fig. 13.3 Activity impediments and work under risk to measure the p-factor 246

Fig. 13.4 The four step research methodology used for the EVM accuracy study 249

Fig. 13.5 Nine simulation scenarios (step 3 of Fig. 13.4) 250

Fig. 13.6 Static drivers of EVM accuracy: project definition and scheduling phase 252

Fig. 13.7 Dynamic drivers of EVM accuracy: project execution and control phase 254

Fig. 13.8 Does dynamic scheduling lead to a higher efficiency in project tracking? 255

Fig. 13.9 The top-down project based tracking approach of earned value management 257

Fig. 13.10 The bottom-up activity based tracking approach of schedule risk analysis 258

Fig. 13.11 The tracking efficiency of a bottom-up and top-down tracking approach 258

Fig. 14.1 A graphical timeline for the current project portfolio 264

Fig. 15.1 Dynamic scheduling in ProTrack..... 276

Fig. 16.1 A project mapping approach to reveal the three dimensions of dynamic scheduling 294

Fig. 16.2 An increasing need for scheduling software tools as the scheduling complexity increases 295

Fig. 16.3 An increasing need for risk analysis as the project uncertainty increases 296

Fig. 16.4 Two important project control drivers that might affect the project success 301

List of Tables

Table 2.1	List of activities with their immediate predecessors.....	16
Table 2.2	A fictitious project example with 12 nondummy activities.....	25
Table 2.3	Enumeration of all possible paths of the project of Table 2.2....	26
Table 2.4	The slack of the activities of the example project of Fig. 2.12...	28
Table 2.5	Three time estimates for the activities of the project of Fig. 2.12.....	31
Table 3.1	An activity list for the PSG project with their time/cost trade-offs.....	47
Table 4.1	Description of the first step of subproject 1.....	63
Table 4.2	Description of the second step of subproject 1.....	65
Table 4.3	Description of the first step of subproject 2.....	68
Table 4.4	Description of the second step of subproject 2.....	69
Table 5.1	Five simulation scenarios to perform a schedule risk analysis...	92
Table 5.2	The sensitivity measures for all activities obtained through a schedule risk analysis.....	92
Table 5.3	Intermediate calculations for the sensitivity measures.....	93
Table 5.4	The effect of multiple parallel paths: the merge bias.....	99
Table 6.1	The project activities for the Mutum-Paraná II bridge project (A).....	104
Table 7.1	Activity and resource data for the example project of Fig. 7.1...	114
Table 7.2	Four renewable resources for the example project of Fig. 7.1 ...	117
Table 7.3	Various priority rules used to construct a schedule for the example project of Fig. 7.1.....	126
Table 7.4	The parallel schedule generation scheme procedure to obtain the bottom schedule of Fig. 7.8.....	128
Table 7.5	Intermediate calculations to obtain the critical sequence lower bound value.....	130

Table 7.6	All possible (duration, resource demand) combinations for the example project of Fig. 7.1 under a fixed work mode.....	134
Table 7.7	The calculation of activity costs from their resource use.....	138
Table 8.1	Activity durations of the activities of Fig. 8.5 for five units.....	149
Table 8.2	The quality dependent time slot data for Fig. 8.7.....	154
Table 8.3	Iterative search for the best possible resource availability combination.....	157
Table 8.4	Illustrative learning effects on activity/resource combinations of activity 7 of Table 8.5.....	170
Table 8.5	Activity durations, resource requirements and schedule information for the example project.....	171
Table 9.1	Original activity description of the unit network activities (in Dutch).....	179
Table 9.2	The activity time estimates for the Westerschelde tunnel project (in weeks).....	181
Table 9.3	The idle time calculations for various scenarios.....	184
Table 10.1	Resource requirements for each activity i	201
Table 10.2	Estimated standard deviations for each activity i	203
Table 11.1	The resource availability and cost for the highway bridge construction project.....	210
Table 11.2	The resource use for the highway bridge construction project...	211
Table 11.3	The minimal time-lag precedence relations for the highway bridge construction project (in weeks).....	213
Table 12.1	Comparison of possible SPI and SPI(t) values at the project finish.....	228
Table 12.2	Time forecasting methods (EAC(t)) (Source: Vandevoorde and Vanhoucke (2006)).....	230
Table 12.3	Cost forecasting methods (EAC).....	233
Table 12.4	The cumulative planned value PV, actual cost AC and earned value EV for each activity along the life of the example project and the performance measures on the project level.....	236
Table 13.1	Illustrative calculations for the p-factor at review period 6 of Fig. 13.2b.....	246
Table 14.1	Network, time and cost information for the three projects.....	263
Table 14.2	Overview of the main results reported to the management committee during the previous meetings.....	264
Table 14.3	Monthly EVM metrics for the three projects used as internal performance communication tool.....	265
Table 14.4	Activity list template used by Curitiba Pontes Ltd.....	268

