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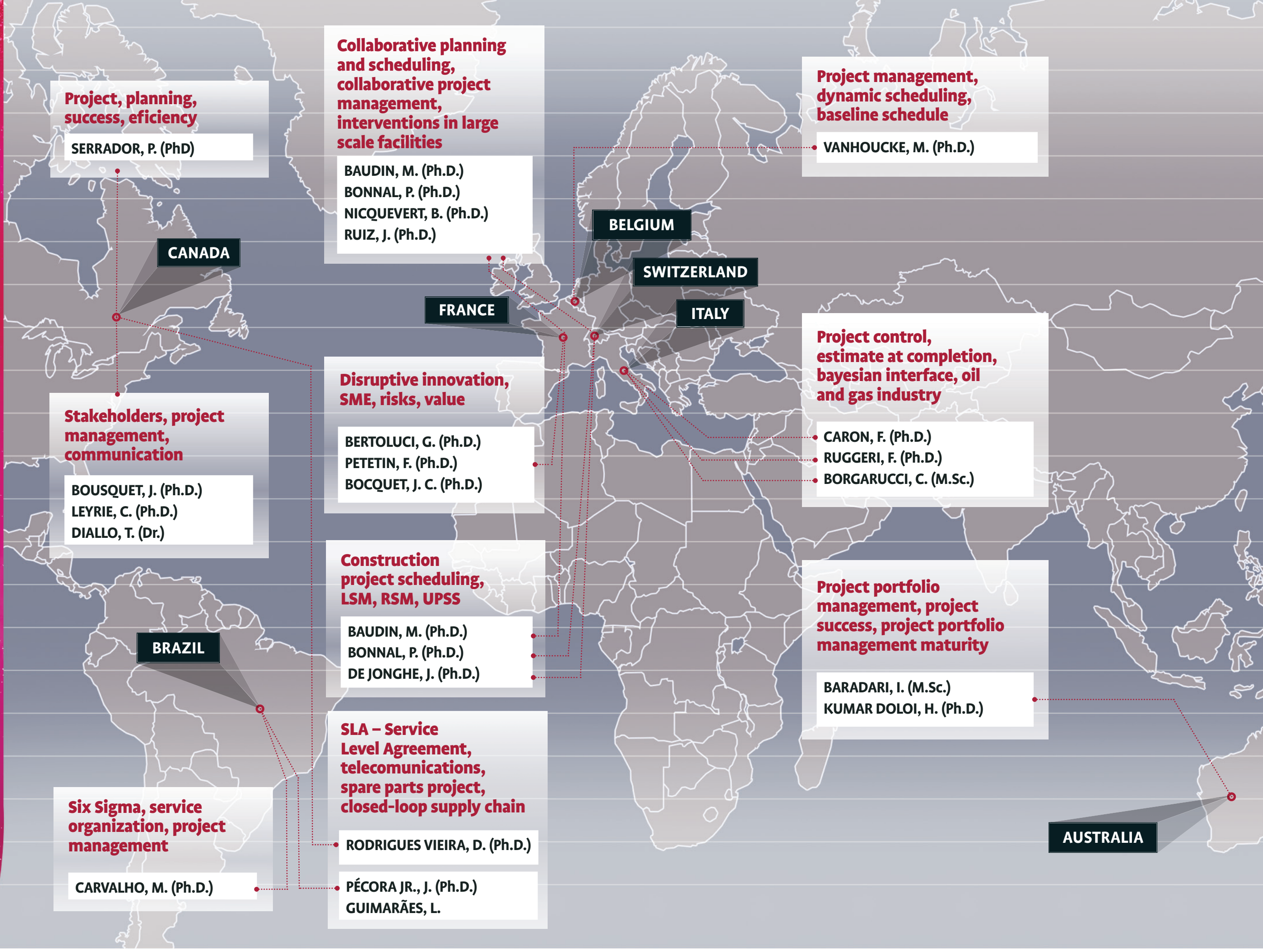

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PROJECT BASELINE SCHEDULING: An overview of PAST EXPERIENCES

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ABSTRACT

Dynamic project scheduling is a term used to refer to the dynamic nature of project management. It consists of three dimensions, known as baseline scheduling, schedule risk analysis and project control (Uyttewaal, 2005; Vanhoucke, 2012b). In previous studies, it has been shown that both the schedule risk analysis and project control should go hand in hand as useful tools to measure the project performance of a project in progress and to improve the project control process and the corrective action decision making process in case the project is in danger. In an article in the International Journal of Project Management (Vanhoucke, 2012a), the project control dimension was highlighted based on a comparison between academic results obtained on fictitious project data and additional tests performed on a set of real-life data from 8 Belgian companies from various sectors. However, little or nothing has been said about the first dimension of dynamic scheduling: the construction of a project baseline schedule. In the current article, a similar approach to the previously published article will be followed. Based on the extensive knowledge of the algorithmic developments in the academic literature and on the past experience of using some of these (adapted) algorithms in a practical environment, it will be illustrated how and why research can contribute positively to practice when constructing a project baseline schedule. In doing so, we believe that the gap between academic results and practical relevance is bridged, gradually moving the dynamic project scheduling discipline to a higher level.

