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Invited Review

An updated survey of variants and extensions of the resource-constrained project scheduling problem[☆]

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A B S T R A C T

The resource-constrained project scheduling problem is to schedule activities subject to precedence and resource constraints such that the makespan is minimized. It has become a standard problem in the context of project scheduling which has attracted numerous researchers who developed both exact and heuristic scheduling procedures. However, it is a rather stylized model with assumptions that are too narrow to capture many real world requirements. Consequently, various extensions of the basic resource-constrained project scheduling problem have been developed. This paper builds on an overview which was published 10 years ago. Due to the unabated interest in the scientific community since it has been published the overview at hand delivers an update focussing on the last decade. The problem extensions are classified according to the structure of the resource-constrained project scheduling problem. We summarize generalizations of the activity concept, of the precedence relations, and of the resource constraints. Alternative objectives and approaches for scheduling multiple projects are discussed as well.

1. Introduction

Project scheduling is an integral part of project management. Typically, activities depend on each other in at least two ways. First, they compete for scarce resources that are required to conduct activities. Second, precedence constraints between pairs of activities call for each such pair to be conducted in a predetermined order. A well-known formalized problem setting covering these two interdependencies is the resource-constrained project scheduling problem (RCPSP) which has become a standard problem for project scheduling in the literature.

The input to the RCPSP can be summarized as follows. We consider a project with J activities which are labeled $j = 1, \ldots, J$. The processing time (or duration) of an activity j is denoted as p_j. Once started, an activity may not be interrupted, i.e., preemption is not allowed. Due to technological requirements, there are precedence relations between some of the activities. They are given by sets of immediate predecessors P_j indicating that an activity j may not be started before each of its predecessors in P_j is completed. We have K renewable resources labeled $k = 1, \ldots, K$. For each resource k the per-period availability is assumed to be constant over time, it is given by R_k. Each activity j requires r_{jk} units of resource k in each period it is in process. We consider two additional activities $j = 0$ and $j = J + 1$ representing the start and the completion of the project, respectively. Both are "dummy" activities with durations of 0 and no resource requests. All information is assumed to be deterministic and known in advance. The parameters are assumed to be non-negative and integer valued.

A schedule is an assignment of a non-negative start time S_j to each activity $j = 0, 1, \ldots, J + 1$. The objective of the RCPSP is to find a schedule which leads to the earliest possible end of the project, i.e., the completion time of activity $J + 1$. The completion time of the project in a schedule is referred to as the schedule's makespan. Blazewicz, Lenstra, and Rinnooy Kan (1983) have shown that the RCPSP belongs to the class of the strongly NP-hard problems. A mathematical model representing the RCPSP has been developed by Pritsker, Watters, and Wolfe (1969).

While the RCPSP as given above is already a powerful model, it cannot cover all situations that occur in practice. Therefore, many researchers have developed more general project scheduling problems, often using the standard RCPSP as a starting point. Since the 1990s, several survey papers on project scheduling have been published. Most of those papers focus on methods for the stan-

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dard RCPSP (see Hartmann and Kolisch (2000); Kolisch and Hartmann (1999, 2006); Pellerin, Perrier, and Berthaut (2020)) and the main variants (see Brucker (2002), Brucker, Drexl, Möhring, Neumann, and Pesch (1999), Herroelen, de Reyck, and Demeulemeester (1998), Herroelen (2005), Kolisch and Padman (2001), Özdamar and Ulusoy (1995), and Tavares (2002)). The books of Schwindt and Zimmermann (2015a,b) contain more than 60 papers covering many important models and methods for project scheduling. Hartmann and Briskorn (2010) provide a broad overview over variants and extensions of the RCPSP that have been proposed in the literature.

The aim of the paper at hand is to provide an update to Hartmann and Briskorn (2010) focussing on the most recent decade, that is, after Hartmann and Briskorn (2010) has been published. As in Hartmann and Briskorn (2010), we restrict ourselves to an overview of problem variants and models rather than of methods and algorithms and refer to the above mentioned surveys instead. Furthermore, we focus on deterministic approaches (for an introduction to stochastic problems, the reader is referred to Neumann (1990) and Herroelen and Leus (2005)). In order to keep Hartmann and Briskorn (2010) and the paper at hand as consistent as possible we take up notation and structure from Hartmann and Briskorn (2010) wherever possible.

The outline of the paper, hence, is as follows. Section 2 lists generalizations of the activity concept. Alternative precedence constraints and network characteristics are summarized in Section 3. Section 4 gives extensions of the resource concept. Different objectives are outlined in Section 5. Section 6 deals with the simultaneous consideration of multiple projects. Finally, Section 7 provides a summary of how the focus of research has been shifted in the last decade as compared to those before.

2. Generalized activity concepts

2.1. Preemptive scheduling

The basic RCPSP requires each activity to be processed non-preemptively, that is, once it is started, it cannot be interrupted but must be processed continuously until it is completed. Moukrim, Quilliot, and Toussaint (2015) deal with the preemptive version of the RCPSP where activities may be interrupted without any restriction. Shou, Li, and Lai (2015) allow for at most one interruption of each activity, and interruptions are restricted to integer points in time. Afshar-Nadjafi and Majlesi (2014) and Vanhoucke and Coelho (2019) permit multiple interruptions at integer points, and they take setup times into account when resuming interrupted activities, see Section 2.3. Zhu, Li, and Shen (2011) permit each activity to be interrupted at most M times. Quintanilla, Lino, Pérez, Ballestín, and Valls (2015) deal with a more general variant where the number of allowed interruptions depends on the activity and there is a minimum duration of each part of an activity.

Kreter, Rieck, and Zimmermann (2016); Kreter, Schutt, and Stuckey (2015) apply the calendar concept that allows a subset of activities to be interrupted due to weekends or holidays. Activities have a start-up phase during which interruption is not allowed. The calendar concept is embedded into an RCPSP with minimal and maximal time-lags (see Section 3.1). A variant of this setting with the objective to minimize the resource availability costs is presented in Kreter, Schutt, Stuckey, and Zimmermann (2018), see also Section 5.4.

Dhib, Soukhal, and Néron (2015) allow activities to be interrupted at integer points in time and consider resources with multiple skills, see also Section 4.3. Afshar-Nadjafi (2018), Turkgenci, Guden, and Gülsen (2020), and Van Peteghem and Vanhoucke (2010) discuss preemptive scheduling within a multi-mode setting, see also Section 2.4. Cheng, Fowler, Kempf, and Mason (2015) allow for activity splitting due to temporary resource unavailability (but not for general preemption) within a multi-mode setting with release times and deadlines for activities, see also Section 3.2. Schwindt and Paetz (2015) consider a problem which generalizes the preemptive RCPSP with respect to precedence constraints and objective function.

2.2. Resource requests varying with time

In the standard RCPSP, activity j requires a constant amount r_{jk} of resource k, that is, the resource requirement does not change during the processing time. Hartmann (2013, 2015) discusses the case that the resource requests vary over time, that is, activity j requires r_{jkt} units of resource k in the t-th period of its processing time. Zimmermann and Trautmann (2018) show how this concept can be used in order to model scheduling problems arising for assessment centers. They interpret the scheduling of candidates performing tasks as an MRCPSP with a single resource, resource requests varying with time, and mode assignment constraints, see Section 2.4. Hosseinian, Baradaran, and Bashiri (2019) consider time-dependent resource requests within a problem setting that includes multiple skills, see Section 4.3.

