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REVIEW ARTICLE

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Planning projects with scarce resources: Yesterday, today and tomorrow's research challenges

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Abstract This paper is an invited request to describe the main research challenges in the domain of resource-constrained project scheduling. The paper is split up in three parts. In today's challenges, research endeavors that have received a significant, but still not enough, attention have been described. In tomorrow's research challenges, some promising research avenues for future research have been given. Finally, in yesterday's challenge, a research topic that started decades ago, is said to have still a huge potential in tomorrow's research agenda. This paper does not intend to give a full literature overview, nor a summary of all possible research paths. Instead, it is inspired from the author's experience in academic research and practical consultancy and it serves as a personal opinion on a non-exhaustive set of promising research avenues, rather than giving a full literature-based advice for future research directions.

Keywords project management, project scheduling, resource constraints, PERT/CPM, RCPSP

1 Introduction

Project management is the discipline of planning, organizing and managing resources to aim for a 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 scope management, human resource management (e.g. assigning the roles and responsibilities of all participants and stakeholders of a project), project planning and resource allocation management and much more. This paper focuses on a specific sub-domain of the project management discipline known as *resource-constrained project scheduling* that has been investigated widely in the academic literature. Resource-constrained project scheduling aims at the construction of a so-called project baseline schedule that can and should be used throughout the whole life of the project. The construction of such a project baseline schedule consists of designing a timetable for the project's activities within the technological precedence relations and renewable resource constraints (Demeulemeester and Herroelen, 2002; Vanhoucke, 2012). It involves the assignment of start and finish times to each activity such that a scheduling objective is optimised. Ever since the introduction of formal planning methodologies in the '50s, the development of fast and efficient algorithms for scheduling problems under a set of assumptions has been a growing research topic, and has now led to a wide variety of solution procedures to solve a huge amount of variants of the same scheduling problem. Despite the overwhelming amount of research done in this exciting research field, the gap between research and practice is still wide enough to continue doing research, and the end of the search to challenging scheduling problems is not even near its end. It is worth noting that this gap is a necessary feature and typifies the nature of research, but it should not lead to the creation of two separate worlds with no bridges. Practical needs (i.e. having access to quick and good tools for scheduling problems) often differ from academic ambitions (i.e. developing complex scheduling algorithms that result in publications), and the professional needs often change quicker than what academics can produce. On the other hand, academics sometimes develop complex

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methodologies and scheduling algorithms that cannot be used by professionals due to their complexity and inability to solve real scheduling problems. To avoid that the two worlds grow apart, it is often — as a researcher — necessary to stand still and reflect on the past research attempts, in order to (re)define today's current research challenges (in line with practice) and to predict the potential future research directions (in line with the upcoming business trends), and adapt the research agenda to these changing needs.

Increasing the realism of a project baseline schedule to reflect real needs and wishes of a project manager is key for the future research. Ever since the initial endeavors in the field of algorithmic design for project scheduling problems, the research has grown in the variety of its theoretical models, in its magnitude and in its applications. While the research has expanded over the last decades, leading to project scheduling models with many deterministic and stochastic features, single and multiple objectives, and a wide variety of resource assumptions, the practitioners and software tools mainly stick with the often basic project scheduling principles. In Vanhoucke (2013), I gave some examples of how some of the algorithms for various types of resource-constrained project scheduling problems have been used for solving practical problems, but the widespread use of the overwhelming amount of algorithms and procedures available in literature for practical purposes still remains limited. This can probably be explained by the limited capability of a project baseline schedule to cope with the real-life needs and wishes inherent to the project problems. In this paper, some current challenges in the field of resource-constrained project scheduling optimisation are given, and some potential promising new research directions to explore are described. This paper does not aim at providing a summary of the literature, nor does it intend to give an exhaustive overview of promising future research avenues based on a literature overview. Instead, the paper gives a personal reflection on the future research in project scheduling based on two decades of research and practical consultancy done in the past 20 years by the author of this article.

Figure 1 gives a graphical summary of the current knowledge (today's challenges) and future directions (tomorrow's challenges) in project scheduling as discussed in the next sections. Section 2 gives a brief summary of the main challenges of the current research on project scheduling. Section 3 highlights some important research directions for the future based on needs defined by business. Section 4 shows that the vast amount of research done in the past is still valuable and should be continued. Section 5 draws general conclusions and shows that the new directions are ready to be explored, and some advice and guidelines are given to stimulate researchers to turn their research agenda in these new directions.

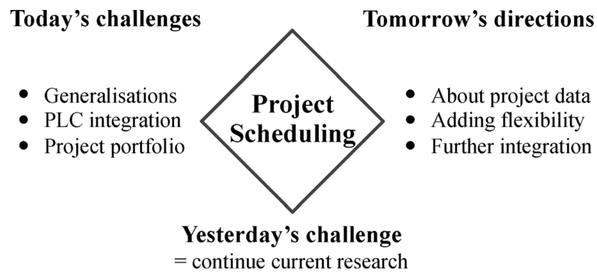


Fig. 1 Project scheduling: current challenges and future directions

2 Today's challenge

In this section, some of the current challenges on the (resource-constrained) project scheduling research will be highlighted, and some of these challenges will be illustrated by recently obtained results from studies done at the research group of the author. It is needless to say that an overview of the literature on such a research topic is inevitably biased by the author's experience and past research track record. Any research topic is investigated from a certain angle, and although research should not be narrow minded, it is impossible to view a research topic from all possible angles. Hence, in this overview, my view on the project management discipline lies on the construction of a project schedule, and this sub-domain is discussed from the angle of algorithmic design and combinatorial optimisation. It means that the construction of the project baseline schedule is seen as a combinatorial optimisation problem in which finding a feasible or optimal solution is not an easy task (many of the project scheduling problems are known to be NP hard). Moreover, I restrict my overview to the so-called reactive planning approaches in which all the project data are assumed to be deterministic. In reality, projects are subject to uncertainty, and in case problems occur, the project needs to be rescheduled. However, this research overview excludes the stream of research on the so-called pro-active planning approaches, and hence does not contain references to e.g. robust planning and optimisation (which focus on the minimisation of changes in the original schedule when problems occur) or stochastic planning approaches (taking project uncertainty into account during planning). In short, the approach in this paper is restricted to a *deterministic reactive planning approach.*

A deterministic research focus does not mean that uncertainty is completely ignored. While deterministic algorithms rely on non-stochastic (hence deterministic) data, some research endeavors take multiple possible activity executions into account, or add some sort of agility to be able to cope with the inherent project uncertainty. The reason why deterministic planning is a valuable research topic, despite the inherent uncertainty that typifies real projects, is threefold. First, solving complex project planning problems under certainty enhances the understanding of the relation between project variables (such as the relation between the project's network structure and its resource parameters). Second, although deterministic optimisation algorithms assume that the data are without any uncertainty, some of the planning problems aim at adding flexibility in the project schedule such that they anticipate part of the inherent uncertainty in advance (and hence, these approaches could be classified as robust). Finally, deterministic plans of course should be used as a first step in the life of a project, and can be considered as a foundation and point of reference for risk analysis and project control. This integrated view on project management in which the project schedule is nothing more than a first step in a sequence of data-driven analyses to improve the management of a project is known as *dynamic scheduling* (Vanhoucke, 2012; Uyttewaal, 2005) or *integrated project management and control* (Vanhoucke, 2014).