Table 14.5	Activity information and the network logic for the three projects.....	269
Table 14.6	Status report of the three projects at 29/03/2013.....	270
Table 14.7	Time sensitivity (in %, based on SRA without resource constraints).....	271
Table 15.1	Forecasting accuracy measures in ProTrack.....	283

References

- Abba W (2008) The trouble with earned schedule. *The Measurable News* Fall:29–30
- Agrawal M, Elmaghraby S, Herroelen W (1996) DAGEN: a generator of testsets for project activity nets. *Eur J Oper Res* 90:376–382
- Akkan C, Drexl A, Kimms A (2005) Network decomposition-based benchmark results for the discrete time-cost tradeoff problem. *Eur J Oper Res* 165:339–358
- Alvarez-Valdes R, Tamarit J (1989) Heuristic algorithms for resource-constrained project scheduling: a review and empirical analysis. In: Slowinski R, Weglarz J (eds) *Advances in project scheduling*. Elsevier, Amsterdam
- Amor J, Teplitz C (1998) An efficient approximation procedure for project composite learning curves. *Proj Manag J* 29:28–42
- Amor J (2002) Scheduling programs with repetitive projects using composite learning curve approximations. *Proj Manage J* 33:16–29
- Amor J, Teplitz C (1993) Improving CPM's accuracy using learning curves. *Proj Manage J* 24:15–19
- Anbari F (2003) Earned value project management method and extensions. *Proj Manag J* 34(4): 12–23
- Archibald RD (1976) *Managing high-technology programs and projects*. Wiley, New York
- Ash R, Smith-Daniels DE (1999) The effects of learning, forgetting, and relearning on decision rule performance in multiproject scheduling. *Decis Sci* 30:47–82
- Badiru A (1995) Incorporating learning curve effects into critical resource diagramming. *Proj Manage J* 2:38–45
- Bartusch M, Möhring R, Radermacher F (1988) Scheduling project networks with resource constraints and time windows. *Ann Oper Res* 16(1):199–240
- Bein W, Kamburowski J, Stallmann M (1992) Optimal reduction of two-terminal directed acyclic graphs. *SIAM J Comput* 21:1112–1129
- Billstein N, Radermacher F (1977) Time-cost optimization. *Method Oper Res* 27:274–294
- Blazewicz J, Lenstra J, Rinnooy Kan A (1983) Scheduling subject to resource constraints: classification and complexity. *Discret Appl Math* 5:11–24
- Book S (2006a) Correction note: “earned schedule” and its possible unreliability as an indicator. *The Measurable News* Fall:22–24
- Book S (2006b) “Earned schedule” and its possible unreliability as an indicator. *The Measurable News* Spring:24–30
- 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
- Cho J, Yum B (1997) An uncertainty importance measure of activities in PERT networks. *Int J Prod Res* 35:2737–2758