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 assigning the roles and responsibilities of all participants and stakeholders of a project, planning principles and resource allocation models, etc.

Dynamic scheduling is a term used to illustrate that project scheduling is a dynamic process that involves a continuous stream of changes in order to support decisions that need to be made along the life of the project. It consists of three dimensions, known as baseline scheduling, schedule risk analysis and project control *(Uyttewaal, 2005; Vanhoucke, 2012b)*. In an article in the International Journal of Project Management *(Vanhoucke, 2012a)*, the project control dimensions were highlighted based on a comparison between academic results obtained on fictitious project data and additional tests performed on a set of real-life data from 8 Belgian companies from various sectors. This study demonstrates that both the schedule risk analysis and project control should go hand in hand as useful tools to measure the project performance of a project in progress and to improve the project control process and the corrective action decision making process in case the project is in danger.

In the paper presented herein, the focus lies on only one dimension of the dynamic scheduling approach, i.e., the construction of a baseline schedule. More precisely, the objective is to show that many algorithmic developments published in the academic literature are useful in a practical setting to improve the way baseline schedules are constructed. Based on a sample of real-life projects, it will be shown that many state-of-the-art developments from the literature have influenced the way project baseline schedules are constructed and have had a positive *(financial)* implication compared to the standard non-academic approach. A link between the methodological approaches *(i.e., the algorithms from the literature)* are given to illustrate that in conjunction many excellent academic endeavors often lead to useful principles in a real-life and commercial project management environment. It should be noted that the aim of this article is not to give a full overview of the literature, but rather to unite some interesting academic research efforts and bring them closer to the daily project management practice, based on the past experiences of the author.

The outline of this paper is as follows. Section 1 provides an overview of the three dimensions of dynamic project scheduling. In this paper, only the baseline scheduling dimension will be discussed by means of references to the academic literature as well as to empirical project data. Section 2 discusses in detail the baseline scheduling dimension of dynamic project scheduling. An overview is given of the use of scheduling algorithms applicable to practical settings as well as various scheduling objectives that have led to major improvements in real-life projects. A number of extra features that can be used during the construction of a baseline schedule are also discussed with interesting references to the literature. Section 3 explains the baseline scheduling techniques and features discussed in the previous section based on a set of real-life projects coming from various consultancy projects in the past few years. The purpose of this section is to show that the link between academic research results and practical relevance is often an inspiring challenge and acts as a tool to suggest improvements in the daily scheduling approach taken by project managers. In this section, it will be shown that various real-life projects have been scheduled by novel techniques borrowed from the literature, often leading to major improvements. Section 4 outlines the overall conclusions and highlights interesting paths for future research.

1. Dynamic scheduling

Dynamic scheduling is a term 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 throughout the course of the project. This dynamic scheduling point of view implicitly assumes that the usability of a project's baseline schedule is to act as a point of reference in the project life cycle and should therefore be considered as nothing more than a predictive model. However, this point-of-reference gives the baseline schedule a crucial role when it is embedded in a wider dynamic scheduling perspective. It acts as a tool for resource efficiency calculations, time and cost risk analyses, project control, performance measurements and much more and is therefore the starting point in any dynamic scheduling analysis. The three dimensions of dynamic scheduling can be briefly summarized along the following lines *(Uyttewaal, 2005; Vanhoucke, 2012b)*:

Baseline 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 its scheduling objective.

Schedule 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 the course of the project.

Project 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.

In the next section, the project baseline scheduling step is discussed in detail, making references to the algorithms that are widely available in the academic literature. A short overview of three classes of algorithms that are used by academics to solve different kinds of resource-constrained project scheduling problems to construct baseline schedules is presented, and their link to the scheduling objectives used in academia and references to options to extend these algorithms to practical settings are given.

2. Baseline scheduling

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 conducted 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 research, in the last decennia, was mainly on the static development of algorithms to deal with the complex scheduling problems, the recent research activities have gradually started to focus on the development of dynamic scheduling tools that are able to respond to a higher uncertainty over the course of the project.

The construction of a project's baseline schedule boils down to the construction of a timetable for the project within the technological precedence relations and renewable resource constraints *(Demeulemeester and Herroelen, 2002; Vanhoucke, 2012b)*. It involves the assignment of start and finish times to each activity such that a scheduling objective is optimized. This scheduling objective is a crucial element in the construction of a baseline schedule and determines the quality of the project's baseline schedule and hence the scheduling performance of the algorithm or software that is used to construct the schedule. Most reviews of project scheduling software tools have a clear focus on the time minimization as the primary scheduling objective, and do not report scheduling performance results on other objectives. The outline of this section is as follows. Section 3.1 offers a brief overview of the algorithmic approaches that can and are used to solve the empirical projects discussed in section 4. Section 3.2 presents scheduling objectives that are different from the minimization of time. Section 3.3 offers a brief discussion about additional scheduling features borrowed from the literature that have been used in the construction of the empirical baseline schedules. The next sections mention relevant references to the literature when they have contributed to the construction of the real life baseline schedules, without having the intention to give a full literature review.