The research on project scheduling knows a long history and dates back to the '20s of the previous century with the introduction of the so-called Gantt chart that is now the default screen in any commercial project management software tool. Ever since the development of the *Programme Evaluation and Review Technique* (PERT) and *Critical Path Method* (CPM) methodologies, researchers have introduced an endless stream of new problem formulations and solution approaches for constructing project schedules. While the traditional PERT/CPM methodologies assumed that the project's renewable resources are not limited in availability, it quickly became clear that the real challenge was to extend these basic methodologies to more realistic settings with limited resources. The PERT/CPM are now considered as easy and straightforward scheduling techniques that can be used as a foundation for the more complex resource-constrained scheduling methods.

Resource-constrained project scheduling is the process of constructing a project schedule within the limited amount of resources available. It requires the examination of the possible unbalanced use of resources over time to resolve over-allocations (the so-called resource conflicts) when more resources are required than available. While the PERT/CPM methods will schedule many activities simultaneously, these activities will often require more resources than there are available. Hence, these activities will have to be rescheduled (shifted in the schedule) to resolve the resource conflicts. Resource-constrained project scheduling is the process of resolving these resource conflicts under different scheduling objectives, with various activity and project features and with numerous extensions to cope with real and practical needs.

The basic problem type is now known as the *resource-constrained project scheduling problem* (RCPSP) and has since its introduction been investigated by many researchers in the field. At the peak of its popularity in the late '90s, several overview papers have been written (Icmeli et al., 1993; Elmaghraby, 1995; Özdamar and Ulusoy, 1995; Herroelen et al., 1998 and Brucker et al., 1999). To bring structure in the overwhelming amount of problem formulations, both Brucker et al. (1999) and Herroelen et al. (1999) have almost simultaneously presented a classification framework to uniquely define each problem. Moreover, handbooks such as the book written by Klein (2000) and the research summary handbook by Demeulemeester and Herroelen (2002) give an overview of the then state-of- the-art in the research. In 2014, a summary of the resource-constrained project scheduling problem has been written from the dynamic scheduling point-of-view, integrating project scheduling with schedule risk analysis and project control (Vanhoucke, 2012). Finally, a recent excellent summary article has been written by Hartmann and Briskorn (2010), this time focusing on the numerous extensions that have been presented so far in the literature. Despite the excellent overviews available in the literature highlighting new and promising research directions, I believe that more research is necessary in this direction to make the academic output more relevant to practice. In the next three sections, three important research challenges – *generalisations, integration and portfolio planning* – are mentioned that are now on the research agenda of various research groups. Many of these current challenges have been published in numerous research papers, but some of these topics still require – in my opinion – more attention as they have been largely overlooked, or even completely ignored, in many of today's research projects.

2.1 Generalisations

The most obvious and most important challenge in research is the on-going process of adding practical features to the problem formulations. The overwhelming amount of algorithms developed for the RCPSP have not been used widely outside academia, and have therefore little to no practical value. However, more and more research attention is given to extended features of the RCPSP to bring the problem closer to the practical needs of project managers. In an excellent summary paper of Hartmann and Briskorn (2010), the authors give a survey of variants and extensions of the resource-constrained project scheduling problem. They mention, among other things, three classes of generalisations, each of them aiming at tightening the gap between the academic research and the practical needs. These classes aim at extending activity features to more realistic settings, but also include extensions related to the relations between activities (i.e. the project network) and modifications on the basic assumptions for project resources.

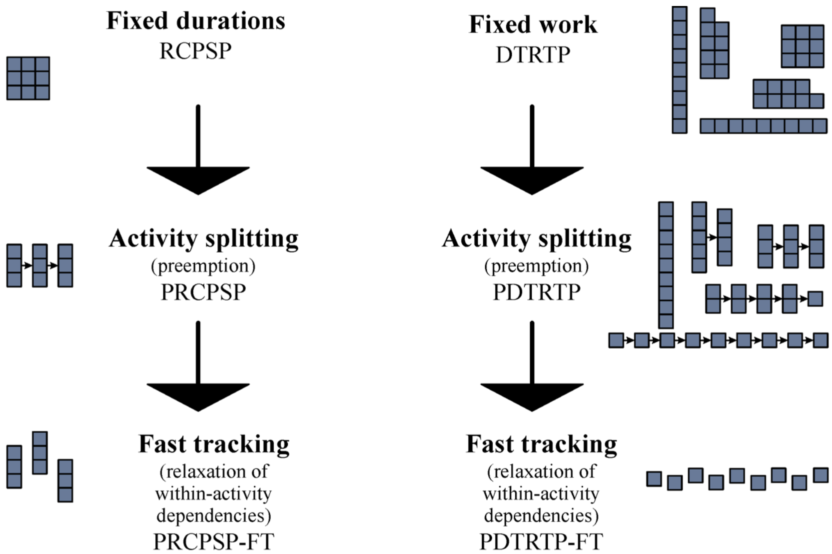
2.1.1 Activity generalisations

Generalized activity concepts include activity preemption (splitting of activities in smaller parts), variable use of resources (the amount of resources demanded by activities changes along their duration), setup times (additional time between (parts of) activities), fast tracking (overlaps between (parts of) activities), multiple modes (choices between durations and resource use for each activity) and many other trade-off problems. Numerous papers have been written to extend the activities with features that could make the project schedule more realistic. These research efforts have not only resulted in new algorithms to better solve these complex scheduling problems, but also enhanced the insights into the important trade-offs of the project parameters. While the search for new and extended activity features should continue in order to make the research output more realistic, attention should also be given to the comparison of and integration between these extended features to create additional insights. Two illustrations are given along the following lines.

Comparing activity generalisations: Software tools often provide the user with options for activity features, each resulting in a slightly different schedule but without knowing or completely understanding the real impact of these options on the quality of the schedule. Take as a typical example the relation between the use of work content (activities under a fixed duration or fixed work content), activity preemption (splitting activities into smaller pieces) and fast tracking (allowing overlaps between the splitted activity pieces). While it is obvious that these extended features result in a decrease of the project makespan compared to the traditional RCPSP (fixed duration instead of fixed work, no preemption and no fast tracking), little is known what the impact is of each of these features separately. In a study by Vanhoucke and Debels (2008) and Vanhoucke (2008), the impact of these three extensions on the project makespan and the total resource use has been tested in a computational experiment. While it is obvious that adding extra flexibility (from the basic problem to allowing activity preemption and fast tracking) will lead to a project makespan reduction, and an increase in the average resource utilization, it is interesting to understand how big the impact is and how the size of the impact depends on the project parameters. Figure 2 shows a summary of this study and illustrates that adding activity preemption without fast tracking hardly pays off and only leads to a makespan reduction of 0.5%. Adding activity tracking reduces the makepan with an average value of almost 15%, but this schedule will show many activities split into smaller pieces that overlap each other, and one can question how realistic and manageable such a schedule is. The table below the picture also shows that switching from fixed duration activities to fixed work activities (in which the activity duration multiplied by its resource use is kept fixed, but individual values for the activity durations and resource use can vary) leads to more promising results. Makespan reductions of more than 20% are in reach, and the resources will be used more efficiently, with an average resource utilization of almost 95%. One can question whether such a high resource utilization is desirable in the presence of uncertainty, but the research at least shows that these values can be obtained.

I believe that these results are not only interesting from an academic point-of-view, but also for creating insights for business. For that reason, more research should be spent on these (and other) activity generalisations, since only after a siginicant number of studies, general conclusions can be drawn that hold for a wide range of projects. This can be perfectly illustrated by another, more recent study, in which it has been shown that activity preemption pays off under certain circumstances, even when these splits come at an additional setup time. This study is briefly explained in the next paragraph.