- Christensen D (1993) The estimate at completion problem: a review of three studies. *Proj Manag J* 24:37–42
- Colin J, Vanhoucke M (2013a) A multivariate approach to statistical project control using earned value management. Working Paper, Ghent University (submitted)
- Colin J, Vanhoucke M (2013b) Setting tolerance limits for statistical project control using earned value management. Working Paper, Ghent University (submitted)
- Cooper D (1976) Heuristics for scheduling resource-constrained projects: an experimental investigation. *Manag Sci* 22:1186–1194
- Cooper K (2003) Your project's real price tag? Letters to the editor. *Harv Bus Rev* 81:122–122
- Crowston W (1970) Network reduction and solution. *Oper Res Q* 21:435–450
- Crowston W, Thompson G (1967) Decision CPM: a method for simultaneous planning, scheduling and control of projects. *Oper Res* 15:407–426
- Dar-El E (1973) MALB - A heuristic technique for balancing large single-model assembly lines. *IIE Trans* 5:343–356
- Davies E (1974) An experimental investigation of resource allocation in multiactivity projects. *Oper Res Q* 24:587–591
- Davis E (1975) Project network summary measures constrained-resource scheduling. *AIIE Trans* 7:132–142
- Dayanand N, Padman R (1997) On modelling payments in projects. *J Oper Res Soc* 48:906–918
- Dayanand N, Padman R (2001a) Project contracts and payment schedules: the client's problem. *Manag Sci* 47:1654–1667
- Dayanand N, Padman R (2001b) A two stage search heuristic for scheduling payments in projects. *Ann Oper Res* 102:197–220
- De Boer R (1998) Resource-constrained multi-project management - A hierarchical decision support system. PhD thesis, Institute for Business Engineering and Technology Application, The Netherlands
- De P, Dunne E, Ghosh J, Wells C (1995) The discrete time-cost tradeoff problem revisited. *Eur J Oper Res* 81:225–238
- De P, Dunne E, Ghosh J, Wells C (1997) Complexity of the discrete time/cost trade-off problem for project networks. *Oper Res* 45:302–306
- Delisle C, Olson D (2004) Would the real project management language please stand up? *Int J Proj Manag* 22:327–337
- Demeulemeester E (1995) Minimizing resource availability costs in time-limited project networks. *Manag Sci* 41:1590–1598
- Demeulemeester E, Herroelen W (1996) An efficient optimal solution for the preemptive resource-constrained project scheduling problem. *Eur J Oper Res* 90:334–348
- Demeulemeester E, Herroelen W (2002) Project scheduling: a research handbook. Kluwer Academic Publishers, Boston
- Demeulemeester E, Dodin B, Herroelen W (1993) A random activity network generator. *Oper Res* 41:972–980
- Demeulemeester E, De Reyck B, Foubert B, Herroelen W, Vanhoucke M (1998) New computational results on the discrete time/cost trade-off problem in project networks. *J Oper Res Soc* 49:1153–1163
- Demeulemeester E, Vanhoucke M, Herroelen W (2003) Rangen: a random network generator for activity-on-the-node networks. *J Sched* 6:17–38
- De Reyck B (1998) Scheduling projects with generalized precedence relations: exact and heuristic procedures. PhD thesis, Katholieke Universiteit Leuven
- Drexl A, Nissen R, Patterson J, Salewski F (2000) ProGen/ πx - an instance generator for resource-constrained project scheduling problems with partially renewable resources and further extensions. *Eur J Oper Res* 125:59–72
- El-Rayes K, Moselhi O (1998) Resource-driven scheduling of repetitive activities. *Constr Manage Econ* 16:433–446
- Elmaghraby S (1977) Activity networks: project planning and control by network models. Wiley, New York

