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Multi-Mode Resource Constrained Project Scheduling Problem: A Survey of Variants, Extensions, and Methods

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Multi objective model;
OR planning and scheduling;
ε-constraint method;
Data envelopment analysis.

ABSTRACT
Surgical theater is one of the most expensive hospital resources which accounts for a high percentage of hospital receptions. Therefore, efficient planning and scheduling of the operating rooms (ORs) is necessary to improving the efficiency of any healthcare system. In this paper, weekly OR planning and scheduling problem was addressed to minimize waiting time of elective patients, overutilization and underutilization costs of ORs, and the total completion time of surgeries. In our model, the available hours of ORs, recovery beds, the surgeons, legal constraints and job qualification of surgeons, and priority of patients were taken into account. A real-life example was provided to demonstrate the effectiveness and applicability of the model and was solved using ε-constraint method in GAMS software. Then, data envelopment analysis (DEA) was employed to obtain the best solution among the Pareto solutions obtained by ε-constraint method. Finally, the best Pareto solution was compared with the schedule used in the hospitals. The results indicated that the best Pareto solution outperforms the schedule offered by the OR director.

1. Introduction

Project scheduling is an important task in project management context, which plays a vital role in today's enterprise management. In practice, project managers deal with numerous internal/external constraints, which make project objectives too difficult to achieve. Among these constraints, scarce resources and precedence relations between activities make project scheduling a difficult task. On the other hand, project-oriented organizations achieve their objectives through accomplishment of projects, almost all of which require manpower resources, which is a renewable resource; this is while renewable resources have not even received sufficient attention.

The MMRCPSP has become a standard problem in the project scheduling literature during the last decades and can be summarized as follows. Projects usually consist of activities that are labeled as $j = 1, ..., J$, and d_j denotes processing time of activities (or duration). Once started, an activity cannot be interrupted, i.e., preemption is not allowed. Technological requirements dictate some precedence relations between activities, preventing activates from starting before accomplishment of their immediate predecessors P_j. The precedence relations among activities may be demonstrated using activity-on-node

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networks. Each activity requires a certain amount of resources labeled as $k = 1, ..., K$. Per-period resource requirements of activities are assumed to be known and remain constant as they progress. Usually, two additional activities $j = 0$ and $j = J + 1$ are considered to represent project's start and completion time, respectively. Both are "Dummy" activities with 0 durations, and they do not require any resources.

A schedule is an assignment of activities start times S_j, which leads to the earliest possible completion time of a project. Sprecher and Drexl (Sprecher & Drexl 1998) and Kolisch and Drexl (Kolisch & Drexl 1997) proved that MMRCPSP belongs to NP-complete class from problem complexity point of view. Graham et al. (Graham et al. 1979) introduced a three-field notation α|β|ɣ to identify machine scheduling problems, which formed the foundations for classification of project scheduling problems by Bruker et al. (Brucker et al., 1999). In the context of project scheduling problem, α|β|ɣ describes resource characteristics, activities, and objectives of problem, respectively. In this regard, the general MMRCPSP is identified by $MPS|prec|C_{max}$ (Brucker et al., 1999).

As a matter of fact, the MMRCPSP is a general form of resource-constrained project scheduling problem, which may occur more often in practice. Some survey papers on project scheduling problem have been published since 1990's. Most of them focused on solving methodologies (see Hartmann and Kolisch (Hartmann and Kolisch 2000), Kolisch and Hartmann (Kolisch and Hartmann 2006), and Kolisch and Hartmann (Kolisch and Hartmann 1999)), and a few more focused on common variants (see Brucker (Brucker et al., 1999), (Herroelen, De Reyck and Demeulemeester 1998), Herroelen (Herroelen 2005), and Hartmann (Hartmann and Briskorn 2010)).