Adding setup times: Traditionally, the extended activity features described earlier are often investigated in isolation, each time presenting a new solution approach with one or two extensions, but often ignoring relations and trade-offs between these features. However, these extended features are often in conflict with each other, or occur in a variety of ways in real projects, and hence, creating understanding of the relations between extensions is often more important than developing an algorithm to solve the extended problem. A typical example is the use of activity preemption (splitting of activities in subparts) investigated in literature. Splitting activities can reduce the project duration and hence results in a better project makespan (as discussed before), but little is known whether this is generally true for all projects or only occurs for projects with certain parameters. Moreover, since activity splitting is not always very desirable for a schedule (containing many activities split up in multiple smaller pieces), not much work is done on measuring the degree of preemption in relation to the makespan reduction. In a recent paper, the presence of activity splitting has been investigated under the presence of four types of setup times (Vanhoucke and Coelho, 2018a). These setup times are used as a penalisation factor to avoid that the resulting project schedule contains only small split activities such that no-one can recognize the original project anymore. In the study, the size of setup times depends on the way the activity is split (set as a fixed setup time, or as depending on the total work, the work done so far or the remaining work to be done). Moreover, the research also includes the option to fast track the preemptive activity parts, as discussed before. The authors show via a computational experiment that activity preemption can slightly reduce the project makespan, even with relatively high values for the setup times. The extension to within-activity fast tracking obviously could reduce the makespan even further, and – most importantly – this decrease does not require a lot of activity splits in the schedule. Hence, activity preemption



Problem abbreviations in literature

- **RCPSP:** Resource-constrained project scheduling problem
- **DTRTP:** Discrete time/resource trade-off problem
- **PRCPSP:** Preemptive resource-constrained project scheduling problem
- **PDTRTP:** Preemptive discrete time/resource trade-off problem (no results in literature)
- **PRCPSP-FT:** Preemptive resource-constrained project scheduling problem with fast tracking
- **PDTRTP-FT:** Preemptive discrete time/resource trade-off problem with fast tracking

	Fixed duration		Fixed work	
	Average lead time reduction	**Average resource utilization**	**Average lead time reduction**	**Average resource utilization**
Basic problem (RCPSP and DTRTP)	0%	75.26%	21.09%	94.76%
Activity preemption (PRCPSP and PDTRTP)	0.50%	75.58%	n.a.	n.a.
Fast tracking (PRCPSP-FT and PDTRTP-FT)	14.80%	88.28%	21.87%	95.73%

Fig. 2 Impact of activity assumptions

and fast tracking has some merits, since it does not change the schedule dramatically (not many preemptions and overlaps) while small benefits can be obtained. Hence, this study sheds a somewhat different light on the use of activity assumptions in project scheduling compared to the study discussed earlier.

The two illustrative examples clearly show that adding activity generalisations to the project schedule is not as easy as it sounds, and research should devote some attention to investigating the impact of combinations of generalisations on the scheduling objectives (such as project duration and resource efficiency). Moreover, the underlying assumptions and data used in the research studies heavily influence the results, and therefore, a comparison between research studies is more important than the results of a single study. While a discussion of the reasons for the discrepancies between the two illustrative studies discussed in this section is outside the scope of this paper, it illustrates that much more work should be done before academics and business can draw general conclusions about the clever use of activity generalisations.

2.1.2 Network generalisations

Rather than extending the activity assumptions to more general and realistic features, the use of generalized temporal constraints have also been studied widely in the academic literature. Probably the most interesting and most widely investigated generalisation is the extension of the so-called minimal time-lags to maximal time-lags, but other extensions such as release dates (cannot start earlier than), due dates (must finish on) or time/switch constrains (calendars) have been topics of research studies in the past. I believe it is somewhat surprising that the research attention to the so-called *generalized precedence relations* including both minimal and maximal time-lags between activities) has been faded away a little bit in the last decade, since these general constraints are promising extensions that can be used easily to incorporate other network features (e.g. ready times and due dates can be easily modeled using minimal/maximal time-lags). I recommend researchers to build further on the initial research efforts done by Elmaghraby and Kamburowski (1992), De Reyck and Herroelen (1998), Neumann et al. (2002) and others and include the maximal time-lags back into the problem formulations. Apart from this straightforward and somewhat forgotten extension, some network generalisations have received much less attention in the past, but should be put on the research agenda, since they embed very specific features in the project schedule that are commonly used in practical projects. A non-exhaustive list is given along the following lines.

• Calendars: The majority of the research on project scheduling does not make use of calendars and assumes that resources are available at all times to work on the project activities. However, one of the most used features in any software tool is the use of calendars to model unavailabilities of e.g. people or closing days of the company. As an example, MS Project makes use of base calendars, project calendar, resource calendar and activity calendar, and while the difference is easy to understand, a clever combined use of these calendars often leads to unexpected surprises. Hence, researchers should develop and compare algorithms and test the impact of these calendars on scheduling objectives, similar to what has been done in the previous illustrative example of activity generalisations. To the best of my knowledge, no such integrative study has been done. Of course, the use of calendars has not been ignored by researchers, but the research is often restricted to detailed algorithmic changes (Franck et al., 2001) or very specific calendars such as time/switch constraints (Yang and Chen, 2000; Vanhoucke, 2005). For a summary of the current state-of-the-art research, the reader is referred to Kreter et al. (2016).

• Logical dependencies: Traditionally, precedence relations between activities are so-called AND relations to stipulate that any activity can only start after the finish of all its predecessor activities. However, recent extensions to OR relations (an activity can start after the finish of one of its predecessors) (Möhring et al., 2004) or bi-directional constraints (an activity can start before the finish of another activity, or vice versa) (Vanhoucke and Coelho, 2016) have been investigated. These extensions are not only enriching the realism of the project schedules, but can also be seen as a first step in adding flexibility into the project network, which is – given the ever-increasing need to react fast and in a flexible way – a promising research area that deserves more attention than it gets today.

• Extended relations: Recently, extended relations between activities, known as point to point relations (Hajdu, 2015) and continuous precedence relations (Hajdu et al., 2017), have been introduced to the literature that deserve some future research attention. The extensions are presented to introduce a general description of activity-time-production functions, and define activity overlapping as a continuous relation that uses time or work units between all points of a predecessor activity and all points of its successor, rather than only on their start and end points, as is the case with the 'classic' precedence relations.

2.1.3 Resource generalisations

The majority of resource-constrained project scheduling research focuses on the optimisation of renewable and non-renewable (or consumable) resources of the project. Generalized resource constraints include partially renewable resources (Böttcher et al., 1999), cumulative resources (Neumann and Schwindt, 2003) as well as continuous resources (Weglarz, 1981), for which quite some research results are available in literature nowadays. However, the extensions of resource features in resource-constrained project scheduling should aim at adding real resource-specific features, and should not only focus on defining additional resource types. Two illustrative challenges are briefly outlined along the following lines, with some references to publications that might be useful for further exploration:

• Resource efficiency: In the project scheduling literature, most models assume static and often homogeneous efficiencies of resources (Heimerl and Kolisch, 2010). However, since human resources are a critical factor in the scheduling process and their productivity varies over time, the incorporation of resource skills and the effect of resource learning should be incorporated in the scheduling phase. Kolisch and Heimerl (2012) have incorporated the use of skills and simultaneously schedule the activities of multiple projects and assign the project work to multi-skilled internal and external human resources with different efficiencies. Van Peteghem and Vanhoucke (2015) have introduced resource learning into the multi-mode resource-constrained project scheduling problem, and have analyzed the impact of learning from three different perspectives, as will be briefly discussed at the end of this section.