2.1 Scheduling approach

During the construction of real life baseline schedules presented in section 4, the software tool ProTrack *(www.protrack.be)* was used as a visual tool to visualize the project baseline schedules. This tool is a commercialized version of a research tool based on various algorithms developed at Ghent University *(Belgium)* incorporating many recent state-of-the-art techniques and solution procedures. This research tool, known as P2 Engine *(www.p2engine.com)* has been extended with a graphical user interface to use it in a practical and commercial setting. In most cases, the use of the standard leveling algorithms of the tool has led to a resource leveled baseline schedule within a minimum time scheduling objective. However, when further improvements could be made, changes were necessary to further optimize a scheduling objective *(see section 3.2)*, and therefore manual user interventions or add-in algorithms were used to modify and improve the project baseline. Since add-in algorithms often involve high computational demands, they were often truncated after a predefined time to speed up the search process.

Resource-constrained project scheduling has been a research topic for decades, and has led to a variety of solution procedures. The procedures used to construct the real life baseline schedules are classified in the three classes mentioned below. More references to academic developments in this field can be found in the books by Demeulemeester and Herroelen *(2002)* and Vanhoucke *(2012b)*.

Single-pass heuristics: Simple priority-based priority scheduling rules using priorities for project activities and generation schemes to construct schedules has been a research topic for decades. Although the advantage of these rules is their ability to generate a project baseline in a very limited time and because of the ease and flexibility to use them in a variety of settings, they are often considered as inferior in the academic literature due to their simplicity and hence their inability to generate high-quality project schedules. An overview of algorithmic developments in project baseline scheduling is given in the update paper of Kolisch and Hartmann (2006).

Multi-pass heuristics: Multi-pass algorithms can be implemented in a wide variety of ways and using various underlying optimization principles. The construction of project baseline schedules as proposed in section 4 have been done based on genetic algorithms (Holland, 1975), scatter search optimization (Marti et al., 2006) or electromagnetic optimization (Birbil and Fang, 2003), but obviously many other approaches that are widely available in literature could have been used.

Exact methods: When the theoretical best possible solution must be found, the construction of a baseline schedule can be constructed using exact methods. These often time-consuming methods generate multiple alternative project schedules and evaluate them in such a way that the best one will be retained. In the following section, these methods are sometimes used in conjunction with multi-pass heuristics. The exact method used in the current paper is the branch-and-bound approach (Agin, 1966) to generate optimal solutions. Multi-pass heuristics are then used to generate alternative schedule within a reasonable time.

In the next section, an overview will be given of various scheduling objectives that can be used during the construction of a baseline schedule. In section 4, these various scheduling objectives will be illustrated on empirical project data, and the solution techniques *(single-pass, multi-pass or exact algorithms)* used to construct these baseline schedules will be mentioned.

2.2 Scheduling objectives

It was mentioned earlier that the construction of a baseline schedule involves the definition of a scheduling objective that needs to be optimized. This scheduling objective is referred to as the dominant force *(Uyttewaal, 2005)*, and can vary from project to project, from sector to sector, etc. In Herroelen et al. *(1999)* and Brucker et al. *(1999)*, an overview is given of the various scheduling objectives that can be or have been used in the academic literature. In Vanhoucke *(2012b)*, some well-known scheduling objectives are illustrated on fictitious project examples, and will be briefly reviewed hereunder. In section 3.3, their features will be explained in detail and their use in empirical settings will be discussed.

Resource-Constrained Project (RCP): This scheduling problem involves the minimization of the total lead time of the project and has been the most widely studied problem in the academic literature. Overviews are given in Icmeli et al. (1993), El-maghraby (1995), Özdamar and Ulusoy (1995), Herroelen et al. (1998) and Brucker et al. (1999). These papers primarily focus on the modeling aspect and algorithmic developments necessary to schedule complex projects. At that time, the wide diversity of project scheduling topics and research projects was also translated into two classification schemes developed by Brucker et al. (1999) and Herroelen et al. (1999). In these papers, the authors summarize and classify the main features and characteristics of various kinds of project scheduling problems according to project features, resource characteristics and scheduling objectives.

Resource Availability Cost Project (RACP): This scheduling problem can be considered as the opposite scheduling problem to the RCP. While the RCP minimizes the project duration given a predefined resource availability, the RACP aims at minimizing the total cost of the resource availability within a predefined project deadline. References can be found in Demeulemeester (1995), Drexl and Kimms (2001), Hsu and Kim (2005), Shadrokh and Kianfar (2007), Yamashita et al. (2006) and Van Peteghem and Vanhoucke (2013).

Resource Leveling Project (RLP): The RCP tries to schedule project activities in such a way that no over-allocations of resources occur and that the total lead time is minimized. If over-allocations occur, they are resolved by shifting activities further ahead in time. However, the resulting pattern of total resource use over the complete time horizon of the baseline schedule is not taken into account, and hence, project schedules with very irregular resource use (peak demands as well as low resource demands) are a matter of degree. The resource leveling project aims at the construction of a precedence and resource feasible schedule within a predefined deadline with a resource use that is as leveled as possible within the project horizon. In order to avoid 'jumps' from peaks to low resource demands, the total use of all resources needs to be balanced over the total schedule horizon. Various procedures have been described in the paper written by Neumann and Zimmermann (1999) and Neumann and Zimmermann (2000).