In the above papers, an activity's resource requests may change from period to period, but for each period the request is fixed. A more flexible approach can be taken by assuming that only the total request w_{jr} of activity j for resource r is given. The per-period requests are determined by the schedule. When the activity is finished, the total request must be met. This is often referred to as *flexible resource profile*. Further typical constraints are that the processing time and the requested amount per period must be between a lower and upper limit, respectively. After a change, it must remain constant for a certain number of periods before it can change again (this is referred to as minimum block length).

Naber and Kolisch (2014) and Tritschler, Naber, and Kolisch (2017) present models with flexible resource profiles that are motivated by real-world pharmaceutical research projects. They assume that some resources are so-called principal resources (an activity can require only one principal resource). An activity's request for a so-called dependent resource depends on its request for the principal resource in the same period (a linear relationship is assumed). This synchronizes an activity's requests for different resources over time. There are also independent resources for which the resource request does not depend on other resources. Naber (2017) suggests a version of this model with continuous time.

Fündeling and Trautmann (2010) and Baumann, Fündeling, and Trautmann (2015) consider flexible resource profiles as well. In their approach, a single work content resource is given for the project. A work content resource is similar to a principal resource described above. The remaining resources can be viewed as dependent resources.

Bianco and Caramia (2011a) and Bianco, Caramia, and Giordani (2016, 2017) employ another variant of flexible resource profiles in which it is decided in each period what fraction of the workload of an activity is carried out in each period. This is referred to as variable execution intensity here. There is no minimum block length, and there are no specific principal or work content resources. Bianco and Caramia (2011a) join this approach with feeding precedence constraints (see Section 3.3). Bianco et al. (2016, 2017) consider resource leveling problems (see Section 5.6) with variable execution intensity as well as minimal and maximal time lags (see Section 3.1).

2.3. Setup times

Hanzalek and Sucha (2017) assume that sequence-dependent setup times apply to units of resources and distinguish between different units of capacity of each resource. If two activities i and j occupy the same unit of resource consecutively, then between completion of i and start of j this unit undergoes a setup which requires $ST_{i,j}$ periods.

A variant of this concept is a setup time ST_{ijk} that must be taken into account if a resource k has to be transported from the location of activity i to that of activity j. Resource k is not available during transport. This type of setup time is also referred to as transfer time. Quilliot and Toussaint (2012), Poppenborg and Knust (2016a), and Kadri and Boctor (2018) tackle the RCPSP with transfer times (RCPSP-TT). Adhau, Mittal, and Mittal (2013) incorporate resource transfer times into a multi-project model, see Section 6.

Laurent, Deroussi, Grangeon, and Norre (2017) employ setup times reflecting transportation of resources and semi-finished products. Setup times for product transfer occur if precedence-related activities are assigned to different locations.

Okubo et al. (2015) applies sequence-dependent setup times in a problem setting with multiple modes (see Section 2.4). The setup times also depend on the selected modes of the related activities. Moreover, resources are used during the setup time. This is embedded into a rather complex multi-project model which is described in more detail in Section 6.4.

Afshar-Nadjafi and Majlesi (2014) consider a setup time ST_i when restarting an interrupted activity i. The resource request of an activity is the same during the setup time. Vanhoucke and Coelho (2019) extend this approach by adding setup times depending on the activity's duration, on the activity's workload that is already finished, and on the workload that is still remaining.

2.4. Multiple modes

A well-known generalization of the standard RCPSP is the *multi-mode RCPSP* (MRCPSP). Each activity can be associated with several modes, that is, different ways to accomplish the activity. This facilitates, for example, the use of different resource types or the use of more resources to shorten the duration. In its most common form, the MRCPSP includes a second resource category, namely nonrenewable resources which are limited for the entire project rather than on a per-period basis (see also Section 4.1). An in-depth survey of the MRCPSP that also includes various extensions and closely related problems is provided by Węglarz, Józefowska, Mika, and Waligóra (2011).

The standard MRCPSP is tackled by Chakrabortty, Abbasi, and Ryan (2020a); Chakrabortty, Sarker, and Essam (2014); Coelho and Vanhoucke (2011, 2015); Elloumi and Fortemps (2010); Fernandes Muritiba, Rodrigues, and Araùjo da Costa (2018); Gnägi, Rihm, Zimmermann, and Trautmann (2019); Jedrzejowicz and Ratajczak-Ropel (2015); Li and Zhang (2013); Messelis and De Causmaecker (2014); Okada et al. (2014); Schnell and Hartl (2017); Stürck and Gerhards (2018); Van Peteghem and Vanhoucke (2011, 2014); Vanhoucke and Coelho (2018); Wang and Fang (2011, 2012); Wauters, Verbeeck, Vanden Berghe, and De Causmaecker (2011), and Zamani (2019).

Many researchers combine multiple modes with other variants or extensions. Jedrzejowicz and Skakovski (2010), Ballestín, Barrios, and Valls (2013), and Schnell and Hartl (2016) consider the MRCPSP with minimum and maximum time lags, see Section 3.1. Maghsoudlou, Afshar-Nadjafi, and Niaki (2016) add multiple skills of the resources (see Section 4.3) to the MRCPSP but do not include nonrenewable resources. Afshar-Nadjafi (2014), Colak and Azizoglu (2014), Coughlan, Lübbecke, and Schulz (2015), and Qi, Liu, Jiang, and Guo (2015) discuss multi-mode settings with resource investment objective, see Section 5.4.

Van Peteghem and Vanhoucke (2010) take both the standard MRCPSP and the preemptive MRCPSP into account. Afshar-Nadjafi (2018) and Turkgenci et al. (2020) discuss a preemptive variant of the MRCPSP in which a mode change is allowed when resuming an interrupted activity. Cheng et al. (2015) consider an MRCPSP with release dates and deadlines in which activity splitting due to temporary resource unavailability is allowed.

Li and Womer (2012) present an MRCPSP for make-to-order production that includes deadlines as well as a cost-based objective, see Section 5.7. Zoraghi, Shahsavar, Abbasi, and Van Peteghem (2017a) tackle the MRCPSP with lot-sizing aspects and various financial objectives. Toffolo, Santos, Carvalho, and Soares (2016) focus on a multi-project problem (see Section 6) with multiple modes, balancing the total completion of projects and the overall makespan.

Rahimi, Karimi, and Afshar-Nadjafi (2013) consider the MRCPSP with mode identity constraints where several activities must be performed in the same mode. For example, this can be used to force a set of activities to make use of the same resources. Afruzi, Najafi, Roghanian, and Mazinani (2014) deal with a variant of the MRCPSP with mode identity constraints. They add the possibility to crash (i.e., shorten) an activity (it should be noted, however, that for each original mode of an activity two modes could be defined, one with the original duration and one with the crashed duration). Moreover, each mode is associated with costs and a quality level. The objectives are to minimize the makespan, to minimize the total cost, and to maximize the quality.

García-Nieves, Ponz-Tienda, Salcedo-Bernal, and Pellicer (2018) and García-Nieves, Ponz-Tienda, Ospina-Alvarado, and Bonilla-Palacios (2019) propose a multi-mode setting in which activities are divided into sub-activities. The sub-activities of an activity capture the repetitive execution of the activity. Mode changes between sub-activities are allowed but limited, and there are minimal time lags between sub-activities, see Section 3.1.