• Resource rostering: Project scheduling and resource rostering are often two isolated topics that are widely studied in literature. On the one hand, project baseline schedules are typically made within a limited predefined resource availability. In personnel rostering problems, on the other hand, important decisions are made with respect to the construction of personnel timetables to guarantee these resource staffing requirements. Since both topics are centralised around a given pool of resources with certain rostering policies and practices, project characteristics and various employee contracts, these two important optimization problems should be integrated into a single decision support tool (Alfares and Bailey, 1997). However, the relevant literature on the integrated scheduling problem is scarce, and an overview of the limited literature is given in Maenhout and Vanhoucke (2016). These authors integrate the project scheduling problem with the personnel staffing problems in a single project setting.

Incorporating these and other features should be done not only to develop new and efficient solution procedures, but rather to gain insights into their impact on the project schedule under various settings. I will illustrate this statement by an example from my own research that shows, although to a limited extent, that the incorporation of resource learning into existing algorithms can be interesting to test the impact of resource learning in different ways. Figure 3 gives a summary of the research design and shows that the effect of learning is measured along three dimensions. The authors compare three different schedules as follows. The *original schedule* is the resource-feasible schedule for a project without incorporation of the learning effects. The *optimal schedule* is the optimal schedule of the problem with the incorporation of the learning effects during the construction of this schedule. The so-called *realistic schedule* is the schedule constructed in a two-phased approach. In a first phase, the optimal schedule is constructed (ignoring learning) but the activity durations have afterwards been replaced in a second phase by their learning duration. The underlying assumption made is that the project manager is not aware of the existence of learning effects during the construction of a baseline schedule but only realizes (or observes) afterwards that resource learning can occur and changes the original schedule and the start times of each individual activity.

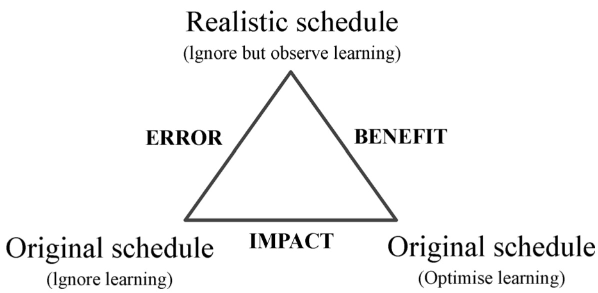


Fig. 3 Research design for learning experiments

The impact of learning can be measured by comparing the original with the optimal schedule and is done not only to test the usefulness of incorporating learning effects in the algorithms, but also to determine the main driving variables of the differences between the project durations of both schedules. The margin of error is also measured to discover how harmful it is when the learning effects are ignored during the project scheduling phase but observed afterwards during project progress. The smaller the deviation between both solutions, the less important it is to spend time and effort to predict the learning effects in advance in order to incorporate them in the project schedule during baseline schedule construction. Finally, the benefits of early knowledge of learning effects are analyzed in order to measure the benefits that can possibly be obtained when learning effects are detected in early stages of the project progress.

2.2 Project life cycle integration

The construction of a resource feasible project baseline schedule can be done under various objectives to be optimised. The main objective used in literature is time, since the classic RCPSP (and many of its extensions) aims at constructing a feasible schedule within the minimum possible project duration (known as the project makespan). However, a significant amount of research has been devoted to solving variants of the RCPSP problem under different objectives. To classify project scheduling objectives, the literature has made a distinction between *regular objectives*, with the time minimisation as the classical example, and *non-regular objectives*, for which the maximisation of the net present value probably is the most well-known objective.

It is tempting to define the current challenge as simply further extending the problem formulations to other (currently unknown or unexplored) objectives, or to combine objectives into multiple objectives (using a weighted objective value or multi-criteria project scheduling techniques). However, I believe that extending the objectives of the scheduling algorithms should not be a goal on itself, but rather should be done with care and with a focus on all the phases of the project life cycle. It has been mentioned earlier in Section 2 that the construction of a (resource-feasible) baseline schedule must be considered a preparatory step for later phases in the project life cycle, such as the analysis of the schedule risk and the control phase. Hence, aligning the scheduling objectives with the objectives in these later project phases should be a concern and should aim at constructing project schedules that can optimally be used in these phases.

In the last decade, I have spent a great part of my research time on integrating baseline scheduling with risk analysis and project control ever since the study published in Vanhoucke (2010a). However, in this study, I have each time analyzed the quality of schedule risk analysis and project control methodologies using the project baseline schedule *as a given*. Moreover, I also have largely ignored the presence of limited resources, and restricted my analysis on the easy-to-use critical path method. However, it might be wise to investigate this integrated project management theme from the opposite direction, starting with the construction of a (resource-feasible) project schedule that optimally contributes to the quality of the two other domains (*risk analysis* and *project control*), rather than taking the schedule as a fixed input. Some ideas and thoughts are outlined in the two following sections.

2.2.1 Risk analysis

Schedule Risk Analysis (SRA, Hulett, 1996; Williams, 1992) is a Project Management methodology to assess the risk of the baseline schedule and to forecast the impact of time and budget deviations on the project objectives. The technique makes use of statistical distributions for the time and cost estimates for the activities (and the resources they use) to express the uncertainty in the initial activity estimates. Artificial project progress is then simulated using Monte-Carlo simulations to analyze the sensitivity of these activity estimates and the impact of their variability on the project objectives. The output consists of a set of charts that show the sensitivity of the project activities and resources and the potential impact of their variability on the project objectives. The sensitivity of activity durations, activity costs and resource costs is reported using sensitivity metrics — such as the criticality index, the significance index and the schedule sensitivity index — which measure the activity or resource sensitivity as a percentage (with higher values denoting more sensitive activities). These metrics can then be used as predictions and enable the project manager to restrict his/her attention to the most influential activities and/or resources of the project that might have the biggest expected impact on the project objectives. In doing so, schedule risk analysis should be cleverly used to set action thresholds and to support better management actions during project progress to improve the overall performance of the project.

It has been shown in academic research studies that the accuracy of these sensitivity metrics depend on the network structure of the project as well as on the constructed baseline schedule (Vanhoucke, 2010b). The accuracy of the sensitivity metrics is measured by their ability to distinguish between highly sensitive and less sensitive activities and resources. A better distinction will enable the project manager to better focus on a strict subset of activities and resources (the highly sensitive ones) and pay much less attention to the others. The network structure of a project is measured by the so-called *serial/parallel network indicator* (SP) (Vanhoucke et al., 2008) and measures the closeness of a project to a completely serial or parallel network. It has been shown that the closer the project lies to a parallel network, the higher the accuracy of the sensitivity metrics, with the *schedule sensitivity index* (SSI, PMBOK, 2004) as the best performing one. However, little has been done to assess the impact of the baseline schedule – given the project network – on the accuracy of such a schedule risk analysis. Such an analysis would nevertheless be an interesting research topic, since the overwhelming amount of papers in the literature have clearly shown that a resource-constrained project schedule can be constructed in various ways (with all the generalisations discussed earlier). Hence, analyzing which of these different ways of baseline schedule construction would benefit most to the accuracy of schedule risk analysis would be a logical next step to integrate scheduling with the other phases of the project life cycle.