Resource-Constrained Project with Discounted Cash Flows (RCP-DC): Optimizing the timing of cash flows in projects has led to the maximization of the net present value scheduling objective, which has been published in various scheduling papers in the literature. The basic idea boils down to shifting activities with a negative cash flow further ahead in time while positive cash flow activities should be scheduled as soon as possible, respecting the precedence relations and limited resource availabilities. Although the literature of the RCP-DC scheduling problem is not as rich as the literature on the RCP scheduling problem, this objective has been studied widely by various authors using various algorithmic methods under very different assumptions. An overview is given by Mika et al. (2005).

Resource-Constrained Project with Work Continuity constraints (RCP-WC): Work continuity constraints (El-Rayes and Moselhi, 1998) have been defined in project scheduling to minimize the total idle time of bottleneck resources used in the project. This type of scheduling problem seeks to focus on an uninterrupted usage of resources and has been a widely investigated topic in the construction industry where repeating activities are a matter of degree. The waste in these so-called repetitive projects stems from resources (crew, equipment, ...) waiting for preceding resources to finish their work and has to be eliminated to maintain work continuity (Harris and Ioannou, 1998). Consequently, in order to maintain work continuity, repetitive units of the project must be scheduled in such a way as to enable the timely movement of resources from one unit to the next, avoiding resource idle time.

Resource-Constrained Project with Weighted Earliness/Tardiness costs (RCP-WET): When activities have a preferred time slots to start and/or end, and penalty costs have been defined to avoid that such activities start/end earlier or later than this preferred time slot, the problem is known as the weighted earliness/tardiness scheduling objective. This baseline scheduling problem is inspired on the just-in-time philosophy from production environments and can be used in a wide variety of practical settings. Algorithmic procedures have been developed by Schwindt (2000), Vanhoucke et al. (2001a) and Ballestín et al. (2006).

Resource-Constrained Project with Quality Time Slots (RCP-QTS): Quality-dependent time slots are considered as an extension of the RCP-WET scheduling objective.

In this scheduling objective, multiple time slots are defined rather than a single preferred start time, and earliness/tardiness penalties must be paid when activities are scheduled outside these time slots. To the best of our knowledge, the problem has only been studied by Vanhoucke (2006a).

Figure 1 illustrates an activity-on-the-node project network. Each node represents a project activity and each arc represents a finish-start relation between activities with a time-lag of zero. The project network starts with a dummy activity *(Start)* and ends with a dummy activity *(End)*. **Table 1** displays the necessary data to illustrate how baseline schedules are constructed under the different scheduling objectives discussed earlier. The duration *(in days)* and resource demand *(in units)* is necessary for all scheduling objectives and is also shown in **figure 1**. Each node represents a project activity with an estimated duration displayed above each node and a resource demand displayed below each node. It is assumed that the availability of a single resource is equal to a maximum of five units and the maximum allowable project duration is equal to 18 days. The cash flows are net cash flows *(cash inflows - cash outflows)* and are relevant activity parameters when constructing a baseline schedule using the RCP-DC objective. The target date are desirable start and/or end times for activities and are useful parameters during the baseline schedule construction using a RCP-WET and RCP-QTS objectives.

Figure 2 displays illustrative project baseline schedules for each of the scheduling objectives discussed above. In **figure 2a**, the project baseline schedule is displayed under a minimal time objective. In this case, project activities are scheduled within the limited availability of the single resource which is equal to 5 units. This results in a project schedule with peaks in the resource use, but with the minimum project lead time *(which is in the example equal to the critical path length of 10 days)*. The RACP schedule displayed in **figure 2a** is constructed exactly the opposite way: rather than trying to minimize the lead time of the project leading to peaks in the resource use, the RACP aims at minimizing the peak use of resources, at the cost of a larger project duration. In the example, the resource peaks are limited to a maximum of 2 units, leading to a project duration of 16 days which is well within the predefined project deadline of 18 days. The resource leveling objective in 2*(c)* follows an approach that is between these two approaches. The objective is to level the use of resources which has led to a baseline schedule where no jumps in the resource use occur, with a project deadline of 10 days. During the construction of the schedules shown in **figures 2d** and **2e**, extra activity parameters have been taken into account. The RCP-DC baseline schedule optimizes cash flows by scheduling activities with negative cash flows as late as possible and activities with positive cash flows as soon as possible. For this very reason, activities 1, 6 and 7 have been scheduled after activity 8 *(there are no precedence relations between these activities)*, leading to an improved net present value. The RCP-WET baseline schedule aims at scheduling project activities with a predefined start or finish time as close as possible to these preferred time slots. When this is not possible, a penalty has to be paid. In the example, activity 8 could not be scheduled to finish at its target finish date of 9 days due to the target finish date of activity 5 set at day 7. The problem with quality dependent time slots *(RCP-QTS)* was shown in the figure since it is similar to the RCP-WET but has instead multiple target days defined as intervals rather than single time moments. More examples and algorithms to construct these baseline schedules are shown in the book by Vanhoucke *(2012b)*. Section 4 illustrates the usefulness of using these scheduling objectives using empirical data.