Chakrabortty, Sarker, and Essam (2016) discuss an MRCPSP where rescheduling must be done after a resource disruption (e.g., breakdown of a machine). Activities in progress when the disruption occurred can either be resumed or must be restarted after a repair time. Activities may not be started earlier than planned in the original schedule. Elloumi, Fortemps, and Loukil (2017) consider rescheduling for the MRCPSP as well, but they also take schedule stability into account as additional objective, see Section 5.3.

Bartels, Gather, and Zimmermann (2011) represent the problem to schedule dismantling activities as an MRCPSP with cumulative resources, see Section 4.2. Poppenborg and Knust (2016b) model evacuation of hospitals as MRCPSP with blocking constraints on resources.

Leyman and Vanhoucke (2016) tackle an MRCPSP with net present value objective and different payment types, see Section 5.8. Tirkolaee, Goli, Hematian, Sangaiah, and Han (2019) consider an MRCPSP where in addition to scheduling activities payments have to be planned. They consider two objectives, namely maximization of net present value and minimization of makespan, see Section 5.9.

Qi et al. (2015) propose a generalization of the resource investment problem, see Section 5.4, where activities can be conducted in one of multiple modes. Gerhards and Stürck (2018) tackle a slightly more general problem where instead of accounting for a hard project deadline tardiness cost are charged if the project misses its due date.

2.5. Trade-off problems

The *discrete time-cost trade-off problem* (DTCTP) is a special case of the MRCPSP. One nonrenewable resource is given which represents a budget for activity costs. There are no renewable resources. Usually the standard precedence constraints are given. The objective is to minimize the makespan. This setting is considered by Hazır, Haouari, and Erel (2010).

In the deadline variant of the DTCTP, the project duration is limited by a deadline constraint (see Section 3.2) while the usual objective is to minimize costs. Hazır, Erel, and Günalay (2011) and Hazır, Haouari, and Erel (2015) study the deadline version of the DTCTP with an objective that also takes robustness with respect to project cost into account, see Section 5.2. Szmerekovsky and Venkateshan (2012) tackle the deadline variant with generalized precedence relations (see Section 3.1) and a payment maximization objective (rather than cost minimization). Leyman, Van Driessche, Vanhoucke, and De Causmaecker (2019) consider a DTCTP with deadline and net present value maximization, see Section 5.8.

The DTCTP is extended to a time-cost-quality trade-off problem by Khalili-Damghani, Tavana, Abtahi, and Santos Arteaga (2015). Three objectives are considered. They include the minimization of both makespan and cost and the maximization of quality. In addition, constraints for time, cost and quality are given as well. Also, generalized precedence relations are taken into account, see Section 3.1.

The *discrete time-resource trade-off problem* (DTRTP) is a similar special case of the MRCPSP. Here we have a single renewable resource only (and no nonrenewable resources). Again, the usual precedence constraints are given. Van Peteghem and Vanhoucke (2015b) study the DTRTP where the activity durations are adapted based on learning effects and thus increasing efficiency.

A few authors consider the DTRTP with a deadline. Colak and Azizoglu (2014) tackle a variant with resource investment objective, see Section 5.4. Van Den Eeckhout, Maenhout, and Vanhoucke (2019) deal with a variant in which manpower is the only renewable resource. Several staff-related constraints such as minimum and maximum consecutive working days are added. The objective is to minimize total staff costs.

2.6. Further activity concepts

The special case of activities with processing times of zero is often referred to as events. Note that an event is processed in a single instant of time. Sahli, Carlier, and Moukrim (2016) and Carlier, Moukrim, and Sahli (2018) consider an event scheduling problem, that is, all activities are events. They additionally take minimal and maximal time lags (cf. Section 3.1) and cumulative resources (cf. Section 4.2) into account.

3. Generalized temporal constraints

3.1. Minimal and maximal time lags

The standard RCPSP includes the requirement that an activity does not start before its predecessor is finished. This can be extended by allowing minimal time lags between between the start and the start time, between start and finish time, between finish and start time, and between finish and finish time of any two precedence-related activities (each of these types can be transformed into each other type since processing times of activities are given). Analogously, maximal time lags can be added.

The model that is obtained from including minimal and maximal time lags into the RCPSP is often referred to as RCPSP with generalized precedence relations or as RCPSP/max. Ballestín, Barrios, and Valls (2011), Bianco and Caramia (2011b, 2012a), de Azevedo, Pessoa, and Subramanian (2021), and Schutt, Feydy, Stuckey, and Wallace (2013, 2015) consider this problem setting.

Bagherinejad and Majd (2014), Ballestín et al. (2013), Barrios, Ballestín, and Valls (2011), Jedrzejowicz and Skakovski (2010), and Schnell and Hartl (2016) employ minimal and maximal time lags within the multi-mode RCPSP, which leads to the MRCPSP/max.

Kreter, Schutt, and Stuckey (2017) add minimal and maximal time lags to the RCPSP with calendar constrained resources, while Kreter et al. (2018) combine the latter setting with a resource investment objective, see Section 5.4. Rieck, Zimmermann, and Gather (2012), Li, Xiong, Liu, and Li (2018a), and Li and Dong (2018) embed minimal and maximal time lags into a resource leveling problem, see Section 5.6. The approach of Li and Dong (2018) also contains multiple modes and mode-dependent time lags. Szmerekovsky and Venkateshan (2012) deal with mode-dependent finish-to-finish time lags in a DTCTP, while Khalili-Damghani et al. (2015) employ mode-independent time lags of all four types (start-start, start-finish, finish-start, finish-finish) in an extended DTCTP, see also Section 2.5. Bianco et al. (2016) add minimal and maximal time lags to a resource leveling problem where the activities have flexible resource profiles, see Section 2.2. Watermeyer and Zimmermann (2020) add partially renewable resources (Section 4.1) to the RCPSP/max. Hanzalek and Sucha (2017) consider minimal and maximal time lags in an RCPSP with setup times (see Section 2.3) and specific resource constraints (see Section 4.2).

Note that negative minimal time lags allow precedence-related activities to overlap. This is extended by Chu, Xu, and Li (2019) by introducing a set of negative minimal time lags for a pair of precedence-related activities (i, j). Each such time lag is associated with a rework duration that is added to the regular duration of the second activity j. This allows to incorporate that the more two activities overlap, the more rework time is needed.

3.2. Release dates and deadlines

According to the RCPSP no time window restrictions for activities have to be accounted for. Depending on the application, however, there might be a time window for each activity restricting the time interval where the activity can be feasibly scheduled in. Such a time window is marked by a release date as earliest possible start time and a deadline as latest possible completion time. Note that some papers also use the term due date for a deadline. Here, we consider a deadline to be a date that cannot be exceeded whereas we consider a due date to be a date that can be exceeded although this is not desirable (due dates are often used for tardiness objectives, see Section 5.1).

Cheng et al. (2015) employ release dates and deadlines in a setting that also includes multiple modes and activity splitting. Hill, Lalla-Ruiz, Voß, and Goycoolea (2019) apply an MRCPSP variant with time windows for activities but without precedence constraints in order to plan ship arrivals and departures at maritime ports. Zimmermann and Trautmann (2018) ensure that candidates in an assessment center have a lunch break in a prescribed time window by considering an activity with a release date and a due date for each candidate representing the break.