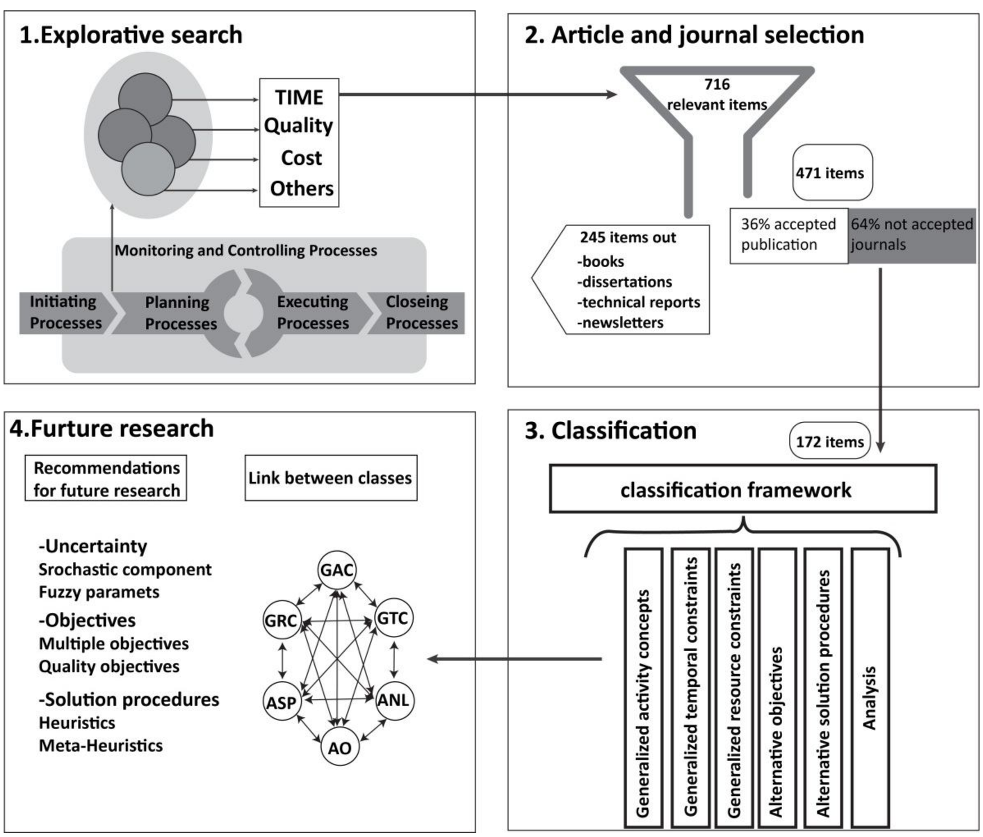

Fig. 1. Graphical representation of the methodology (scope definition and journal selection)

This research presents two distinct contributions. Our first goal is to collect related academic research studies on MMRCPSP variants and extensions. Then, some suitable classes are suggested to classify relevant papers. The other objective of this paper is to recognize research trends and gaps in order to highlight potential areas of improvements. Due to a huge number of available researches, the paper is organized to mention the diversity of problem settings lacking

concept, recently published papers have been prioritized. Fig. 1 illustrates the proposed methodology in order to classify current researches.
The objectives of this study are presented in the following order: Section 2 provides article and journal selection method. Section 3 addresses literature classification framework and a review of the most important publications in each class. A novel gap and trend identification procedure is elaborated in Section 4, and a list of potential gaps and trend resulting from applying the proposed literature is highlighted in this section. At last, Section 5 describes the main findings of this study and also describes directions for future researches.

1-1. Article and journal selection
This research is conducted through an explorative study on MMRCPSP in academic databases such as Web of Sciences, Science Direct, and Google scholar. The search is mainly performed in light of the following notions: project scheduling, resource constraints, multi-mode project scheduling, and scarce resources.
Project scheduling and particularly MMRCPSP literature is a rich and diverse literature, and related research studies have been published by various journals. This diversity and variety makes it hard to draw a line between journals while considering quality of published articles. In this regard, a two-step procedure is followed in order to objectively single out journals.