2.2.2 Project control

The ability to measure project delays and cost overruns during the project progress, and accurately forecasting its expected time and cost are essential to successful project management. The technique known as *Earned Value Management* (EVM, Fleming and Koppelman, 2010) is considered to provide an effective methodology for obtaining such measurements and predictions, and relies on a set of performance metrics that compare the project's real progress with the expected progress of the baseline schedule. Hence, the ultimate goal of constructing a resource-feasible baseline schedule is to provide the project manager with a reference to facilitate the performance monitoring and control of the project during its execution. During the project execution and control stage, the baseline schedule is used as a point of reference, and deviations that are not acceptable should serve as triggers to take corrective actions to bring the project back on track, to reschedule the project (constructing a new modified baseline schedule) or in the extreme case to kill the project. During this control phase, objectives such as project plan stability (minimising changes in the schedule after disruptions) or forecasting accuracy (predicting the expected project time and cost given the current project performance), to name a few, are vital for good project control. Hence, these objectives should be integrated into the construction of the baseline schedule such that the use of control systems such as earned value management and its statistical extensions (known as statistical project control) can fully benefit from the way the baseline schedule is built.

In a study done on real project data, it has been shown that the so-called *regularity index* (RI) (Batselier and Vanhoucke, 2017), which measures the shape of the planned value curve (i.e. the cumulative increase in planned costs), determines the accuracy of different control metrics. Since this PV curve not only depends on the project network and the estimated costs of the activities, but also on the way the schedule is constructed, it demonstrates that the construction of the project schedule plays a central role in the accuracy of the EVM predictive measures during project control. However, this study did not take limited resource constraints explicitly into account. The study by Martens and Vanhoucke (2017) has taken scarce resource constraints explicitly into account, and presented a new buffer- based EVM methodology to better control projects. This research is another small step into the direction of integrating resource-constrained project scheduling with other phases of the project life cycle. I believe that more extensions of these research topics should be on the research agenda, in order to better align the project control objectives with the objectives used during the construction of the baseline schedule.

2.3 Project portfolio planning

In this paper, the resource-constrained project scheduling problem (and its extensions) is discussed from a single-project point-of-view, assuming that resources are 100% reserved for one and only one project. However, most businesses manage multiple projects in parallel, and the planning and optimisation of the project portfolio involves the optimal allocation of the scarce resources to different projects. It is therefore somewhat surprising that the literature on the obvious extension from single-project resource planning to project portfolio planning is scarce and still in its infancy. Of course, the literature on project portfolio management is not void, and is instead very rich and diverse, but the amount of research on the algorithmic design for portfolio planning constitutes only a small fraction of the overwhelming amount of research for the single-project case. The obvious reason is of course the underlying complexity of the problem formulations (the classic RCPSP is known to be NP hard so any extension will be hard to solve too), but despite the complexity, a better understanding and improved methodologies to optimise resources for project portfolios is all what project managers need.

The extension of the RCPSP to a project portfolio environment is known as the *resource-constrained multi-project scheduling problem* (RCMPSP). This problem type resembles the classic RCPSP, but now consists of a set of projects to schedule. It is therefore tempting to consider the portfolio as a super-project (i.e. one big project with a huge number of activities belonging to different projects), and solve the scheduling problem as a single project within the limited availability of shared resources. In this view, there is no need to develop specific procedures to solve the RCMPSP since the solution procedures for the RCPSP can be easily used (with some adaptations if necessary). However, it is much more relevant to treat the RCMPSP as a totally different problem, and to develop procedures that can cope with the challenges of this problem type, rather than treating the problem as merely an extension of the RCPSP. Generally, the resource-constrained multi-project scheduling problem consists of the following stepwise approach:

- Step 1. Sizing the resource pool: The resource pool consists of a set of resources with the right mix of technical skills that can be used for the execution of the (dynamically arriving) set of projects in the portfolio. Determining the right pool of resources should be done based on the expected arrival rate of projects and given the right budget constraints. Changing this resource pool (hiring and firing) along the life of projects makes this step a dynamic and continuous decision problem.
- Step 2. Resource clustering: Clustering of resources to create teams (with e.g. similar skills or certain relations between resources) should be done prior to the allocation of these resources to projects. By determining the optimal mix of resources, the teams (of resources) are put at a central place, which recognizes that the success of projects highly depends on the quality of these teams. This human resource management view has been largely ignored in single-project planning where it is assumed that resources (people) are available at all times.
- Step 3. Resource allocation: Assigning resources to projects is key to the success of the project portfolio and guarantees the timely delivery of them. Since resources are not working 100% of their time, optimal rostering algorithms could and should be merged with project scheduling algorithms to optimally assign these resources to a (dynamic) set of projects.
- Step 4. Resource scheduling: Scheduling projects under limited resource constraints is the topic of this paper, and assumes that the resource availability is known prior to the construction of the baseline schedule. Hence, the scheduling problem boils down to assigning start and finishing times to project activities within the precedence and resource constraints (defined in the previous steps) to optimise a predefined scheduling objective.

This basic outline of the project portfolio planning process should not necessarily be done in the proposed sequence, and phases can consist of feedback loops or might be merged into a single integrated phase. However, the crucial point is that the single-project scheduling problem discussed in this paper (the RCPSP) assumes that steps 1 to 3 are a given, and solely consists of step 4. Of course, the academic literature has not been blind for these 4 phases, and research efforts have been done to integrate one of more of these phases into resource-constrained project scheduling. However, most of these efforts still investigate this problem from a single project point of view, and the extensions to multiple projects are still very limited.

The *resource availability cost problem* (Demeulemeester, 1995) or the *resource investment problem* (Neumann and Zimmermann, 2000) assumes that the availability of the renewable resources can be changed at a certain cost, and therefore merges step 1 with step 4. Hence, the problem consists of deciding the optimal number of resources (step 1) as well as the scheduling of the project activities within this limited resource availability (step 4) in order to minimize the total resource cost. However challenging and realistic the problem is, it still ignores the presence of multiple projects that typifies a portfolio.

The *resource renting problem* (Nübel, 2001) assumes that resources can be added or removed from the resource pool (hired and fired) along the project life, and their availability is therefore no longer fixed. To that purpose, they rely on two types of costs. The procurement costs are incurred only once when the resource is introduced in the project schedule (i.e. when the resource is added to the resource pool (step 1)). The renting costs are incurred for every time unit that a resource is in the resource set. In a paper by Vandenheede et al. (2016), the resource renting problem is combined with the so-called *total adjustment cost problem* by adding three additional costs. The adjustment costs are added to the problem formulation and are incurred when the total resource requirements in the project fluctuate. These adjustment costs are split up into three parts. The removal costs occur when a resource is permanently removed from the resource set. Deactivation costs occur when a resource in the resource set is made idle. The activation costs occur when a resource is used again to execute an activity after it was made idle. More recently, this problem is extended to overtime costs by Kerkhove et al. (2017) to temporarily allow the availability of extra resources at a higher cost. Although these problem formulations still solve the single-project scheduling problem, these various cost categories are used to model the fluctuation of resources to imitate a reality in which resources are shared between projects. Adding all kinds of resource costs in the RCPSP is of course a way to model that the availability of resources is not fixed. The costs for hiring and firing resources, or for activating and deactivating resources, are used to reflect that resources are shared between projects in a project portfolio. While this comes closer to the real needs of project portfolios, most of the previously mentioned research endeavors still investigate the problem from a single project point of view. Despite fruitful results, multi-project planning and scheduling is still not widely investigated from a resource optimisation point-of-view. I believe that research on project portfolio resource planning should therefore be stimulated, creating a research agenda in which the overwhelming amount of excellent results for single-project planning can be used as a start for the investigation of the project portfolio planning problem. Undoubtedly, the research on this challenging problem will lead to new problem formulations, realistic extensions and solution procedures that might create synergies between single- and multi-project planning, and both research areas have a lot of potential to improve the current state-of-the-art knowledge on project management with practical relevance.