Deadlines are often considered when the minimization of the makespan is replaced with another objective such as resource investment (see Section 5.4), resource renting (see Section 5.5), resource leveling (see Section 5.6) or net present value (see Section 5.8). Variants of the DTCTP and the DTRTP with deadline are described in Section 2.5.

3.3. Further temporal constraints

Hartmann (2013) proposes three types of temporal constraints, namely the restrictions that two activities may not start at the same time, may not finish at the same time, and may not be in process at the same time (i.e., may not overlap), respectively. Note that precedence relations (i.e., an order of the activities) are not imposed. It is mentioned that these temporal relations can in fact be modeled by means of resources (for the first two cases, time-dependent resource requests are needed).

Vanhoucke and Coelho (2016) also deal with temporal constraints that force two activities not to overlap (called bidirectional constraints here). They add a minimal time lag called changeover time between the finish time of the first activity and the start time of the second. Moreover, in addition to the usual constraint that all predecessors must be finished before an activity can start, they suggest a constraint that at least one predecessor must be completed before an activity can start.

Alfieri, Tolio, and Urgo (2011) and Bianco and Caramia (2011a, 2012b) discuss four types of *feeding precedence relations* that allow precedence-related activities to overlap to a certain degree. The first type implies that an activity j can start when the percentage of predecessor activity i that has already been processed is greater than or equal to q_{ij}. The second type means that an activity j can be completed when the percentage of predecessor activity i that has already been processed is at least q_{ij}. The third type enforces that executing more than g_{ij} percent of activity j is only possible when predecessor activity i has already started. The last type means that executing more than g_{ij} percent of activity j is only possible when predecessor activity i has already finished. These approaches also employ flexible resource profiles (or variable execution intensity, see Section 2.2) which provide a useful foundation for feeding precedence relations. Baydoun, Haït, Pellerin, Clément, and Bouvignies (2016) consider a model with the first type of feeding precedence relation where the percentage of the predecessor activity that has to be processed depends on modes in which the activities are performed.

Quintanilla, Pérez, Lino, and Valls (2012) follow a related concept referred to as *work precedence relations*. Here, percentages apply to both the activity and it predecessor. For example, a finish-start work precedence relation means that the first q_j percent of activity j can be completed only when the last q_i percent of its predecessor activity i have been started. This is defined for start-start, start-finish, and finish-finish relations as well. Motivated by a practical application, the model of Quintanilla et al. (2012) also includes time-lags, due dates, preemption and multiple modes. Schwindt and Paetz (2015) consider start-finish work precedence relations as well. Pérez, Quintanilla, Lino, and Valls (2014) deal with a similar model but without preemption.

3.4. Generalized network structures and logical dependencies

In the standard RCPSP all activities must be carried out. Several researchers have proposed generalized network structures in which some activities must be carried out while others are optional.

Kellenbrink and Helber (2015) distinguish between so-called mandatory activities which must be carried out and optional (non-mandatory) activities. Each set of optional activities is associated with a triggering activity. If the triggering activity is mandatory (or optional and implemented), one of the optional activities in the related set must be implemented. Otherwise, if the triggering activity is optional and not implemented, then none of the optional activities in the related set are implemented. An optional activity j may be related to a set of dependent optional activities, which means that if j is implemented then all dependent activities must be implemented as well. Precedence relations between two activities are only enforced if both activities are carried out. Kellenbrink and Helber (2015) remark that this approach includes the multi-mode RCPSP as a special case.

Kyriakidis, Kopanos, and Georgiadis (2012) consider a network structure that contains specific activities called “decision boxes.” These activities are associated with a constraint that either all, exactly a given number of the predecessor activities, or at least a given number of them must be carried out. Another constraint is to carry out either exactly one or at least one of the successor activities.

Tao and Dong (2017) introduce so-called activity chains, that is, sets of activities connected by precedence relations. Alternative processes can be captured by different activity chains, and when the project is scheduled, one of the alternative activity chains has to be selected. The activities of the selected chain are then carried out while those of the other chains are not. This is achieved by employing AND as well as OR nodes in the project network. An AND node corresponds to an activity of which all successors must be carried out (this applies to all activities in the standard RCPSP), whereas an OR node reflects an activity of which only one successor must be carried out. Moreover, nonrenewable resources are taken into account (see Section 4.1). Čapek, Šůcha, and Hanzálek (2015) consider a similar setting restricted to renewable resources. Tao and Dong (2018) extend the model of Tao and Dong (2017) by adding multiple modes and a second, cost-based objective.

Servranckx and Vanhoucke (2019) propose an approach in which exactly one path of optional activities between a so-called principal activity and a so-called terminal activity must be selected to be carried out. Thus, principal activities can be viewed as XOR nodes in the project network. These subgraph structures with alternative paths of activities can be nested.

A different approach using logical concepts is proposed by Vanhoucke and Coelho (2016) who distinguish between two types of logical precedence constraints in networks where, in contrast to the models discussed above, all activities must be carried out. AND constraints imply that all predecessors must be finished before an activity can start (these are the usual precedence relations of the RCPSP). OR constraints mean that at least one predecessor must be completed before an activity can start.

4. Generalized resource constraints

4.1. Nonrenewable and partially renewable resources

According to the basic RCPSP resources are available with their full capacity in each period. However, if a mode can be chosen for processing activities, then nonrenewable resources which have their capacities available for the entire project and are consumed over time can easily be motivated. A project budget which is utilized by processing activities depending on the chosen mode serves as a prime example here.

Nonrenewable resources are common as integral part of multi-mode problems, see Section 2.4. Tao and Dong (2017), however, consider nonrenewable resources in a single-mode problem with logical nodes, see Section 3.4.

Partially renewable resources have an associated set of subsets of periods. The capacity of a partially renewable resource is available in each of these subsets. Note that partially renewable resources generalize both, renewable resources and nonrenewable resources.

Okubo et al. (2015) employ partially renewable resources within a multi-project scheduling problem, see Section 6.4. Watermeyer and Zimmermann (2020) consider an RCPSP with partially renewable resources and minimal and maximal time lags, see Section 3.1.

4.2. Cumulative resources

Cumulative resources cannot only be used by activities but also can be supplied by activities. Each activity occupies capacity at its start and provides capacity at its completion. Hence, availability of capacities over time depends on the schedule and can increase. Typically, it is required that at each point of time at least zero units of capacity need to be available.

Kone, Artigues, Lopez, and Mongeau (2013) provide mixed-integer models for the standard RCPSP with multiple cumulative resources with no upper bound on the maximal availability. Sahli et al. (2016) and Carlier et al. (2018) consider cumulative resources in a problem setting focussing on events (cf. Section 2.6) with minimal and maximal time lags that can represent, e.g., start and completion of activities. In Carlier and Moukrim (2015) only cumulative resources with an upper bound on the maximal availability but no renewable resources are considered.

Hanzalek and Sucha (2017) consider the special case with pairs of activities where the first activity occupies capacity at its start time and the same amount of capacity is released at completion of the second activity. The related resources are referred to as *take-give resources*. The concept is inspired by a real-world lacquer production planning problem.

In Bartels et al. (2011) the maximum availability of the cumulative resources in an MRCPSP setting is bounded, which is motivated by limited inventory capacities. Kyriakidis et al. (2012) consider a similar approach. In addition, they take a specific network structure into account that imposes constraints on the activities that have to be carried out, see Section 3.4.