2.3 Scheduling options

While the scheduling objective discussed in the previous section is a way to define the project objective during baseline schedule construction, various other options are available in the academic literature to add flexibility to the scheduling process to make the final baseline schedule more realistic. A list of extensions to the traditional resource-constrained project scheduling algorithms is outside the scope of this paper and would lead us too far from the scope of this manuscript. However, in a survey article of variants and extensions of the resource-constrained project scheduling problem, Hartmann and Briskorn *(2010)* present a variety of options that can be taken into account during the construction of a resource feasible baseline schedule. The incorporation of resource learning, the presence of activity setup times, and many more have led to the development of algorithms and techniques tailored to the needs and underlying assumptions of the scheduling problem. This article was used as a useful initiative to make the scheduling algorithms applied to empirical data more realistic, as discussed in the next section.

3. Empirical evidence

Table 2 gives an overview of the scheduling objectives discussed earlier and their link with the real life projects used in this section. The table reports the scheduling method used to construct the baseline schedule *(column 'method')*, and the type of project for which the method is used *(column 'project type')*. The main results, contribution to the Project Management community and practice and/or the improvements obtained by using the scheduling method are also briefly mentioned *(column 'results')*.

In the following subsections, each project application is briefly discussed. It will be shown which algorithms from the literature have acted as an inspiration for the development of a decision-support tool to optimize the scheduling objective under study. It should be noted that the remaining part of this section has no intention to provide a full overview of empirical project examples taken from the literature, but instead, serves to illustrate that the use of algorithmic developments from the academic literature can be used to make improvements in real life projects, based on the author's past experience.

3.1 Resource constrained project scheduling (RCP and RLP)

Leveling resources is an automatic technique to resolve over-allocations in the resource use throughout the life of the project. It is a complex search process which is sometimes controversial to project management software users. It allows the user to automatically delete unwanted over-allocations, but at the same time leads to a sudden change in the schedule that is often incomprehensible to the software user. In the academic literature, however, thousands of algorithms have been written and published to resolve over-allocations of resources in projects that have never passed the threshold to practical use. In solving real-life project scheduling problems, we believe the challenge is to bring together the best elements of various academic procedures into an easy, understandable yet excellent performing solution approach that can help practitioners to better build baseline schedules.

During the construction of all baseline schedules described next, we sought to balance on that fragile bridge

Activity ID	Duration (in days)	Resource demand	Cash flow (net cash)	Target date (day number)
1	1	1	-€ 25	-
2	2	1	€ 0	Start = 3
3	2	2	€ 0	-
4	2	1	€ 0	-
5	3	2	-€ 100	Finish = 7
6	1	1	-€ 25	-
7	2	1	-€ 25	Finish = 13
8	3	2	€ 75	Finish = 9
9	2	2	-€ 100	-
10	2	1	€ 1,000	Finish = 18