3 Tomorrow's directions

The current research challenges discussed in the previous sections constitute research directions for which (lots of) results are already available in the literature and for which it is very likely that much more will become available in the near future. The current section however gives a summary of promising new research directions in the field of resource-constrained project scheduling. Although the difference between current challenges and new directions is thin and vague, I have selected a list of topics for which currently not much work has been done, or for which I believe that the current existing body of work should slightly change into another direction to become relevant for the future. Hence, much of the topics discussed next are still in a very premature phase, but I believe that they will gain importance in the future. I therefore hope that – by explicitly mentioning such a list of possible new directions – researchers will be stimulated to spend their attention on these (or similar) topics. Three topics will be discussed sequentially in the next sections: the presence of *project data*, the incorporation of *flexibility* and the on-going need for *integration*.

3.1 Project data

Ever since the development of algorithms for a wide variety of project planning problems, researchers relied on project data to validate the performance of the procedures. These project data consists of project networks generated by a network generator, extended with resource data to model the resource demand and availability. The majority of these project data are generated under a well-defined generation process. Indeed, through the use of a careful design, a project data set can be constructed that incorporates a wide and diverse set of different project parameters to assure that new methodologies can be tested for various project settings. This approach is inspired by the recommendations of Elmaghraby and Herroelen (1980), who drew attention to the need for project data sets that span the full range of problem complexity. To that purpose, different network and resource metrics have been proposed to describe the characteristics of projects, and most data generators rely on a set of these metrics to control their generation process.

Some researchers have used these generators to present a data set to the literature that can be used as a benchmark set for research. The most well-known set is the PSPLIB set (Kolisch and Sprecher, 1996) which is used widely in the literature, and has become the dominant set to test and validate new solution procedures. The projects in this data set can be used both for solving the single-mode RCPSP (each activity has exactly one time/resource combination) and the multi-mode RCPSP (each activity has multiple possible time/resource combinations). More recently, Van Peteghem and Vanhoucke (2014) have proposed an alternative set, known as the MMLIB set, for the multi-mode RCPSP. Apart from these two sets, other data sets are available in the literature which will not be mentioned here. A summary of the most well-known network and resource metrics, the existing project data generators and the most widely used data sets in literature would lead us too far in the current manuscript. A summary is given in the paper written by Vanhoucke et al. (2016). Despite these efforts done in the academic literature to generate, classify and structure project data, I believe additional research is necessary to further tighten the gap between academic research and practical needs, which are outlined along the following sections.

3.1.1 Empirical data

The reader has noticed that the previous work done on project data are mainly restricted to artificial project data. To have project data available, researchers should ideally rely on a well-considered and balanced view between theoretical artificial project data and empirical real project data. In a paper in the Measurable News (Vanhoucke, 2016), I highlighted that the main focus of research should be on artificial project data based on a controlled and full-factorial design. In doing so, the researchers have full control over the project parameters in order to obtain and present general results that are applicable in a wide variety of projects. This allows researchers to test any research hypothesis without being dependent of business. But that does not mean that real empirical data are superfluous. After performing the studies on artificial data, the obtained results should be translated into practical guidelines and rules-of-thumb that differ from project to project, company to company and sector to sector. For that purpose, researchers need empirical project data. Despite the overwhelming amount of artificial data, not much empirical data are available in the academic literature. To the best of my knowledge, only Batselier and Vanhoucke (2015) have presented a formal framework to collect and analyze empirical project data that is publicly available. They present a so-called project cards approach and propose new metrics to measure the authenticity of the project data. The authors conclude that the database could become the basis for many future studies related to project management, and suggest a few future research avenues. As a co-author of this paper, I support this claim and call upon the researchers not only to use the database, but also to continuously extend it with richer and more practical features relevant to the project management discipline.

3.1.2 Artificial and empirical data

While no-one will disagree that academic research should be done to meet the needs and solve the problems of practice, it is surprising that not many research papers bring this mission in reality when it comes to project data. A notable exception is the research initiated by Trietsch et al. (2012) who present a framework for analyzing empirical data using a statistical stepwise procedure. This calibration procedure aims at analyzing the real activity durations of the project, and compares them with the planned duration in a sequence of hypothesis tests, in order to find out whether activity times can be modeled by the Parkinson distribution with a lognormal core. The ultimate goal is to cluster activities in groups and to define distributions on their durations that reflect real activity distributions, such that researchers can then rely on Monte Carlo simulation studies that make use of real activity distribution inputs. Colin and Vanhoucke (2015) were the first to apply the procedure on a set of 24 empirical projects from the previously mentioned empirical database, and give some examples of the relevance of such an analysis for future project management studies. I conjecture that this procedure (and its possible extensions that hopefully appear soon in the academic literature) will contribute to the narrowing gap between research studies and practical needs. In a world where big data and fast and complex algorithms (using machine learning, artificial intelligence, ...) become the standard, the data should more and more fit into the real needs of business. This procedure connects the two worlds, and helps researchers using distributions based on observed data instead of (known) statistical functions. I believe that with the increasing availability of data, more advanced methodologies will find their way into the project management research theme. As an example, my research group has investigated whether machine learning algorithms can be used for improving the accuracy of project control methods (Wauters and Vanhoucke, 2014, 2016, 2017). Promising results could be reported which – hopefully – will inspire future researchers to enrich other project management and scheduling methods with big data features. The increased availability of data availability and the upcoming use of machine learning/artificial intelligence procedures will probably stimulate the creation of hybrid methods. Such hybrid tools should combine the advantages of intelligent data-driven tools with the classical mathematical programming optimisation engines in order to solve challenging and realistic project scheduling problems. For a glimpse of the recent work done by various authors in the field of project scheduling, the reader is referred to the summary books of Schwindt and Zimmermann (2015a,b)

3.1.3 Project portfolio data

A portfolio is not merely a collection of projects, but has unique features such as shared resources and dynamic arrivals. It has been discussed before that the single-project algorithms should not be simply extended for solving project portfolio scheduling problems, and this is also the case for the presence of data. Despite the overwhelming availability of data for single projects, not much effort is done for generating or collecting project portfolio data. To the best of my knowledge, only Browning and Yassine (2010) have presented a random project data generator for the resource-constrained multi-project scheduling problem. While their generation process makes use of complexity indicators similar to the single-project network generators, they have extended it with two important characteristics of the RCMPSP, the longitudinal distribution or loading of resource requirements across the problem duration (measured by the normalized average resource loading factor (NARL)) and the degree of contention for various resource types (measured by the modified average utilization factor (MAUF)).

This generator is a necessary first step in the creation of data for the multi-project planning, and will hopefully stimulate researchers to adapt their algorithms to multi-project planning problems. The authors of the paper conclude that the generation of data for the RCMPSP and solution procedures to solve this challenging problem is an area for continued research. They particularly mention that it would be interesting to see which of the multi-project problem characteristics and summary measures are best able to predict the computational effort required by solution procedures. This has been the research topic for decades, focusing on single project environments, and I agree with the authors' conclusion that the time is right to extend this challenging search – supported by artificial (and empirical) data – to portfolios of projects.