In Hurink, Kok, Paulus, and Schutten (2011) a particular setting is considered where subsets of activities occupy capacity of the cumulative resource. At the first start of an activity of such a subset a subset-dependent number of capacity units is occupied. These units are freed only at the last completion of an activity of this subset. As an additional requirement the capacity units are numbered and each subset needs to get assigned consecutively numbered capacity units.

4.3. Resources with multiple skills

In the multi-skill RCPSP (MS-RCPSP), the resources have multiple skills that are needed to carry out an activity. A set of skills is given, and each resource masters one or more of these skills. Moreover, each activity requires resources with certain skills. The goal is to determine a start time as well as appropriate resources for each activity with the objective to minimize the makespan. This standard MS-RCPSP has been tackled by Correia, Lourenco, and Saldanha-da Gama (2012), Correia and Saldanha-da Gama (2015), Almeida, Correia, and Saldanha-da Gama (2018); Almeida, Correia, and Saldanha-da-Gama (2016, 2019), and Montoya, Bellenguez-Morineau, Pinson, and Rivreau (2014, 2015).

Some variants of the MS-RCPSP have been considered as well. Santos and Tereso (2014) deal with the same setting aiming for various objectives such as minimization of total cost of resources and earliness/tardiness cost, while Laszczyk and Myszkowski (2019) take minimization of makespan and costs of resources into account. Maghsoudlou et al. (2016) add multiple modes and employ three objectives, namely makespan and cost minimization as well as maximization of weighted quality. Dhib et al. (2015) allow preemption of activities in the standard MS-RCPSP. Correia and da Gama (2014) introduce a deadline while minimizing the sum of fixed and variable costs related to resource usage.

Myszkowski, Olech, Laszczyk, and Skowronski (2018), Lin, Zhu, and Gao (2020), and Zheng, Wang, and Zheng (2017) present multi-skill problems in which resources master skills at different levels, and an activity requires resources that master skills at least at a certain level. Wang and Zheng (2018) tackle a similar setting, with cost minimization as second objective in addition to makespan minimization. Maghsoudlou, Afshar-Nadjafi, and Niaki (2017) consider different levels for skills as well. Here, however, choosing a resource that masters a skill at a higher level is assumed to reduce the risk to rework an activity. Two objectives are considered, namely the minimization of the rework risk and the minimization of costs that arise from assigning resources to activities. Yannibelli and Amandi (2011) take into account the effectiveness that reflects how well a resource masters a skill. The objective is to maximize the total effectiveness of the resource assignment. Yannibelli and Amandi (2013) extend this model by including makespan minimization as second objective.

Xiao, Ao, and Tang (2013) suggest an extended version of the MS-RCPSP in which activities are related to a workload such that the duration then depends on the number of assigned resources (which implies a relationship to the DTRTP, see Section 2.5). The objective is to minimize total costs which includes costs for resources (both regular and overtime) and makespan-related costs.

Several researchers consider multi-skill problem with learning effects. Zabihi, Kahag, Maghsoudlou, and Afshar-Nadjafi (2019) consider learning effects that increase the efficiency of the resources with regard to their skills. The objectives are to minimize the makespan, to maximize the total efficiency and to minimize the total resource-based costs. Gutjahr, Katzensteiner, Reiter, Stummer, and Denk (2010) propose a concept that includes dynamic competencies and learning effects. The degree to which a resource (employee) possesses a certain competency increases when this competency is used during the execution of an activity. However, it decreases when it is not used. The competency degree is linked to the efficiency with which a resource can perform an activity. This is embedded into a complex multi-project setting, see Section 6. Hosseinian et al. (2019) deal with learning effects due to cooperation. When two resources work on the same activity, the one with the lower efficiency learns from the other and increases its efficiency. The objectives are makespan and cost minimization.

4.4. Continuous resources

Continuous resources allow to assign an arbitrary fraction of its capacity to each activity at each point of time. The processing rate of each activity, then, depends on the amount of capacity assigned. Waligóra (2011) and Waligóra and Weglarz (2014, 2015) consider the basic RCPSP with an additional single continuous resource. Furthermore, in Waligóra and Weglarz (2014) the same setting with the goal to maximize the net present value is presented.

Naber and Kolisch (2014), Tritschler et al. (2017), Naber (2017), and Bianco et al. (2016) discuss resources with continuously divisible amounts in models with flexible resource profiles, see Section 2.2.

4.5. Resource capacities varying with time

In the basic RCPSP, the capacity R_k of each resource k is constant over time. Hartmann (2013, 2015) employ resource capacities R_{kt} that may change and thus depend on the period t. Kreter et al. (2016); Kreter et al. (2015, 2017) consider the special case where in each period the capacity of a resource is either fully available or not at all. Note that time-dependent resource capacities constitute a special case of partially renewable resources, see Section 4.1.

In the resource leveling problem (see Section 5.6), time-varying resources capacities have to be determined such that the changes from period to period are minimized.

4.6. Further resource constraints

Fu (2014) and Zoraghi, Shahsavar, and Niaki (2017b) add a resource category called materials to the multi-mode RCPSP. Materials are consumed by the activities, thus from this perspective they correspond to nonrenewable resources. In addition to the calculation of a start time and a mode for each activity, it has to be decided at which points in time material for the project is ordered. Zoraghi et al. (2017b) also take quantity discounts for the orders into account, whereas Tabrizi (2018) includes the selection of the supplier when ordering material.

Li, Zhang, Yan, Hu, and Zhao (2018b) develop an extension for the RCPSP in hazardous environments (e.g., nuclear power plants). Carrying out an activity may be related to a certain degree of risk for the resources (e.g., a health risk for workers). The accumulated risk of each resource must not exceed a given level.

Lacomme, Moukrim, Quilliot, and Vinot (2017, 2019) integrate the RCPSP with routing aspects for resources (only a single resource type is considered). Assuming that resources must visit activities a limited fleet of vehicles with limited capacity needs to be routed in order pick up a resource and deliver it to the next activity to be processed. Transportation times can be seen a setup times which do not depend on the schedule of activities only but also on the routing.

Poppenborg and Knust (2016b) consider resources that might be blocked by an activity until the next resource handling the activity is available.

5. Alternative objectives

5.1. Time-based objectives

The classical objective of the RCPSP is to minimize the makespan. Also several other time-based objectives have been proposed. Wang, Liu, and Zheng (2019) employ the objective to minimize the total weighted tardiness with regard to due dates of the activities. Bagherinejad and Majd (2014) consider the objective to minimize total earliness and tardiness cost of activities with respect to given due dates.

Ranjbar, Hosseinabadi, and Abasian (2013) introduce the objective to minimize the total weighted late work. The late work of an activity is defined as the minimum of its tardiness and its processing time. That is, the late work reflects the number of periods an activity is in process after its due time.

Aouni, d'Avignon, and Gagnon (2015) aim for, among other objectives, a minimum delay of the project with respect to a given due date. Gerhards and Stürck (2018) and Van Peteghem and Vanhoucke (2015a) consider the same objective in the resource availability cost problem, see Section 5.4.

In Hill et al. (2019) the authors aim for schedules minimizing total flow time of activities. Since the flow time is defined as the difference between completion time and earliest possible start time and the latter is given, this goal is equivalent to minimizing the total completion time.