- Elmaghraby S (1995) Activity nets: a guided tour through some recent developments. *Eur J Oper Res* 82:383–408
- Elmaghraby S (2000) On criticality and sensitivity in activity networks. *Eur J Oper Res* 127: 220–238
- Elmaghraby S, Herroelen W (1980) On the measurement of complexity in activity networks. *Eur J Oper Res* 5:223–234
- Elmaghraby S, Kamburowsky R (1992) The analysis of activity networks under generalized precedence relations. *Manag Sci* 38:1245–1263
- Elmaghraby S, Fathi Y, Taner M (1999) On the sensitivity of project variability to activity mean duration. *Int J Prod Econ* 62:219–232
- Etgar R, Shtub A (1999) Scheduling project activities to maximize the net present value - the case of linear time-dependent cash flows. *Int J Prod Res* 37:329–339
- Fleming Q, Koppelman J (2003) What's your project's real price tag? *Harv Bus Rev* 81:20–21
- Fleming Q, Koppelman J (2005) *Earned value project management*, 3rd edn. Project Management Institute, Newtown Square
- French S (1982) *Sequencing and scheduling: an introduction to the mathematics of the Job-shop*. Ellis Horwood/Wiley
- Goldratt E (1997) *Critical chain*. North River Press, Great Barrington
- Goldratt E, Cox J (1984) *The goal*. North River Press, Croton-on-Hudson
- Gong D (1997) Optimization of float use in risk analysis-based network scheduling. *Int J Proj Manag* 15:187–192
- Goto E, Joko T, Fujisawa K, Katoh N, Furusaka S (2000) Maximizing net present value for generalized resource constrained project scheduling problem. Working paper, Nomura Research Institute, Japan
- Gutierrez G, Paul A (2000) Analysis of the effects of uncertainty, risk-pooling, and subcontracting mechanisms on project performance. *Oper Res* 48:927–938
- Harris R, Ioannou P (1998) Scheduling projects with repeating activities. *J Constr Eng Manag* 124:269–278
- Hartmann S, Briskorn D (2010) A survey of variants and extensions of the resource-constrained project scheduling problem. *Eur J Oper Res* 207:1–15
- Heimerl C, Kolisch R (2010) Scheduling and staffing multiple projects with a multi-skilled workforce. *OR Spectr* 32:343–368
- Herroelen W, De Reyck B (1999) Phase transitions in project scheduling. *J Oper Res Soc* 50: 148–156
- Herroelen W, Leus R (2001) On the merits and pitfalls of critical chain scheduling. *J Oper Manag* 19:559–577
- Herroelen W, Van Dommelen P, Demeulemeester E (1997) Project network models with discounted cash flows a guided tour through recent developments. *Eur J Oper Res* 100:97–121
- Herroelen W, De Reyck B, Demeulemeester E (1998) Resource-constrained project scheduling: a survey of recent developments. *Comput Oper Res* 25:279–302
- Herroelen W, Demeulemeester E, De Reyck B (1999) A classification scheme for project scheduling problem. In: Weglarz J (ed) *Project scheduling - Recent models, algorithms and applications*. Kluwer Academic Publishers, Dordrecht, pp 1–26
- Herroelen W, Leus R, Demeulemeester E (2002) Critical chain project scheduling: do not oversimplify. *Proj Manag J* 33:48–60
- Hindelang T, Muth J (1979) A dynamic programming algorithm for decision CPM networks. *Oper Res* 27:225–241
- Hulett D (1996) Schedule risk analysis simplified. *Project Management Network* July:23–30
- Icmeli O, Erenguc S, Zappe C (1993) Project scheduling problems: a survey. *Int J Oper Prod Manag* 13:80–91
- Jacob D (2003) Forecasting project schedule completion with earned value metrics. *The Measurable News* March:1, 7–9
- Jacob D (2006) Is “earned schedule” an unreliable indicator? *The Measurable News* Fall:15–21

- Jacob D, Kane M (2004) Forecasting schedule completion using earned value metrics? Revisited. *The Measurable News Summer*:1, 11–17
- Kaimann R (1974) Coefficient of network complexity. *Manag Sci* 21:172–177
- Kaimann R (1975) Coefficient of network complexity: erratum. *Manag Sci* 21:1211–1212
- Kang L, Park IC, Lee BH (2001) Optimal schedule planning for multiple, repetitive construction process. *J Constr Eng Manag* 127:382–390
- Kao E, Queyranne M (1982) On dynamic programming methods for assembly line balancing. *Oper Res* 30:375–390
- Kazaz B, Sepil C (1996) Project scheduling with discounted cash flows and progress payments. *J Oper Res Soc* 47:1262–1272
- Klein R (2000) *Scheduling of resource-constrained projects*. Kluwer Academic, Boston
- Kolisch R, Hartmann S (2006) Experimental investigation of heuristics for resource-constrained project scheduling: an update. *Eur J Oper Res* 174:23–37
- Kolisch R, Sprecher A, Drexl A (1995) Characterization and generation of a general class of resource-constrained project scheduling problems. *Manag Sci* 41:1693–1703
- Kuchta D (2001) Use of fuzzy numbers in project risk (criticality) assessment. *Int J Proj Manag* 19:305–310
- Kelley J, Walker M (1959) *Critical path planning and scheduling: an introduction*. Mauchly Associates, Ambler
- Kelley J (1961) Critical path planning and scheduling: mathematical basis. *Oper Res* 9:296–320
- Lipke W (2003) Schedule is different. *The Measurable News Summer*:31–34
- Lipke W (2004) Connecting earned value to the schedule. *The Measurable News Winter*:1, 6–16
- Lipke W (2006) Applying earned schedule to critical path analysis and more. *The Measurable News Fall*:26–30
- Lipke W, Zwikael O, Henderson K, Anbari F (2009) Prediction of project outcome: the application of statistical methods to earned value management and earned schedule performance indexes. *Int J Proj Manage* 27:400–407
- Loch C, De Meyer A, Pich M (2006) *Managing the unknown: a new approach to managing high uncertainty and risk in project*. Wiley, New Jersey
- MacCrimmon K, Ryavec C (1967) An analytical study of the PERT assumptions. In: Archibald, R.D. and Villoria, R.L. (eds) *Network-based management systems (PERT/CMP)*. Wiley, New York, pp 24–26
- Mastor A (1970) An experimental and comparative evaluation of production line balancing techniques. *Manag Sci* 16:728–746
- Mika M (2006) Modelling setup times in project scheduling. In: *Perspectives in modern project scheduling*, vol 92, International series in operations research & management science. Springer, New York, pp 131–163
- Moder J, Phillips C, Davis E (1983) *Project management with CPM PERT and precedence diagramming*. Nostrand Reinhold, New York
- Möhring R (1984) Minimizing costs of resource requirements in project networks subject to a fixed completion time. *Oper Res* 32:89–120
- Moselhi O, El-Rayes K (1993) Scheduling of repetitive projects with cost optimization. *J Constr Eng Manag* 119:681–697
- Nembhard D, Uzumeri M (2000) An individual-based description of learning within an organization. *IEEE Trans Eng Manag* 47(3):370–378
- Özdamar L, Ulusoy G (1995) A survey on the resource-constrained project scheduling problem. *IIE Trans* 27:574–586
- Pascoe T (1966) Allocation of resources - CPM. *Revue Française de Recherche Opérationnelle* 38:31–38
- Patterson J (1976) Project scheduling: the effects of problem structure on heuristic scheduling. *Nav Res Logist* 23:95–123
- Patterson J (1979) An implicit enumeration algorithm for the time/cost trade-off problem in project network analysis. *Found Control Eng* 6:107–117