3.2 Adding flexibility

In Section 2.1, various activity, network and resource generalisations have been discussed that are currently under investigation in the academic literature to enrich the academic problems with realistic features. Tomorrow's research should continue enriching theoretical problems with practical features, and I believe that priority should be given to adding *flexibility* in the problem formulations. Of course, the concept of flexibility could be interpret in various ways, and will steer the research into different directions, but it is used here to refer to ways of providing solutions to the scheduling problems that are less case-specific and can be used under various settings and assumptions. In doing so, the project manager who makes use of the constructed schedule can rely on one and the same schedule under different circumstances. A number of examples are given along the following lines, in which a difference is made between the flexibility of the project schedule (schedule flexibility) and flexibility in the solution procedure used to construct this schedule (algorithmic flexibility).

3.2.1 Schedule flexibility

In line with Section 2.1, examples of adding flexibility to the project schedule can be subdivided into flexibility to the activities, the network and the resources of the project. This section will only highlight some recent illustrations of adding flexibility and many more examples could have been used to illustrate the need for extra flexibility.

A good example of adding *activity flexibility* is the study on continuous preemption problems by Schwindt and Paetz (2015) in which the authors study the project scheduling problem under continuous (rather than discrete) preemption and flexible resource allocation. Shifting from a discrete to continuous preemptive mode undoubtedly opens doors for adding more flexible ways of activity splitting in the schedule, and should receive attention in the future research.

Adding *network flexibility* to the project has been investigated in various ways. Among others, Capek et al. (2012) have incorporated alternative process plans in the RCPSP that differ in terms of activity, precedence and resource characteristics and define a problem formulation that selects only a subset of activities to construct a schedule. Kellenbrink and Helber (2015) investigate the so-called *resource-constrained project scheduling problem with a flexible project structure* (RCPSP-PS) and introduce concepts such as mandatory and optional choices, optional activities and dependent activities. Using these concepts, they introduce an extension of the RCPSP with model-endogenous decisions on the project structure to substantially increase the power and flexibility of modeling real-world resource-constrained project scheduling projects. Servranckx and Vanhoucke (2017) have summarized the literature on network flexibility and have presented a formal problem description as *the resource-constrained project scheduling problem with alternative subgraphs* (RCPSP-AS). The paper introduces several types of alternative subgraphs in the project network for which only a subset must be selected for constructing a resource-feasible baseline schedule. The authors make a distinction between nested and linked subgraphs and present a fast and easy tabu search algorithm to optimise the project makespan using the best possible selection of each subgraph.

It has been mentioned earlier that *resource flexibility* has been incorporated in the resource-constrained project scheduling problem literature in various ways by defining new types of resources. From the known extensions such as the introduction of partially renewable resources and cumulative resources, I believe that the shift of focus from discrete to continuous resource allocation models is the most promising one to add flexibility of resources into the project schedule. The continuous resource models have been introduced decades ago in book chapters such as Weglarz (1981) and Józefowska et al. (1999). Since then, different papers have been written (cf. the recent paper by Waligóra (2011), who presents heuristic approaches to discrete-continuous project scheduling problems to minimize the makespan), but little effort has been done by other researchers (than the ones mentioned) to incorporate these continuous resources in their models and combine them with other types of flexibility (such as the ones mentioned earlier in this paragraph). Integrating various types of flexibility should be put on the research agenda to detect possible trade-offs in flexibility parameters and develop generic procedures to solve problems using different types of flexibility parameters.

Apart from adding flexibility to the components of a project (activities, network and resources), Burgelman and

Vanhoucke (2017) have extended the concept of flexibility to *schedule flexibility* by defining the so-called *project scheduling problem with multiple execution alternatives* (RCPSP-MA). In this problem formulation, multiple modes exist for the project activities for which traditionally exactly one mode must be selected to enter the schedule. However, the authors aim at maximising the number of modes in the constructed baseline schedule such that the project manager can – once the project is in progress – easily select those modes that are most relevant at the certain moment in time without disrupting the remaining activities of the schedule.

These previously mentioned (and other non-mentioned) extensions of the classic RCPSP show that allowing flexibility in the project results in a wide variety of extensions that increase the realism of the resulting schedule. While it should be noted that care must be taken not to merely construct new solution approaches (that often do not differ much from each other) for these new problem formulations, I believe that this research path is promising and can lead to more interesting insights and results, and should therefore be explored further in the future.

3.2.2 Algorithmic flexibility

In the last two decades, numerous solution procedures have been presented, ranging from easy and fast heuristic priority rules to efficient meta-heuristic solution procedures and complex exact algorithms. Each procedure is often finetuned to the specific assumptions of the problem formulation, and solves the problem to (near-) optimality only under this strict set of assumptions. Hence, these solution procedures are good in creating insights into the characteristics of the problem under study, but often are by no means flexible (i.e., able to solve problem instances that are only a little bit different than the original problem definition). I believe that future research should search for more general solution procedures that are not only able to solve large real-life instances to near-optimality in a reasonable time, but that can also be used to solve a range of problem instances, each time containing a set of identical assumptions, but allowing to vary some of these assumptions to a certain degree.

I will illustrate this by using an example from my own research (Coelho and Vanhoucke, 2011). When I was working with my co-author on the well-known multi-mode resource-constrained project scheduling problem (MRCPSP), we aimed at presenting a general solution procedure that could solve this, and other related problems, at least as good as the specific algorithms from literature. Typically, most procedures in the literature solve this MRCPSP in two separate runs, using two priority lists to model the activity start times and the selected modes for each activity. However, our new solution procedure could solve the two sub-problems (the mode selection step and the activity scheduling step) in an integrated procedure – consisting of a meta-heuristic search procedure to construct a schedule and a boolean satisfiability (SAT) problem solver to select the activity modes – using only one priority list. In my opinion, the most important contribution of this paper was not that only one priority list was necessary instead of the two to simultaneously solve the two sub-problems of the MRCPSP, but the observation that this approach allowed us to solve many other, closely related problems without changing the procedure. It has been shown in the paper that e.g. *mode identity constraints* (Salewski et al., 1997) that force activities belonging to the same subset to be processed in the same mode can be easily incorporated in the solution procedure without any need for change. Other extensions such as the incorporation of *logical constraints* (Vanhoucke and Coelho, 2016) and *activity preemption with setup times* (Vanhoucke and Coelho, 2018a) have been proposed and solved using one and the same solution procedure.

I believe that a quest to these general solution approaches should receive research attention, not only because it will stop the development of an overwhelming amount of very case-specific procedures that often do not add much value compared to the already existing solutions procedures, but certainly because this is what practice needs the most: general solution procedures that perform well on a wide set of similar problem formulations.

3.3 Further integration

Academic research is the act of exploring new problems and developing new solutions for well-defined problems under specific assumptions. Also in the research of project scheduling, the assumptions define the problem statement, and the solution procedures are often very case-specific algorithms that can solve the problem under study under these strict assumptions. The ultimate idea is that these small contributions (each publication solves one particular problem) one day can be integrated into an integrated solution approach, enabling to solve bigger, more realistic (i.e., with less assumptions) problems. At least, this should be the dream of any researcher. So, the integration of solution procedures and the relaxation of assumptions should have a high priority on the research agenda, and should therefore be part of the future research endeavors. In line with this remark, another promising research direction could be the comparison of the currently existing project scheduling software tools available on the market. These tools mostly rely on fast and efficient, hence generic scheduling algorithms that perform relatively well under a wide set of assumptions. However, little effort has been done to compare the underlying algorithms in terms of scheduling quality, and most comparisons are written down in white papers that focus on user-specific features such as ease of use, integration capabilities, and the ability to create rich project dashboards. A more profound study of the quality of the underlying algorithms of these software tools (to be published in peer-reviewed academic journals) would undoubtedly stimulate researchers to develop high-quality, yet rather generic algorithms, that could be – just maybe – incorporated in these tools. If the reader does not know what I am talking about, I refer to two old, and therefore outdated but nevertheless interesting, articles written by De Wit and Herroelen (1990) and Kolisch (1999).