1-2. Minimum threshold
The explorative study on MMRCPSP resulted in a collection of 716 items including academic articles, books, master/PhD dissertations, and technical reports. Thus, we assumed the inclusion of a journal in the Google Scholar database as the minimum threshold of considering one publication in classification framework. Due to this minimum threshold, almost 65% (471) of initial explorative search results were considered in journal selection procedure described next.

1-3. Journal selection
In order to objectively rank 69 journals retaining from initial screening step, a selection procedure suggested by Willems and Vanhoucke (Willems and Vanhoucke 2015) was utilized. This selection procedure ranks journals based on nine citation-based criteria collected from three databases, and Fig. 2 illustrates these nine criteria. Then, the weighted average of these nine criteria was utilized to rank each individual journal. Median of journals score distribution was selected as cut-off value to distinguish those articles retained for classification. In this regard, 36% (172) articles of updated datasets were kept for classification (see Fig. 3. for distribution of selected papers between journals).

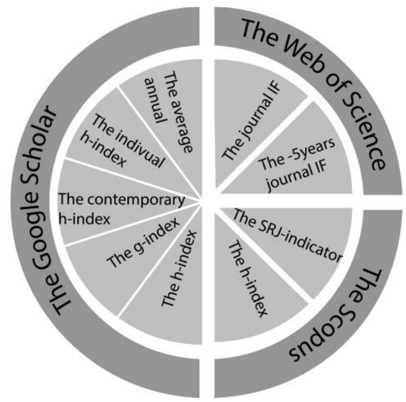

Fig. 2. The Nine citation-based criteria collected from three databases

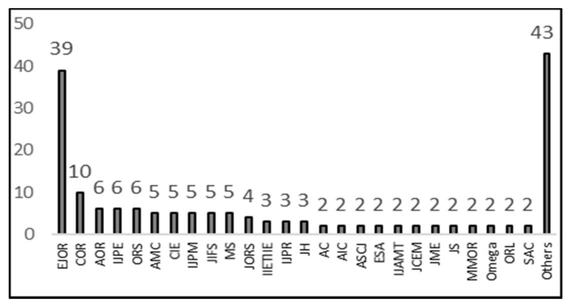

Fig. 3. Distribution of articles based on journals in classification phase

1. Classification Framework

After identifying and processing articles related to the defined scope (section 1-1), a classification framework is suggested to represent different aspects of an academic research. The proposed classification framework consists of the following six classes: (i) generalized activity concept, (ii) generalized temporal constraints, (iii) generalized resource constraints, (iv) alternative objectives, (v) alternative solution procedures, and (vi) analysis.

2-1. Generalized activity concepts
2-1-1. Preemptive scheduling
Although activity preemption is not allowed in basic MMRCPSP, meaning that activities are not allowed to be interrupted once they are started until accomplishment, some researchers allowed activities to be preempted at discrete milestones in project horizon (Demeulemeester and Herroelen (Demeulemeester and Herroelen

1996), Nudtasomboon and Randhawa (Nudtasomboon and Randhawa 1997), Vanhoucke and Debels (Vanhoucke and Debels 2008), Tavana et al. (Tavana, Abtahi and Khalili-Damghani 2013), Azimi and Azouji (Azimi and Azouji 2017)). Preemptive resource-constrained project scheduling problem is represented by α|prmtβ|ɣ in Brucker (Brucker et al., 1999).

Franck et al. (Franck, Neumann and Schwindt 2001) introduced the concept of calendars in MMRCPSP and considered a binary parameter which determines whether activities can be executed in a specific time period or not. They also suggested using a minimum time of execution for activities before preemption. Schwindt and Trautmann (Schwindt and Trautmann 2000) allowed activity preemption, yet only due to calendar breaks. Buddhakulsomsiria and Kim (Buddhakulsomsiri and Kim 2006), Buddhakulsomsiria and Kim (Buddhakulsomsiri and Kim 2007) also suggested a similar approach which allows activities to be interrupted due to varying resource capacities (i.e., resource vacations). Cheng et al. (Cheng et al., 2015) emphasized varying capacity of renewable resources by introducing non-preemptive activity splitting.

In non-preemptive activity splitting, an activity that is started is allowed to be interrupted if required resource levels are temporarily insufficient and must resume in the next eligible processing time period.