- Pinnell S, Busch J (1993) How do you measure the quality of your project management? *PM Network* December:35–36
- Piper C (2005) *Cpsim2: the critical path simulator (windows version)*. Richard Ivey School of Business, London
- PMBOK (2004) *A guide to the project management body of knowledge*, 3rd edn. Project Management Institute, Inc., Newtown Square
- Port O, Schiller Z, King R, Woodruff D, Phillips S, Carey J (1990) A smarter way to manufacture. *Business Week* April 30:110–115
- Robinson D (1975) A dynamic programming solution to cost/time trade-off for CPM. *Manag Sci* 22:158–166
- Schwindt C (1995) A new problem generator for different resource-constrained project scheduling problems with minimal and maximal time lags. *WIOR-Report-449*, Institut für Wirtschaftstheorie und Operations Research, University of Karlsruhe
- Sepil C, Ortac N (1997) Performance of the heuristic procedures for constrained projects with progress payments. *J Oper Res Soc* 48:1123–1130
- Shtub, A. (1991). Shtub A (1991) Scheduling of programs with repetitive projects. *Proj Manage J* 22:49–53
- Shtub A, Bard J, Globerson S (1994) *Project management: engineering, technology and implementation*. Prentice-Hall Inc, Englewood Cliffs
- Shtub A, LeBlanc L, Cai Z (1996) Scheduling programs with repetitive projects: a comparison of a simulated annealing, a genetic and a pair-wise swap algorithm. *Eur J Oper Res* 88:124–138
- Skutella M (1998) Approximation algorithms for the discrete time-cost tradeoff problem. *Math Oper Res* 23:909–929
- Tavares L (1999) *Advanced models for project management*. Kluwer Academic Publishers, Dordrecht
- Tavares L, Ferreira J, Coelho J (1999) The risk of delay of a project in terms of the morphology of its network. *Eur J Oper Res* 119:510–537
- Thesen A (1977) Measures of the restrictiveness of project networks. *Networks* 7:193–208
- Ulusoy G, Cebelli S (2000) An equitable approach to the payment scheduling problem in project management. *Eur J Oper Res* 127:262–278
- Uyttewaal E (2005) *Dynamic scheduling with Microsoft Office Project 2003: the book by and for professionals*. Co-published with International Institute for Learning Inc, Boca Raton
- Vandevoorde S, Vanhoucke M (2006) A comparison of different project duration forecasting methods using earned value metrics. *Int J Proj Manag* 24:289–302
- Vanhoucke M (2005) New computational results for the discrete time/cost trade-off problem with time-switch constraints. *Eur J Oper Res* 165:359–374
- Vanhoucke M (2006a) An efficient hybrid search algorithm for various optimization problems. *Lect Notes Comput Sci* 3906:272–283
- Vanhoucke M (2006b) Work continuity constraints in project scheduling. *J Constr Eng Manag* 132:14–25
- Vanhoucke M (2007) Work continuity optimization for the Westerscheldetunnel project in the Netherlands. *Tijdschrift voor Economie en Management* 52:435–449
- Vanhoucke M (2008a) Measuring time using novel earned value management metrics. In: *Proceedings of the 22nd IPMA World Congress (Rome)*, vol 1, pp 99–103
- Vanhoucke M (2008b) Project tracking and control: can we measure the time? *Projects and Profits*, August:35–40
- Vanhoucke M (2008c) Setup times and fast tracking in resource-constrained project scheduling. *Comput Ind Eng* 54:1062–1070
- Vanhoucke M (2009) Static and dynamic determinants of earned value based time forecast accuracy. In: Kidd T (ed) *Handbook of research on technology project management, planning, and operations*. Information Science Reference, Hershey, pp 361–374
- Vanhoucke M (2010a) *Measuring time - Improving project performance using earned value management*, vol 136, *International series in operations research and management science*. Springer, New York

