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 (Jettevaal, 2005; Vanhoucke, 2012a). 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 experiences 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.

ABSTRACT

An overview of past experiences

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 (Jettevaal, 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) is 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 (Houwewouw, 2012b).

### 2. Baseline scheduling

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 minimizing its schedule's duration.

**Schedule risk analysis:** Analyze the strengths and weaknesses of the project schedule in order to determine information about the schedule's sensitivity and the likely changes that unnecessarily 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 schedule and risk analysis steps to monitor and update the project and to take corrective actions.

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 academicians to solve different kinds of resource-constrained project scheduling problems to construct baseline schedules is presented, and their advantages and disadvantages are discussed.

### 2.2 Scheduling objectives

It was mentioned earlier that the construction of a baseline schedule involves the definition of a scheduling objective. This scheduling objective is referred to as the dominant force (Ytterwael, 2005), and can vary from project to project, from sector to sector, in Herroelen et al. (1999) and Brucker et al. (1999), an overview is given to the reader. It is evident that many different objectives can be used in the academic literature. In Vanhoucke (2012b), some well-known scheduling objectives are illustrated. This section will review these examples, and how they can be used.

#### 2.2.1 Resource Availability Cost Project (RACP)

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. Overview of the most important papers: 

- Agin, 1966: Use of the CPM method in the current paper is the branch-and-bound approach (Agin, 1966) to generate optimal solutions. Multi-pass heuristics are then sometimes used in conjunction with multi-pass heuristics. The exact methods. These often time-consuming methods generate multiple approaches that are widely available in literature could have been used.
- Vanhoucke et al. (2006). This work seeks to focus on an unrestricted use of resources and has led to a variety of different scheduling objectives, with the hope that this can be more efficient.
- Project schedules have been developed by Schwindt (2000) and Vanhoucke et al. (2012b).

#### 2.2.2 Resource Availability Cost Project (RACP-WC)

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. Overview of the most important papers: 

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#### 2.2.3 Resource Availability Cost Project (RACP-DC)

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. Overview of the most important papers: 

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### 2.3 Scheduling algorithms

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 the result of a research on a tool based on various algorithms developed at Ghent University (Belgium) incorporating many recent advances in project scheduling algorithms. This research tool, known as P2 Engine (www.p2engine.com), has been extended with a graphical user interface to use in a practical and operational environment. The use of the standard level scheduling algorithm of the tool has led to a resource level baseline schedule within a minimum time scheduling problem. However, some new scheduling algorithms that can be used in the academic literature. In Vanhoucke (2012b), some well-known scheduling objectives are illustrated. This section will review these examples, and how they can be used.

#### 2.3.1 Simple priority-based priority scheduling

Simple priority-based priority scheduling rules using priorities for project activities and generation schemes for project activities have been used as a research topic in the past. 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 scheduling produces a scheduling objective that is used to construct the schedule. The schedule in this case is obtained by solving its three dimensions simultaneously. The three dimensions following lines in any dynamic scheduling analysis. The three dimensions

#### 2.3.2 Multi-pass heuristics

Multi-pass heuristics can be implemented in a variety of ways and are based on various underlying optimization principles. The project construction of baseline schedules as proposed in section 4 have been done based on genetic algorithms (Holland, 1975), scatter search optimization (Karti et al., 2004) or electromagnetic optimization (Bibl and Fang, 2002), but obviously many other algorithmic approaches that are not reported in this section can be found in Vanhoucke (2012b). These methods are used to construct baseline schedules, without having the intention to give a full literature review.

#### 2.3.3 Exact methods

When the theoretical best possible solution must be found, the construction of a baseline schedule can be constructed using exact methods. These optimization methods are often time-consuming methods generate multiple approaches that are widely available in literature could have been used.