Vanhoucke and Debels (Vanhoucke and Debels 2008) suggested a new concept called fast tracking option that allows parts resulting from activity preemption to proceed in parallel. Ballestin et al. (Ballestín, Valls and Quintanilla 2008) considered the maximum number of preemption of activities.

Peteghem and Vanhoucke (Peteghem and Vanhoucke 2010) investigated the impact of activity preemption option on project make-span, and revealed that allowing preemption can decrease project duration. Delgoshaei et al. (2014) allowed both resource preemption and activity splitting in MMRCPSP problem and investigated the impact of resource and activity preemption on the Net Present Value (NPV) of project capitals.

2-1-2. Varying resource supply and demand

The basic MMRCPSP assumes that the demand for renewable resources and resource capacities is constant during activity execution. However, in a more practical case, resource requests may change along with activities progress (Drexl and Gruenewald 1993; Mori and Tseng 1997; De Reyck and Herroelen 1999).

In this regard, Özdamar and Dündar (1997) considered projects requiring capitals as nonrenewable resources that follow a demand pattern, which is a function of time and activity modes. Bartusch et al. (Bartusch, Möhring and Radermacher 1988) suggested a transformation method to cope with time-varying resource requests. In their proposed method, an activity with varying resource requests would be divided into two sub-activities with constant resource requests.

Cavalcante et al. (2001) considered time-dependent resource requests in project scheduling problem. Drezet and Billaut (2008) applied the time-dependent resource requests project scheduling in software development projects. There, they considered a minimum and maximum resource request in periods.

On the other hand, standard MMRCPSP assumes that the resource supply remains constant over time. This assumption may be too far from practical situations, where resource capacities might change in response to changing availability of labors due to vacations or varying availability of equipment due to maintenance.

Varying resource capacities have been discussed by Mori and Tseng (1997), Reyck (De Reyck and Herroelen 1999), Bomsdorf and Derigs (2008), Klein and Scholl (1999), Klein (2000), Schwindt and Trautmann (2000).

Bartusch et al. (1988) revealed that by using artificial activities and Minimal/Maximal time lags, a project scheduling problem with varying resource capacities can be transformed into constant resource capacities problem. Icmeli and Rom (1996) allowed resource capacities to change at certain points of time called milestones. Brucker and Knust (1999) considered so-called disjunctive resources with time-dependent capacities of up to 1.

Buddhakulsomsiri and Kim (2007) proposed a novel dynamic measure of tightness of resources called Moving Resource Strength (MRS). MRS simply indicates the portion of allocated recourses to total available resource capacity in any time window. They used MRS in order to reach the shortest project make span. Buddhakulsomsiri and Kim (2006) also showed that activity splitting could improve scheduling results in the presence of resource temporal unavailability.

2-1-3. Setup time

Setup time is the time required to prepare resource (e.g., a machine) for performing the activity. There are three types of setup time considered in the literature: sequence-independent, sequence-dependent, and schedule-dependent setup times. In the first case, Kolisch (1995), set up times only depend on activities and required resources, yet do not depend on the sequence of activities. In sequence-dependent case (Neuman et al. (2002a); Schwindt (2005)), setup times depend on not only the activity and the resource, but also the sequence of activities processed by the resources. In the case of Schedule-dependent setup times for Mika et al. (2008), setup times depend on not only sequences of activities on particular resources, but also the assignment of resources to activities over time.

Drexl et al. (2000) applied sequence-dependent setup times to MMRCPSP. Vanhoucke (2008) incorporated sequence-independent setup times to RCPSP with activity fast-tracking and preemption. He considered a setup time for each activity preempted and resumed.

2-2-Generalized temporal constraints

2-2-1. Time lags

The classical MMRCPSP only considers finish-to-start precedence relationship between activities, meaning that an activity must have finished before any of its successors can start. This simple precedence concept can be extended by considering different time lags between activities, e.g., considering minimal time lag d_{ij}^{FS} between completions time of activity i and start time of successor activity j.