5.2. Robustness-based objectives

When a project is carried out, activities might take longer or cost more than expected. Consequently, project managers may be interested in robust schedules in which disruptions have only a reduced impact. This is leads to the concept of proactive scheduling. There are many approaches to robust scheduling that explicitly employ stochastic concepts to capture uncertainty. Here, however, we restrict ourselves to deterministic settings.

Palacio and Larrea (2017) maximize the sum of the slack times of all activities to obtain a schedule that is robust with regard to longer durations. The project makespan is limited by a deadline. Hazır et al. (2011) and Hazır et al. (2015) tackle the DTCTP with deadline and cost minimization. In order to obtain robust schedules with regard to cost increases, they extend the objective that minimizes the expected activity costs by including worst case activity costs for a limited number of activities.

5.3. Objectives for rescheduling

Rescheduling has to be done if the current schedule becomes infeasible due to a disruption like delay of an activity or breakdown of a resource. Chakrabortty, Rahman, Haque, Paul, and Ryan (2020b) discuss rescheduling of the RCPSP. Their objective is to minimize the makespan plus the weighted deviations from the start times of the previous schedule. Chakrabortty et al. (2016) follow a similar approach for the MRCPSP. Elloumi et al. (2017) consider rescheduling of an MRCPSP as well. They study makespan minimization as well as optimization of schedule stability. As stability measures, they employ the sum of start time changes in the new schedule, the largest start time change, and the changes in the resource profile. Elloumi, Loukil, and Fortemps (2020) consider makespan minimization as the only objective for rescheduling. They add constraints that make sure that activities already started (or even completed) cannot be rescheduled. The remaining activities cannot be started before the current time. Deblaere, Demeulemeester, and Herroelen (2011) tackle the MRCPSP with a rescheduling objective that minimizes the costs for changes of start times and of modes. They add a constraint that does not allow an activity to start earlier than in the previous schedule.

5.4. Resource investment (Resource Availability Cost)

Several objectives take care of the renewable resources. One of them leads to the *resource investment problem* (RIP), also called *resource availability cost problem* (RACP). The start times of the activities s_j and the (constant) resource capacities R_k have to be determined such that the total costs for the resource capacities are minimized (a deadline is given to limit the project duration). If the unit cost of resource k is c_k, the objective is min $\sum_k c_k R_k$. This standard setting is tackled by Rodrigues and Yamashita (2010, 2015), Van Peteghem and Vanhoucke (2013), and Zhu, Ruiz, Li, and Li (2017).

Qi et al. (2015) consider a multi-mode variant of the RIP where only renewable resources are considered, while Colak and Azizoglu (2014) consider the multi-mode RIP with only a single renewable resource, that is, the RIP version of the DTRTP (see Section 2.5). Coughlan et al. (2015) suggest a multi-mode version of the RIP that additionally includes time intervals during which the resources are unavailable. Afshar-Nadjafi (2014) develops another variant of the multi-mode RIP in which a resource is only available in the time interval between the start time of the first and the finish time of the last activity that requires the resource. Costs for resource availability occurs only in this time interval but not during the entire project duration.

Kreter et al. (2018) introduce an extension of the RIP in which minimal and maximal time lags between activities are given. Moreover, they make use of a calendar that specifies breaks during which resources are unavailable (e.g., because of holidays or weekends). Activities can be interrupted but only when a break in the calendar occurs, and interruptions during a start-up phase of an activity are not allowed. Lu, Ren, Wang, and Zhu (2019) suggest a resource investment problem with a resource calendar in which scheduling also includes the assignment of activities to assembly stations.

Aouni et al. (2015) aim for, among other objectives, a minimum violation of a given budget for resource investment. Gerhards and Stürck (2018) and Van Peteghem and Vanhoucke (2015a) consider the trade-off between resource investment and violation of the project deadline in a weighted objective function.

Chen and Li (2018) consider aspects of both the RIP and the resource renting problem (see Section 5.5). They determine both the permanent investment in resources and the on demand renting of additional resources in order to account for workload peaks.

5.5. Resource renting

The *resource renting problem* (RRP) considers renewable resources that are rented; the objective is to minimize the total renting costs. Renting resource k is associated with fixed costs c_k^f per unit and variable (time-dependent) costs c_k^v per unit and period. Consequently, renting a units of resource k over t periods implies costs of $a \cdot (c_k^f + t \cdot c_k^v)$. Again, a deadline is given for the project. The RRP reduces to the RIP if the variable costs are 0.

Afshar-Nadjafi, Basati, and Maghsoudlou (2017) propose an extension of the basic RRP that includes minimal and maximal time lags as well as due dates for the activities. The objective is extended by adding costs for tardiness.

Schnabel, Kellenbrink, and Helber (2018) consider a problem where only variable costs are considered and the trade-off between cost for additional resources and the minimum makespan is reflected in a weighted objective function.

5.6. Resource Leveling

The *resource leveling problem* (RLP) is closely related to the RIP as well. The general objective is to schedule the activities in a way that leads to a smooth resource profile, that is, the resource requirements should be distributed evenly during the project's duration (again, a deadline is given). In what follows, let R_{kt} be the capacity of resource k required in period t, and let c_k be a cost factor associated with resource k.

Several objectives to achieve resource leveling have been proposed. Among the most popular ones is the minimization of the weighted squared capacities, min $\sum_k c_k \sum_t R_{kt}^2$. This has been considered by Christodoulou, Michaelidou-Kamenou, and Ellinas (2015), Ponz-Tienda, Salcedo-Bernal, Pellicer, and Benlloch-Marco (2017a), Ponz-Tienda, Salcedo-Bernal, and Pellicer (2017b), Rieck and Zimmermann (2015), Rieck et al. (2012), and Qiao and Li (2018). Li et al. (2018a) add minimal and maximal time lags to this setting, and Li and Dong (2018) also add multiple modes.

Another important objective is to minimize the squared changes of the resource requests from period to period, min $\sum_k c_k \sum_t (R_{k,t+1} - R_{kt})^2$. This one has been tackled by Qiao and Li (2018) and in similar form by Ponz-Tienda et al. (2017a).

Bianco, Caramia, and Giordani (2017), Ponz-Tienda et al. (2017a), and Rieck and Zimmermann (2015) employ the minimization of the absolute changes from period to period, min $\sum_k c_k \sum_t |R_{k,t+1} - R_{kt}|$. Moreover, Ponz-Tienda et al. (2017a) mention the maximum resource demand objective which is actually the standard objective of the RIP. They also take the resource idle days objective into account which minimizes the number of periods in which less than the maximum capacity is requested.

Rieck et al. (2012), Rieck and Zimmermann (2015), Bianco et al. (2016), Atan and Eren (2018), and Verbeeck, Van Peteghem, Vanhoucke, Vansteenwegen, and Aghezzaf (2017) discuss an objective that minimizes the total overload cost, that is, the requested capacities that exceed a given threshold Y_k, min $\sum_k c_k \sum_t (R_{kt} - Y_k)^+$.

Qiao and Li (2018) minimize the squared deviation from a given threshold Y_k, that is, min $\sum_k c_k \sum_t (R_{kt} - Y_k)^2$ where the threshold is selected as the average resource request, $Y_k = \overline{R}_{kt}$. Moreover, they consider an objective that minimizes the the resource-based entropy.

Atan and Eren (2018) minimize the number of resources (workers) that are released before the project ends and are then rehired during the project. They also examine models in which the smallest makespan is determined that allows for the best possible resource leveling result.