### 2.4 The construction of a baseline schedule

The construction of a baseline schedule involves the definition of a scheduling objective. This scheduling objective is referred to as the dominant force (Ytterwael, 2005), and can vary from project to project, from sector to sector, in Herroelen et al. (1999) and Brucker et al. (1999), an overview is given to the reader. It is evident that many different objectives can be used in the academic literature. In Vanhoucke (2012b), some well-known scheduling objectives are illustrated. This section will review these examples, and how they can be used.

#### 2.4.1 Resource Availability Cost Project (RACP)

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#### 2.4.3 Resource Availability Cost Project (RACP-DC)

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. Overview of the most important papers: 

- Agin, 1966: Use of the CPM method in the current paper is the branch-and-bound approach (Agin, 1966) to generate optimal solutions. Multi-pass heuristics are then sometimes used in conjunction with multi-pass heuristics. The exact methods. These often time-consuming methods generate multiple approaches that are widely available in literature could have been used.
- Vanhoucke et al. (2006). This work seeks to focus on an unrestricted use of resources and has led to a variety of different scheduling objectives, with the hope that this can be more efficient.
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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 five units and the maximum allowable project duration is equal to 18 days. The cash flows are net cash flows (cash inflows - cash outflows). Mainly 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 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 2c 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 5 because 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 dates 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). Figure 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 options that have never been implemented by a software user. In the academic literature, however, thousands of algorithms have been written and published to resolve over-allocations of resources in projects that often incorporate the 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 other factors 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 (columns ‘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...
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 solution (single-pass algorithms based on priority based scheduling);
- 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 rule based scheduling 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 with certain properties and the currently best found project duration automatically generated by the software.

Both scheduling methods can be done in two different ways. In a flexible duration mode, the duration and resource demand of each activity will never change. The resource scheduling algorithms will shift activities further ahead in time. The priority rules used in a fixed duration 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 demand- ing 1 person. Although this is possible 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 scheduling and project control tools (see section 2), the research results have been awarded the IPMA Research Award by the International Project Management Association (IPMA, www.ipma.org) 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 effi- ciently 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. Moreover, it is a specific objective 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 Erengüc (1994) and Vanhoucke et al. (2004, 2012) and by the results published in Balachandran and Zoltick (1981), Chan and Dodin (1986), Dodin and Chan (1994), Dodin and Elkim (1997), Dodin et al. (1998) and Brucker and Schumacher (1999) and extended to specific settings of a Belgian audit firm. 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 (see section 3.2) 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 ac- count during the baseline schedules construction. A first objective function minimizes the number of audit engagements that finish after a prede- fined project deadline. A second similar objective function is to minimize a penalty cost to each day an audit engagement finishes later than the proposed deadline. Both objectives are inspired by the need to maintain a fixed 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 function assigns a value 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 improvements of 8.14% and in 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 research might bring theory closer to practice, hence showing the need 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 €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 not all activities are scheduled at their latest starting time in order to postpone the pay- ments of their underlying cash flows, the slack of each activity is relatively small already. Therefore, the optimization of a schedule objective should be carefully performed, hence a careful trade-off between the quality of the schedule objectives and a certain degree of buffering to add activity slack is a crucial choice to make. A project description and the main conclu- sions are summarized in an article written by Vanhoucke and Demeulemeester (2003).

### 3.3 Optimizing cash flows (RCP-DC)

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 lifetime. However, these methods are not able to take into account 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 single resource in an idle time period. Consequently, there are numerous project

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**TABLE 2. Overview of empirical project data for each of the schedule objectives.**
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 customized 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 transverse links, 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 by 160 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 crews, this would lead to a saving of somewhat more than €1 million. For a detailed description of the project the reader is referred to Vanhoucke (2006b). That brings researchers and practitioners together to advance the current state-of-the-art methodology 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 be used without the need for considerable adaptation to real-life project data. Optimizing a scheduling objective that is different from the default time minimization objective often creates baseline schedule which better reflects 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.evmeurope.eu). Active collaborations with professional project management organizations are guaranteed. Given that all, the best way to advance the state-of-the-art in project management is when research meets practice.


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