On the other hand, a maximal time lag between completion time and start time of two successor activities will be denoted by $\bar{d}_{ij}^{FS}$, meaning that constraint $C_i + \bar{d}_{ij}^{FS} \geq S_j$ must be satisfied. In other words, activity j may not be triggered later than $\bar{d}_{ij}^{FS}$ periods after the accomplishment of activity i. It should be noted that maximal time lags typically lead to cyclic network structures (see Frank and Neumann (1997)).

In addition to the time lag between finish and start time of two successor activities, it may be required to consider time lags between the start and start, the start and finish, or the finish and finish time of two successor activities. Bartusch et al. (1988) showed that all mentioned types of minimal time lags could be transformed to each other.

Time lags have been considered by Czarnowski et al. (2013), Tavana et al. (2013), Klein and Scholl (1999), Klein (2000), Kolisch and Rainer (2000), Vanhoucke (2006b), Amedeo et al. (2002), Dorndorph et al. (2000), and Neumann et al. (2002).

Brucker et al. (2001) showed that maximal time Lags might lead to infeasibility of the project scheduling problem; in addition, the associated feasible problems are NP-Complete. In this regard, Neumann and Zimmermann (2000), Heilmann (2001, 2003), and Barrios et al. (2010) considered minimal and maximal time lags simultaneously. Sabzehparvar and Seyed-Hosseini (2008) assumed durations of minimal and maximal time lags to be varying in accordance with execution mode.

2-2-2. Release date and deadline

In MMRCPSP context, release date is referred to as the earliest time in which an activity should be started; likewise, deadline may interpreted as the latest time which an activity should be finished ((Brucker et al., 1999); Cheng et al. (2015); Beşikci et al. (2015); Drezet and Billaut (2008); Kis (2005)).

Baptiste et al. (1999) introduced the cumulative scheduling problem in which activities were not scheduled based on the precedence relations; however, based on a set of release dates/deadlines for activities, Pérez et al. (2014) applied the cumulative scheduling problem in a multi-mode project scheduling environment.

Deadlines in standard MMRCPSP are not allowed to be violated; however, Najid and Arroub (2010), Branzei et al. (2002), and Chiu and Tsai (2002) considered deadlines that can be violated at some penalty cost in objective function.

2-2-3. Time-switch constraints

Time-switch constraints indicate working periods along with planning horizon in which activities can be performed. The Time-switching concept introduced by Yang and Chen (2000) is very close to forbidden periods introduced by Drexl (Drexl et al. 2000); however, the main difference remains in dependency of forbidden periods on activities. Brucker and Knust (2001) applied the concept of time-switch constraints by introducing one renewable resource with varying capacity. Vanhoucke et al. (2002) also applied the concept of time-switch constraints within a discrete time-cost tradeoff problem.

2-3-Generalized resource constraints

2-3-1. Nonrenewable and doubly constrained resources

In project scheduling problem with multiple modes, often, three different kinds of resources are considered: renewable, nonrenewable, and doubly constrained resources. These categories of resources were first introduced by Słowinski (1981). Renewable resources are those with capacity constraints on period basis, e.g., manpower and machines (Artigues and Billaut (1999); Reddy, Kumanan and Chetty (2001); Lova, Tormos and Barber (2006)).

Nonrenewable resources are limited on project basis, e.g., project budget (Özdamar (Özdamar and Dündar 1997)). On the other hand, there are resources that are available in limited quantity in each period and their total availability throughout the project is also constrained. Such resources are called doubly constrained resources (money is a doubly constrained resource if both the budget and the per-period cash flow of the project are limited). A doubly constrained resource can be formed by combining a renewable and a nonrenewable resource; thus, doubly constrained resources do not enhance complexity of the problem (De Reyck and Herroelen (1999); Ulusoy et al. (2001); Elloumi and Fortemps (2010)).

In practice, there may exist some resources in which the resource capacity would not be fully renewed in each period; this concept is referred to as partially renewable resources. Partially renewable resources were introduced by Böttcher et al. (1999); Alvarez-Valdes et al. (2006 and 2008); Schirmer and Drexl (2001); Zhu et al. (2006).