- Vanhoucke M (2010b) Using activity sensitivity and network topology information to monitor project time performance. *Omega Int J Manag Sci* 38:359–370
- Vanhoucke M (2011) On the dynamic use of project performance and schedule risk information during project tracking. *Omega Int J Manag Sci* 39:416–426
- Vanhoucke M, Debels D (2007) The discrete time/cost trade-off problem: extensions and heuristic procedures. *J Sched* 10:311–326
- Vanhoucke M, Debels D (2008) The impact of various activity assumptions on the lead time and resource utilization of resource-constrained projects. *Comput Ind Eng* 54:140–154
- Vanhoucke M, Vandevoorde S (2007a) Measuring the accuracy of earned value/earned schedule forecasting predictors. *The Measurable News*, Winter:26–30
- Vanhoucke M, Vandevoorde S (2007b) A simulation and evaluation of earned value metrics to forecast the project duration. *J Oper Res Soc* 58:1361–1374
- Vanhoucke M, Vandevoorde S (2008) Earned value forecast accuracy and activity criticality. *The Measurable News* Summer:13–16
- Vanhoucke M, Vandevoorde S (2009) Forecasting a project's duration under various topological structures. *The Measurable News* Spring:26–30
- Vanhoucke M, Demeulemeester E, Herroelen W (2001a) Maximizing the net present value of a project with linear time-dependent cash flows. *Int J Prod Res* 39:3159–3181
- Vanhoucke M, Demeulemeester E, Herroelen W (2001b) On maximizing the net present value of a project under renewable resource constraints. *Manag Sci* 47:1113–1121
- Vanhoucke M, Demeulemeester E, Herroelen W (2002) Discrete time/cost trade-offs in project scheduling with time-switch constraints. *J Oper Res Soc* 53:741–751
- Vanhoucke M, Demeulemeester E, Herroelen W (2003) Progress payments in project scheduling problems. *Eur J Oper Res* 148:604–620
- Vanhoucke M, Coelho J, Debels D, Maenhout B, Tavares L (2008) An evaluation of the adequacy of project network generators with systematically sampled networks. *Eur J Oper Res* 187: 511–524
- Vanhoucke M, Vereecke A, Gemmel P (2005) The project scheduling game (PSG): simulating time/cost trade-offs in projects. *Proj Manag J* 51:51–59
- Van Peteghem V, Vanhoucke M (2010a) A genetic algorithm for the preemptive and non-preemptive multi-mode resource-constrained project scheduling problem. *Eur J Oper Res* 201:409–418
- Van Peteghem V, Vanhoucke M (2010b) Introducing learning effects in resource-constrained project scheduling. Technical report, Ghent University, Ghent, Belgium
- Walker M, Sawyer J (1959) Project planning and scheduling. Technical Report Report 6959, E.I. duPont de Nemours and Co., Wilmington
- Wauters M, Vanhoucke M (2013) A study on complexity and uncertainty perception and solution strategies for the time/cost trade-off problem. Working Paper, Ghent University (submitted)
- Wiest J, Levy F (1977) A management guide to PERT/CPM: with GERT/PDM/DCPM and other networks. Prentice-Hall, Inc, Englewood Cliffs
- Williams T (1992) Criticality in stochastic networks. *J Oper Res Soc* 43:353–357
- Wright T (1936) Factors affecting the cost of airplanes. *J Aeronaut Sci* 3:122–128
- Yelle L (1979) The learning curves: historical review and comprehensive survey. *Decis Sci* 10(2):302–328