TABLE 1: *Activity data for the project network example shown in* **figure 1.**

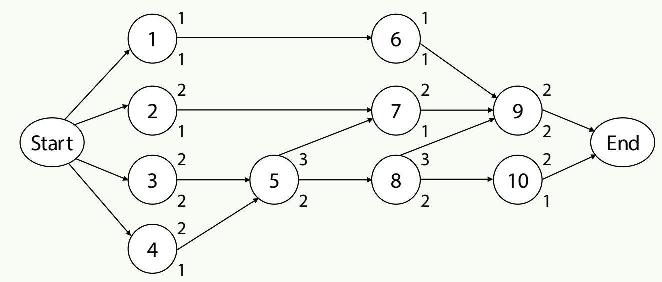


FIGURE 1. *An example activity-on-the-node project network.*

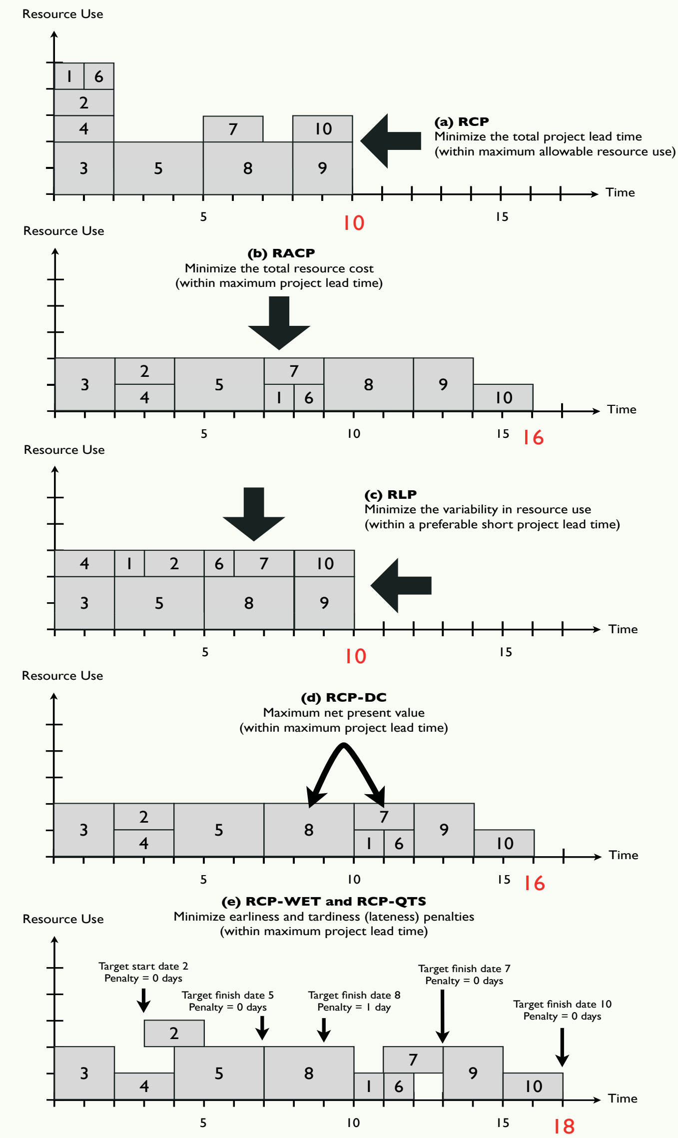


FIGURE 2. *Project baseline schedules under various scheduling objectives: (a) time minimization, (b) resource leveling, (c) resource availability cost minimization, (d) net present value maximization and (e) weighted earliness/tardiness (or quality dependent time slots) minimization.*

Objective	Method	Project type	Results
RCP and RLP	Single-pass PBSR[a] or truncated multi-pass	ProTrack software and P2 Engine tool	PMI-Belgium award *(2007)* IPMA research award *(2008)*
RACP RCP-DC RCP-WC RCP-QTS	Multi-pass heuristic B&B[b], GA[c], SS[d] Time-horizon B&B Dual phased B&B	Audit scheduling Water purification Tunnel construction Bio-technology	Improved resource use *(worth 200 junior assistant working days)* Improved cash flow timing *(e 300,000)* Idle time reduction *(e 1,000,000)* Major quality improvements *(no financial data)*

[a] *PBSR: Priority Based Scheduling Rule* [b] *B&B: Branch-and-bound* [c] *GA: Genetic Algorithms* [d] *SS: Scatter Search*

TABLE 2. *Overview of empirical project data for each of the schedule objectives.*

between user control and automatic resource optimization by offering state-of-the-art search techniques from the academic literature as well as options to increase user control. More precisely, we controlled the intensity of the search to a project baseline schedule without over-allocations, using the two following options:

- Quick and easy procedures that give a good but not necessarily optimal schedule (single-pass algorithms based on priority based scheduling rules);
- Time consuming procedures that seek to further optimize the scheduling objective(s) (multi-pass algorithms truncated when no improvements have been found after some time).

The simple priority rules used in priority rule based scheduling are the quick and easy ways to search for a schedule using a ranked list of the project activities following certain criteria. These criteria have often been chosen by the project owner *(e.g., random, schedule the shortest processing time activity firstly, schedule the activity with the most total successors first, etc...)* and have often been extended when necessary. Despite their simplicity and ability to generate prompt solutions, most of the algorithms we have used are based on various excellent research results from academia. The multi-pass heuristic search methods and exact branch-and-bound methods we used are the methods used to perform an intensive search for an excellent baseline schedule. These consist of generating multiple baseline schedules which often takes a considerable amount of time and the algorithms keep searching until the search is truncated by the user. During the search, it reports how many project schedules have been evaluated, the number of schedules found without over-allocations and the currently best found project duration automatically generated by the software.

Both scheduling methods can be done in two different ways. In a fixed duration mode, the duration and resource demand of each activity will never change. The resource scheduling algorithms will shift activities further ahead in time to resolve over-allocations. In a fixed work mode, activity duration and resource demand for each activity can change, such that the work content remains fixed. As an example, an activity with a duration of 2 days and a resource demand of 2 people *(i.e., a work content of 4 man-days)* can change to an activity with a duration of 4 days only demanding 1 person per day. Although this is common practice in any scheduling software tool, the academic literature has placed its focus mainly on the fixed duration mode *(known as the resource-constrained project scheduling problem)* and has spent less attention to the fixed work mode *(which is known as the discrete time/resource trade-off problem)*.

The algorithms to construct a baseline schedule for the RCP *(time minimization)* and RLP *(leveling of resources)* have been developed under the sponsorship of the Belgian chapter of the Project Management Institute *(PMI, www.pmi-belgium.be)* and has led to the development of the earlier mentioned P2 Engine and ProTrack software tools. Thanks to the integration between these scheduling algorithms and the schedule risk and project control tools *(see section 2)*, the research results have been awarded th IPMA Research Award by the International Project Management Association *(IPMA, www.ipma.ch)* in 2008. The recognition of the practical relevance of these research endeavors have inspired us to extend the current algorithms to other project objectives *(see section 3.2)*, for which a brief overview of their use in practice is given along the following sections.