2-3-2. Cumulative and continuous resources

Cumulative resources concept was introduced by Neumann and Schwindt (Neumann and Schwindt 2003) in order to deal with inventory constraints in batch production. Bartels and Zimmermann (Bartels and Zimmermann 2009) employed cumulative resources within a MMRCPSP with minimal and maximal time lags in order to deal with an engineering and testing activity in an automotive industry. They modeled a test vehicle as a cumulative resource since it can be built, used, and destroyed in a crash test. Neumann et al. (Neumann, Schwindt and Trautmann 2005), Schwindt and Trautmann (Schwindt and Trautmann 2000) used MMRCPSP incorporated with cumulative resources and minimal and maximal time lags to address batch production scheduling in the process industry.

Standard MMRCPSP considers resources to be available in discrete quantities; however, in practice, there are continuously divisible resources, such as energy or raw material like liquids. Weglarz et al. (1977) first introduced the continuous resources concept. Further Jozefowska et al. (Józefowska et al. 2000), Kis (Kis 2005), Waligora (Waligóra 2008) addressed continuous resources in their research. Weglarz (Węglarz 1981) considered doubly constrained continuous resources.

On the other hand, resources that can be assigned to only one activity at a time are called dedicated resources. Bianco et al. (1998) first introduced the concept; Dorndorf et al. (1999) referred to the RCPSP with dedicated resources as disjunctive scheduling problem.

2-3-3. Resource capacities varying with time

The basic MMRCPSP assumes that resources capacities remain constant throughout project lifecycle; however, in some cases, resource capacities may change over time due to working hours and maintenance policies. Time-dependent resource capacities were addressed by cheng et al. (2015), Buddhakulsomsiri and Kim (Buddhakulsomsiri and Kim 2007, Buddhakulsomsiri and Kim 2006), Klein and Scholl (Klein and Scholl 1999), Klein (Klein 2000), Nonobe and Ibaraki (Nonobe and Ibaraki 2002), and Schwindt and Trautmann (Schwindt and Trautmann 2000).

Khalilzadeh et al. (2012) considered the renewable resources to be rented. Each renewable resource is available in predetermined sequential time periods and is not available out of those periods. Brucker and Knust (2001) considered the so-called disjunctive resources with time-dependent capacities of up to 1.

Bartusch et al. (1988) showed that time-varying resource capacities can be transformed into constant resource capacity problem with minimal and maximal time lags. Hartmann and Briskon (2010) showed that time-depended resource capacity MMRCPSP is a special case of the problem with partially renewable resources, where subset period with an individual capacity can be defined.

2-4-Alternative objectives

2-4-1. Time-based objectives

Among several measures of projects' time-based objectives, minimization of make-span is the most important measure of time, addressed in the literature. Nudtasomboon and Randhawa (1997) suggested minimization of sum of all activities' completion times; on the other hand, Rom et al. (2002) minimized the weighted sum of activities completion times. Similarly, Nazareth et al. (1999) proposed minimization of activities' average flow time.

Some other well-known measures include the lateness, tardiness, and earliness of activities. Lateness L_j of activity j is the deviation of completion time C_j from a given due date d_j, hence $L_j=C_j-d_j$. Tardiness T_j of an activity is similar to lateness, yet cannot be negative ($T_j = max\{0, C_j-d_j\}$). Similarly, earliness E_j of an activity is defined as $E_j = max\{0, d_j-C_j\}$.

In this regard, Viana and De Sousa (2000), Nudtasomboon and Randhawa (1997), and Ballestin (Ballestin, Valls and Quintanilla 2006) suggested weighted tardiness as an objective function. Neumann et al. (Neumann, Schwindt and Zimmermann 2002b) considered minimization of the maximum lateness. Vanhoucke et al. (Vanhoucke, Demeulemeester and Herroelen 2001a) and Lorenzoni et al. (Lorenzoni, Ahonen and de Alvarenga 2006) described calculation of earliness and tardiness according to a time window in which an activity should be executed.