It has been mentioned earlier in Section 2.2 that the construction of the baseline schedule should be and has been investigated in the light of the complete project life cycle, and the objectives of different phases should be merged with the objectives used during scheduling. I believe that a further stepwise integration should be on the research agenda, consecutively incorporating more and more data-driven objectives taken from different phases of the project life cycle. Hence, the integration should not be limited to the integration of schedule risk analysis and project control objectives, as discussed earlier, but should be extended to e.g. communication metrics (based on e.g. the work of (Phillips, 2014)), or objectives that typify project portfolios but not single projects. Moreover, an integration between the contracting phase (a phase that is done prior to the scheduling phase) and the project scheduling phase would allow the project manager to better align the project objectives to the stipulated agreement between contractor and owner (Kerkhove and Vanhoucke, 2017). Finally, Willems and Vanhoucke (2015) also mention the need for research on objectives beyond the classic time and cost objectives, and mention sustainability and quality as typical examples. While this list can be extended with many other features, a fact is that a lot of work has been done on optimising these and other objectives for project scheduling, but most of these efforts have been carried out in isolation, without taking a project life cycle point-of-view. I believe that the future research should focus more on the integration of extended objectives into the project schedule to enable the researchers to measure, understand and improve the impact of the quality of the baseline schedule on the later phases of the project life cycle.

4 Yesterday's challenge

The current research challenges (today's challenges) as well as the new promising directions (tomorrow's challenges) discussed in the previous sections constitute research topics for which lots of results are already available in the literature and for which it is very likely that much more will become available in the near future. However, one should not forget the research done in the past. Some of the research topics are undoubtedly outdated and no longer deserve any attention, but other topics are still very relevant, and are – after decades of research – still challenging and important for the future of the scheduling field. One of these topics is the development of exact algorithms for challenging problems such as the resource-constrained project scheduling problem. In the past, researchers have focused very much on the development of exact algorithms to solve the RCPSP and its extensions, using branch-and-bound procedures or one of their extensions. More recently, the research attention has shifted from exact algorithms to meta-heuristic procedures to solve large-sized instances to near-optimality. While this trend is interesting and promising and helps creating more and better algorithms that solve these large and real instances relatively good, care must be taken while drawing conclusions when relying on these heuristic procedures. Comparing solutions to create understanding of the impact of certain problem parameters is hard and could be biased by the sub-optimality of the solution. More specifically, the observed impact of a certain project parameter on the solution quality can be a real impact, but it can also be that the obtained results are due to the fact that the solutions are not optimal (and therefore, different solutions have a different quality, which makes them hard to compare). In this case, it means that the observations cannot be generalized at all. Exact algorithms do not suffer from this bias since solutions are always optimal, and comparisons between solutions are therefore true and not depending on the quality of the solution procedure. Hence, exact algorithms still deserve research attention and should be put back on the research agenda. But here is where the shoe pinches: the exact algorithms we know today are still not able to solve large instances.

In a recent research study by Vanhoucke and Coelho (2018b) and Coelho and Vanhoucke (2018), it has been shown that the integration of the best components available in the literature in a combined branch-and-bound procedure could not solve many more instances compared to the solutions that could be obtained more than a decade ago. Even though all computational experiments in this research study have been carried out on the Stevin Supercomputer Infrastructure at Ghent University (Belgium), which is much faster than the single core computers used during the introduction of most of the branch-and-bound procedures to solve the RCPSP, the unbelievable increase in computer speed over this decade could not lead to an equally impressive improvement in results for these computational tests. The integrated branch-and-bound procedure used in the experiments integrated all of the currently best-performing components into a single procedure, carefully optimising the branching scheme, the search tree, and the use of the dominance rules. It is without any doubt that this procedure should be able to solve a lot of project instances to optimality, at least many more than what was possible a decade ago when computers were much slower and algorithms did not integrate the best performing components. However, the research study showed that the number of instances that could be solved to optimality was more or less the same, with only a few instances solved to optimality for which no solutions were known so far. Moreover, the experiments have shown that even small-sized projects (with only 30 activities) that were thought to be easy to solve are sometimes still unsolvable under certain conditions (like a parallel network structure or under specific resource constraints).

The fact that this integrated algorithm and the super-fast computer are still not able to solve large real project instances means that the research on exact algorithms for the RCPSP is on a dead end, and totally different approaches will be necessary to find a significant breakthrough rather than marginal improvements. Consequently, it seems that yesterday's challenge (solving project instances to optimality) might be the most important challenge for tomorrow. More specifically, the challenge will not be to solve the bigger problems with the same (somewhat modified) tools as used before, but the creation of a totally different and completely new approach in order to solve the same – currently unsolved – project problems to optimality. Such an approach will significantly improve the current algorithms and will create additional insights into the complexity of resource-constrained project scheduling, which is equally (or even more) important than merely solving bigger problems to near-optimality.

5 Conclusions

This paper aimed at describing some interesting research avenues in resource-constrained project scheduling and highlights some challenges for future research. The paper is split up in three parts. Some of today's research challenges are described as research paths that have received considerable attention, and from which the author believes that they should and will receive more attention in the near future. Tomorrow's challenges can be considered as avenues for research that haven't been explored much, or for which the full potential has not been reached. Finally, yesterday's challenge is mentioned as a research path that – despite the fact that it has been investigated widely in the past – still holds a lot of promise for the future.

As I have mentioned at the beginning of the article, this paper is not a summary of the existing state-of-the-art literature, nor is it intended to give a full overview of the existing problem formulations for resource-constrained project scheduling. Instead, the paper serves as a personal view on the research domain, and a reflection of how my own and other's research papers have influenced my own research agenda, and how I believe it will or should influence the research agenda of tomorrow. Hence, this overview is heavily influenced and biased by my own research papers which – when mentioned – were the main inspiration for writing this paper.

Describing research challenges for future research can be – and I hope will be – considered as a kind of good advice to future young researchers in the field of project scheduling. Not only the mentioned topics can hopefully inspire them to start a research career in this wonderful domain, but I hope it will also stimulate them to look beyond the literature and the algorithms available for scheduling. I personally can state that I learned the most by teaching and talking to professionals, coming from different sectors and different cultures (I tried to explain this acquaintance with other cultures in my book Vanhoucke (2017)), and I used the literature mostly to find out whether the problems raised by these professionals had been investigated yet. Hence, I believe that the research should be inspired by integrating academic knowledge (the literature) with professional needs (the practice), in which practice is the trigger for problem formulations and literature the source for finding existing and developing new algorithms to enhance our understanding in this challenging research domain. To me, it has been so far a wonderful journey in the academic world and the real world, and many researchers and professionals have inspired me in more ways I can ever tell. It has recently resulted in my first business novel (which – in my opinion – holds the middle between scientific content and practical relevance) (Vanhoucke, 2018) and I am convinced I will be further inspired by many more researchers/professionals in the future. I therefore hope that my personal and somewhat biased description of the past, present and future challenges can also contribute to the inspiration of the readers of this article such that they help bridging the gap between project management research and practice.

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