3.2 Optimizing resource availability (RACP)

In most projects, human resources are a critical factor in the scheduling process. Not only their availability, but also their productivity will influence the project duration. The need to hire human resources with the right skills and efficiently assign them to project activities is crucial in a project environment. The resource-availability cost problem takes this point-of-view as its scheduling objective since it tries to minimize the use of the most expensive resources. More precisely, it determines for each resource type the number of units *(people)* that have to be assigned to the project. However, it does not take the idle time *(unassigned resource capacity)* into account which is defined as the time some of these resources are not assigned to certain project activities.

Based on this shortcoming, extensions have been made for an audit scheduling problem with sequence-dependent setup times and different audit team efficiencies. Therefore, the general principle of the RACP has been programmed in an algorithm inspired by the algorithms developed by Van Peteghem and Vanhoucke *(2010, 2011)* and by the results published in Balachandran and Zoltners *(1981)*, Chan and Dodin *(1986)*, Dodin and Chan *(1991)*, Drexl et al. *(2006)*, Dodin and Elimam *(1997)*, Dodin et al. *(1998)* and Brucker and Schumacher *(1999)* and extended to specific settings of a Belgian audit form. More precisely, it was used to construct a project baseline schedule for a medium-term audit-staff scheduling problem in which the teams of auditors are assigned to a set of audit engagements. Audit team switches are allowed during the execution of an audit engagement, however, so-called mode identity constraints *(Salewski et al., 1997)* are imposed to some audit tasks, which means that no team switches can be executed due to, for instance, legal restrictions. Since an audit team switch also results in an introduction period, at which time the audit gets to know the company, an extra setup time is added if an audit team switch is applied.

The procedure takes three objectives into account during the baseline schedule construction. A first objective function minimizes the number of audit engagements that finish after a predefined project deadline. A second similar objective function assigns a penalty cost to each day an audit engagement finishes later than the proposed deadline. Both objectives are inspired by the need to minimize the total lead time of projects in progress and can be classified as the RCP scheduling problem discussed earlier. A third objective function is inspired by the RACP scheduling problem and maximizes the value of the remaining resource capacity. The function indicates the resources which are available for other audit engagements and is inspired by the audit office's desire to obtain efficient audit team assignments.

The algorithm is applied to real-life data from a small Belgium audit firm, with 15 auditors and almost 250 audit tasks per year, resulting in the audit team assignment's average efficiency improvement of 8.14% regarding the value of the unassigned resource capacity, which corresponds to almost 200 working days of a junior assistant. Since many audit offices still use relatively simple programs to schedule their auditor teams, this illustration again shows that the use of advanced scheduling algorithms and techniques improves the efficiency of the work schedule in terms of auditor assignment, hence showing the need to bring theory closer to practice

3.3 Optimizing cash flows (RCP-DC)

In a paper written by Herroelen et al. *(1997)*, the relevance of maximizing the net present value has been recognized. They state that "when the financial aspects of project management are taken into consideration, there is a decided preference for the maximization of the net present value of the project as the more appropriate objective, and this preference increases with the project duration".

Both an exact branch-and-bound procedures inspired by the developments of Icmeli and Erengüc¸ *(1996)* and Vanhoucke et al. *(2001b)* and the metaheuristic solution approaches of Icmeli and Erengüc *(1994)*, Vanhoucke *(2009)* and Vanhoucke *(2010)* have been used as an inspiration to develop a baseline scheduling approach for a water purification company located in Belgium.

During the construction of the baseline schedule for this project, it was shown that shifting activities forward and backward lead to an improvement of the cost outline of the project, measured by its net present value improvement of more than e 300,000 or approximately 1% of the total project budget. However, these shifts toward the project end increase the risk since more and more activities become critical. Indeed, since many, if not all, activities are then scheduled at its latest starting time in order to postpone the payments of their underlying cash flows, the slack of each activity is relatively small or zero. Therefore, the optimization of a schedule objective should be carefully performed, hence a careful trade-off between the quality of the schedule objective *(net present value)* and a certain degree of buffering to add activity slack is a crucial choice to make.

A project description and the main conclusions are summarized in an article written by Vanhoucke and Demeulemeester *(2003)*.

3.4 Avoiding idle time (RCP-WC)

The traditional resource-constrained project scheduling techniques focus on resolving the resource conflicts by shifting activities in time. In doing so, these techniques guarantee that project activities do not use more renewable resources than available at each time period of the project life. However, these methods completely ignore the idle time of resources during the execution of the project as they do not try to schedule sets of activities that make use of a similar resource jointly. However, there are numerous project examples where a subset of project activities uses a common set of resources and where this set of resources is in-use from the first moment an activity from the group starts until the last activity. Therefore, so-called work continuity constraints *(El-Rayes and Moselhi, 1998)* have been introduced in order to build a project schedule where the idle time of resources is minimized.