Some of the above-mentioned models with resource leveling objective contain further extensions. While Ponz-Tienda et al. (2017a, 2017b) consider only minimal time lags, Rieck et al. (2012) and Bianco et al. (2016, 2017) include both minimal and maximal time lags, see Section 3.1. Bianco et al. (2016, 2017) further add flexible resource profiles (or variable execution intensity, see Section 2.2).

5.7. Objectives based on costs

Hariga, Shamayleh, and El-Wehedi (2019) minimize the total costs within a multi-mode model with activity preemption. The objective includes costs for carrying out a mode, for interrupting an activity and for fluctuations in the resource demand (as in resource leveling).

Dai, Cheng, and Guo (2018) consider cost arising when resources are used in order to process activities. The weighted sum of total cost and makespan is to be minimized.

Zoraghi et al. (2017a) tackle the MRCPSP with lot-sizing aspects and various financial objectives. Here, processing of activities requires material which has to be ordered beforehand. Inventory cost for holding the material and fixed cost for each replenishment are considered. Furthermore, earliness bonus and tardiness penalties are considered.

5.8. Objectives based on the net present value

Another important type of objective emerges if cash flows occur while the project is carried out. While cash outflows are caused by executing activities and using resources, cash inflows occur when specific parts of the project are completed. Usually, discount rates are taken into account as well. This leads to the objective to maximize the net present value (NPV) of the project. In addition to the standard precedence and resource constraints, a deadline constraint is considered. The RCPSP with NPV objective has been studied by Gu, Schutt, Stuckey, Wallace, and Chu (2015), Leyman and Vanhoucke (2015), Thiruvady, Wallace, Gu, and Schutt (2014), and Vanhoucke (2010). These studies are based on continuous compounding, that is, the cash flows are discounted with factor $e^{-\alpha t}$ (α is the per-period interest rate). Fink and Homberger (2013) tackle the same setting but employ per-period compounding with a discount factor of $(1 + \alpha)^{-t}$. Note, however, that these two types of compounding do not differ substantially as they are convertible to each other.

Leyman and Vanhoucke (2017) extend the RCPSP with NPV objective by considering cash outflows either at the start or at the end of an activity or on a per-period basis throughout its duration (cash inflows occur only at the end of an activity). A constraint ensures that the capital never becomes negative. Leyman et al. (2019) follow a similar approach within the DTCTP, where the three payment models are applied to cash inflows as well. Leyman and Vanhoucke (2016) consider payments at regular and irregular points in time as well as activity-related payments, which are embedded into both the single-mode and the multi-mode RCPSP.

Shahsavar, Niaki, and Najafi (2010) suggest an NPV-based objective that takes into account cash inflows after activity completion, costs for resource capacities as well as bonus and penalty payments depending on project completion with regard to the due date. An inflation rate is also taken account. Costs for resource capacities only apply to the time interval during which a resource is actually used.

Waligóra and Weglarz (2014) consider the RCPSP with the goal to maximize the net present value and an additional single continuous resource. Tirkolaee et al. (2019) aim at maximization of net present value in a MRCPSP setting. Khoshjahan, Najafi, and Afshar-Nadjafi (2013) minimize the net present value of penalties for earliness and tardiness of the activities in an RCPSP with due dates for the activities.

5.9. Multiple objectives

In the presence of multiple conflicting objectives the trade-off between these objectives needs to be addressed. Ballestín and Blanco (2015) give an overview of approaches and models.

A common approach is to consider them in a *weighted objective function*. Aouni et al. (2015) aim for minimizing the violation of a given budget for resource investment and for minimizing project delay with respect to a given due date. Gerhards and Stürck (2018) and Van Peteghem and Vanhoucke (2015a) consider a similar objective. They deal with the trade-off between resource investment (see also Section 5.4) and violation of the project due date.

Several authors combined minimization of makespan and costs in a weighted objective function. Dai et al. (2018) consider costs for employing resources. They minimize the weighted sum of total cost and makespan. Schnabel et al. (2018) consider a problem where only variable costs are taken into account and the trade-off between costs for additional resources and minimum makespan is reflected in a weighted objective function. Zamani (2013) tackles a multi-mode RCPSP with one nonrenewable resource which reflects costs. The objective is to minimize the weighted sum of costs and makespan.

Toffolo et al. (2016) consider a multi-project setting, see Section 6, where both the total completion time of individual projects and the overall makespan are to be minimized.

Another approach is to aim for the set of *Pareto-efficient solutions* with respect to the objectives under consideration. Several researchers made use of this approach when incorporating multiple objectives into the standard RCPSP. Ballestín and Blanco (2011) analyze some fundamentals of multi-objective RCPSPs, taking into account twelve common objectives.

Wang, Dugardin, and Yalaoui (2016) and Xiao, Wu, Hong, Tang, and Tang (2016) employ the objectives to minimize the makespan and the total tardiness. Gomes, de Assis das Neves, and Souza (2014) and Niño, Mejía, and Amodeo (2016) consider the goal of carrying out the activities as late as possible while maintaining a short makespan. This is achieved by two objectives, the minimization of the makespan as well as the maximization of the weighted start times (the latter is transformed into a minimization objective). Nikoofal Sahl Abadi, Bagheri, and Assadi (2018) employ the objectives to minimize the makespan and to minimize the costs for changes in resource demand over time, where the costs are discounted using an interest rate (note that this is a resource leveling objective).

Other papers determine Pareto-efficient schedules for extended models. Shahsavar, Najafi, and Niaki (2015) consider RCPSP with minimal and maximal time lags and three objectives, namely the makespan objective, the resource investment objective, and a resource leveling objective (minimization of squared changes in resource utilization). Tofighian and Naderi (2015) include two objectives, maximization of project benefit and resource leveling, into a multi-project selection and scheduling problem, see Section 6.2. Tabrizi (2018) tackles a problem that includes material procurement and defines two objectives, namely ecological impact of the orders as well as costs for material procurement, inventory holding, resource availability, and penalty or reward depending on the project completion time and the due date.

Several researchers apply the Pareto approach to the MRCPSP. Dridi, Krichen, and Guitouni (2014) consider both makespan and cost minimization where the costs are related to using renewable resources. Tirkolaee et al. (2019) aim for minimization of the makespan and maximization of the net present value. Ghoddousi, Eshtehardian, Jooybanpour, and Javanmardi (2013) incorporate makespan minimization, minimization of costs that depend on modes and project duration, and resource leveling. Elloumi et al. (2017) employ makespan minimization and schedule stability optimization when rescheduling after a disruption, see Section 5.3. Nemati-Lafmejani, Davari-Ardakani, and Najafzad (2019) consider minimization of the makespan and of the net present value of the resource-related costs within an extended MRCPSP that adds setup times and assignment of contractors to activities.

A few studies consider multiple objectives and Pareto fronts within the multi-skill RCPSP (see Section 4.3). This includes Yannibelli and Amandi (2013), Maghsoudlou et al. (2016, 2017), Wang and Zheng (2018), Hosseinian et al. (2019), Laszczyk and Myszkowski (2019), and Zabihi et al. (2019).

A third approach for dealing with multiple objectives is a *lexicographic ordering* of the objectives. Applying this concept, Florez, Castro-Lacouture, and Medaglia (2013) take three objectives into account, namely makespan minimization, cost minimization, and maximization of labor stability. The latter is achieved by minimizing the hiring and firing of resources (workers). Geiger (2017) employs two objectives, minimization of total project delay and total makespan in a multi-mode multi-project setting, see Section 6.