In the case study, the scheduling objective was optimized for the construction of a tunnel in the Netherlands. At every 250 meters the tunnel tubes are connected by transverse links that can be unlocked automatically in case of emergencies. The transverse links account for ten percent of the construction budget and their construction includes a freezing technique to guarantee watertight transverse links. The freezing technique was used in such large scale for the first time during the construction of the Westerscheldetunnel. This freezing machine needs to be operational throughout the entire construction time of each transverse link, regardless of whether other activities are in progress or idle. Therefore, a new algorithm was developed by Vanhoucke *(2006b)* that takes the minimization of resource idle time *(the freezing machine)* into account as the main scheduling objective. The results have been compared to the traditional CPM and RCP schedules and have shown that the total idle time can be reduced from 165 days to 107 days for crews and from 343 days to 5 days for the freezing machine within the same total project duration of 380 days. Taking into account the cost of the freezing machine and the crew, this could lead to a saving of somewhat more than € 1 million. For a detailed description of the project the reader is referred to Vanhoucke *(2007)*.

3.5 Just in time scheduling (RCP-WET and RCP-QTS)

Scheduling activities on a predefined start time or within a predefined time interval involves determining earliness and tardiness penalty costs when the scheduled start times deviate from their desired time window. While the RCP-WET assumes a single time instance for each activity *(e.g., to set up a meeting with a contractor)*, the RCP-QTS defines multiple time intervals from which only one needs to be chosen for each activity.

Quality-dependent time slots refer to predefined time windows where certain activities can be executed under ideal circumstances *(optimal level of quality)* while outside these time windows there is a loss of quality due to detrimental effects. The purpose is to select a quality-dependent time slot for each activity, resulting in a minimal loss of quality.

This scheduling objective was highly relevant to the construction of a baseline schedule of an R&D project from the biotechnology sector working with genetically manipulated plants. In this project, several activities needed to be scheduled in the presence of limited resources and severe quality restrictions. More precisely, some activities needed to be executed preferably within certain predefined periods, referred to as quality-dependent time slots. Although the execution was also possible outside these predefined intervals, it was less desirable since it could have led to a decrease in quality. In the case study, the quality dependent time slots were necessary since the items that were produced *(in this case all kinds of plants)* were perishable. Many project activities consisted of tests on growing plants where quality was time-dependent since there was an optimal known time interval of consumption. Earlier consumption was possible, at a quality loss cost, since the plants were still in their ripening process. Later consumption could also result in loss of quality due to detrimental effects.

The procedure used is based on a branch-and-bound solution approach that consists of a dual run. In the first run one of the possible time slots are assigned to project activities while in the second run, these activities are scheduled as close as possible to the time slot, in order to avoid quality loss. Details of the procedure are given in Vanhoucke *(2006a)*, which also shows that the quality dependent time slot schedule objective can be highly relevant in a variety of scheduling environments. The results obtained by using the procedures could not be measured in financial terms. However, thanks to the insight provided by the algorithms, the project scheduler was able to meet quality standards in a much better way, despite the complex relation between limited resource availabilities, complex network relations between activities and vast number of activities *(over thousand)* in the project.

4. Conclusions

Academic research and empirical relevance is what brings researchers and practitioners together to advance the current state-of-the-art methods and methodologies. Project management and dynamic scheduling have been investigated widely from various angles and for different purposes. In this paper, an overview is given of the academic endeavors that have led to publications in the domain of project management and dynamic scheduling and their specific use and relevance during the development of a new software tool and the construction of realistic and relevant baseline schedules on practical project data. This paper does not aim to give a full overview of the literature but rather to give some illustrations on where theory and practice can work together to construct and improve the project baseline schedule.

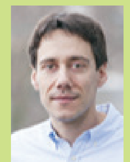
Dynamic project scheduling is a term used to refer to the dynamic nature of project management. It consists of three dimensions, known as baseline scheduling, schedule risk analysis and project control. This paper focuses on the baseline scheduling dimension of dynamic scheduling and discusses the presence of various scheduling objectives in the literature and their use in practical settings.

Based on a small set of empirical data, it is shown that algorithmic techniques developed in the academic literature can often be used without the need for considerable adaptations on real-life project data. Optimizing a scheduling objective that is different from the default time minimization objective often creates baseline schedule which better reflect the wishes and needs of the project *(manager)* leading to improvements in the budget of the project baseline schedule costs. We believe that the use of state-of-the-art algorithmic procedures on empirical project data shows the relevance of academic research and illustrates that the gap between academic results and practical relevance can be bridged, gradually moving the dynamic project scheduling discipline to a higher level.

Future research paths should focus on further developing realistic algorithms and the integration of the three dimensions of dynamic scheduling in a single decision-support tool.

It is worth noting that new research is on its way. Recently, a new research project titled "searching for static and dynamic project drivers to predict and control the impact of management/contingency reserve on a project's success" has been awarded a Concerted Research Actions *(CRA)* grant by Ghent University *(Belgium)*. Preliminary research results will be disseminated in conferences, such as the EVM Europe conference *(www.evm-europe.eu)*. Active collaborations with professional project management organizations are guaranteed. The goal of the researchers is to publish in flagship academic journals, to present their work in international conferences and to continuously bridge the gap between academic research and practical relevance. Given that, after all, the best way to advance the state-of-the-art in project management is when research meets practice.

authors



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