6. Multiple projects

6.1. Objectives for multi-project scheduling

Browning and Yassine (2010) consider a multi-project extension of the RCPSP in which each project has a due time that corresponds to be the earliest project completion time in the resource-unconstrained case. They focus on two objectives. The first one is the minimization of the average percent delay of the projects. The percent delay of a project is defined as its tardiness divided by its due time. The second objective is the minimization of the percentage delay. The percentage delay is essentially the maximum finish time of the projects minus the maximum due time, divided by the maximum due time. Perez, Posada, and Lorenzana (2016) pick up on these objectives but consider the makespan rather than the percentage delay. Gonçalves, de Magalhães Mendes, and Resende (2015) consider a weighted objective function accounting for tardiness of projects, earliness of projects, and deviation of projects' target durations. Toffolo et al. (2016) propose an other weighted objective function where the minimization of each project's completion time and the overall makespan are incorporated.

Araujo et al. (2020) discuss a multi-project problem with multiple modes. They also employ critical path based due times (which, in contrast to Browning and Yassine (2010), takes project release times into account as well). Their objective is to minimize the total delay (tardiness) of all projects. To break ties, they incorporate the minimization of the overall makespan (the latter is the maximum completion time of all projects).

Homberger and Fink (2017) consider a multi-project problem in which each project activity is associated with an agent. Each agent aims at maximizing the net present value of his activities. The objective is to find an overall schedule that satisfies all agents.

6.2. Project selection and scheduling

Shariatmadari, Nahavandi, Zegordi, and Sobhiyah (2017) develop a model with multiple projects that includes the decision which of the projects should be carried out. The objective is to maximize the level of cash at the end of the planning horizon, taking into account revenues as well as resource costs. The level of cash may not be negative at any time.

Gutjahr et al. (2010) suggest a project selection and scheduling model that includes dynamic competencies of the resources, time-dependent capacities as well as release time and deadlines. Two objectives are employed, namely the maximization of the values of the selected projects and the maximization of the efficiency increase of the resources due to learning effects.

Kumar, Mittal, Soni, and Joshi (2018) present a model which considers candidate projects at an aggregated level (i.e., they are not split into activities). Renewable resources with time-dependent capacity are given, but no precedence constraints. The goal is to select and schedule projects within a given horizon such that the total profit is maximized. Further constraints consider complementary projects (a set of related projects can only be selected as a whole) and mutually exclusive projects (at most one out of a set of projects can be selected). Liu and Wang (2011) tackle a similar model which also includes precedence relations between projects. The only resource is a budget for project costs. Tofighian and Naderi (2015) deal with yet another similar approach, albeit without precedence relations and without complementary projects, but with an additional objective, namely resource leveling.

Walter (2015) decides about acceptance, staffing, and scheduling of projects aiming for maximum profit implied by accepted projects, minimum deployment of resources, and workload balancing among workers.

6.3. Local and global resources

Approaches with multiple projects often distinguish between local resources that are assigned to a specific project and global resources that are available for all projects. This can be useful if, e. g., projects are carried out at different locations.

Li and Xu (2018) deal with a multi-project problem that contains both local and global resources as well as a release date for each project. The objective is to minimize total tardiness costs, where tardiness is measured with regard to the earliest project completion time in the resource-unconstrained case. Adhau, Mittal, and Mittal (2012) consider a similar setting with an objective that is based on project delays. Adhau et al. (2013) extend this by taking transfer times into account when transporting global resources between project locations. Transfer costs are added to the objective.

Geiger (2017) deals with a multi-mode multi-project setting with a release date for each project. Some renewable resources are global, whereas other renewable resources as well as the nonrenewable resources are local. The objectives are minimization of total project delay (measured with regard to due dates given by earliest project completion time) and minimization of total makespan (summed up over all projects). Asta, Karapetyan, Kheiri, Özcan, and Parkes (2016) consider a similar case where the main objective is to minimize the sum of all project completion times. As a tie-breaker, the minimization of the overall makespan is applied.

6.4. Further multi-project problems

Okubo et al. (2015) present a multi-project model in which each project must be finished before its deadline. Their approach contains various extensions: Multiple modes for the activities are given, both renewable and partially renewable resources are taken into account, and there are sequence- and mode-dependent setup times between activities during which resources are used.

Beşikci, Bilge, and Ulusoy (2015) deal with a multi-mode multi-project setting as well. In their approach, availability of renewable and nonrenewable resources is not fixed; instead, they are associated with costs, and an overall budget is given. The overall resource availability has to be determined, and the distribution of the capacities among the projects has to be calculated. Each project has a due date, and the objective is to minimize the total weighted tardiness.

Kolisch and Heimerl (2012) propose a multi-project approach in which the activities of each project have a serial network structure. The activities of all projects are embedded into an overall supernetwork. Furthermore, the model includes minimal and maximal time lags as well as resources with skills and efficiencies. The objective minimizes costs for regular and overtime work of internal resources and costs for additional external resources.

7. Conclusions

The RCPSP and its derivatives receive unabated attention from the scientific community. This is true for some of the variants and extensions of the RCPSP which are by now classics in their on right, e. g., multiple modes, generalized precedence relations as well as resource investment and resource leveling objectives. Also, some rather recent extensions such as multiple skills and flexible resource profiles have gained considerable significance, resulting in a substantial number of new publications.

For several extensions of the RCPSP, standard models are available. This includes the MRCPSP, the RCPSP/max, the MS-RCPSP and the RIP/RACP. These standard models continue to attract researchers and inspire them to develop competitive scheduling algorithms.

Other highly interesting extensions have not yet led to standard models. This holds for, e. g., networks with logical nodes and activities with flexible resource profiles. When such extensions are driven by actual real-world cases, it is necessary that individual models are developed. Nevertheless, establishing (possibly simplified) standard models for these extensions might be a promising path for future research.

In the last decade, an increasing number of researchers have developed rather complex project scheduling problems. These problems include more detailed assumptions or combine several extensions. Such complex models are often too specific to become standards. Nevertheless, they may possibly be well suited to capture planning requirements in practice. Therefore it would be valuable to motivate more complex models by discussing their relevance in real-world projects. Several papers describe an actual application for such problem settings, but more real-world case studies would be highly welcome for the scientific community.

Another noteworthy trend is that researchers tackle problems using project scheduling concepts although those problem settings are not related to projects in the strict sense. A few examples of such studies are as follows. Čapek, Šůcha, and Hanzálek (2012) address the production of wire harnesses. Customer service requests at IT service providers are considered by Cavalcante, Cardonha, and Herrmann (2013), while Hill et al. (2019) schedule ship arrivals and departures at maritime ports. Knust (2010) deals with scheduling table-tennis leagues. Riise, Mannino, and Lamorgese (2016) capture the scheduling of patients' appointments at hospitals, while Riedler, Jatschka, Maschler, and Raidl (2020) discuss a patient treatment scheduling problem at hospitals. Zimmermann and Trautmann (2018) schedule activities in an assessment center. These researchers apply various extensions of the RCPSP discussed in this paper including multiple modes, generalized time lags, enhanced resource constraints, and several objectives. This shows that extending modeling concepts in project scheduling has a positive impact also on applications beyond projects.

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