Vanhoucke (Vanhoucke 2006a) studied a bio-technology project and suggested considering a time window for execution of each activity. Then, he proposed an objective which minimizes penalties caused by executing activities outside their original time windows.

Mungle et al. (2013), Tareghian and Taheri (2007) considered the influence of activities durations on project costs, while multiple execution modes exist.

2-4-2. Resource-based objectives

While the conventional MMRCPSP deals with project make-span minimization, with respect to the resource capacity constraints, a dual variant of this problem exists, namely *resource investment problem*. Resource investment problem aimed to minimize the cost of providing resources while a certain deadline for project should be respected. Thus, the objective is to minimize the sum of availability costs of all resources. The resource investment problem has been recently considered by Drexl and Kimms (Drexl and Kimms 2001), Neumann and Zimmermann (Neumann and Zimmermann 2000), Neumann et al. (Neumann et al. 2002b), Ranjbar et al. (Ranjbar, Kianfar and Shadrokh 2008), Ghoddousi et al. (Ghoddousi et al. 2013), and Yamashita et al. (Yamashita, Armentano and Laguna 2007).

Shadrokh an Kianfar (Shadrokh and Kianfar 2007) proposed a variant of resource investment problem with project due date instead of deadline, where the objective function includes both resource costs and cost of project tardiness penalty. In this regard, Nubel (Nübel 2001) introduced resource renting problem in which the renewable resources have to be rented. The objective is to minimize costs associated with renting resources.

Resource leveling tends to be an important objective in project scheduling problems, especially in organizations with various short-time projects, e.g., telecommunication projects. The objective there is to reach a smooth level of resources with minimum changes between periods, respecting project deadline. Smoothness of project resource profiles may be measured as the maximum change between two consecutive periods, sum of all changes, or sum of all squared changes (See Ghoddousi et al. (Ghoddousi et al. 2013), Tiwari et al. (Tiwari, Patterson and Mabert 2009), Bandelloni et al. (Bandelloni, Tucci and Rinaldi 1994), Nudtasomboon and Randhawa (Nudtasomboon and Randhawa 1997), and Neumann and Zimmermann (Neumann and Zimmermann 2000)).

In this regard, Davis et al. (1992), Viana and De Sousa (2000) suggested minimizing overrun of resource utilization from a given resource level. Nudtasomboon and Randhawa (Nudtasomboon and Randhawa 1997) minimized the cumulative deviation of resource utilization from a given resource level. Kis (Kis 2005) distinguished between internal and external resources and the proposed minimization of utilizing external resources. Bomsdorf and Derigs (Bomsdorf and Derigs 2008) considered minimization of numbers and length of gaps between resource profiles.

Analogous to the resource investment problem, there exists an alternative problem setting which tries to complete a project with minimum nonrenewable resources respecting project deadline.

In this regard, Akkan et al. (Akkan, Drexl and Kimms 2005), Demeulemeester et al. (Demeulemeester and Herroelen 1996), Nudtasomboon and Randhawa (Nudtasomboon and Randhawa 1997), and Tareghian and Taheri (Tareghian and Taheri 2007) considered money as the only nonrenewable project resource and solved the time-resource tradeoff problem. Nudtasomboon and Randhawa (Nudtasomboon and Randhawa 1997) and Viana and De Sousa also suggested minimizing consumed nonrenewable resources that exceed project resource capacities.

2-4-3. Cost-based objectives

Along with minimization of make span, the other well-known objective for MMRCPSP is cost minimization. In the MMRCPSP literature, it is usual for non-financial objectives to be interpreted with monetary language; in this regard, Zhang and Xu (2014) suggested minimizing cost of project which includes penalty cost of project tardiness. Analogously Achuthan and Hardjawidjaja (Achuthan and Hardjawidjaja 2001) proposed project cost minimization; their proposed cost function consists of execution costs and costs of earliness and tardiness.

Maniezzo and Mingozzi (1999), Mohring et al. (2003), and Mohring et al. (2001), and Mungle et al. (2013) considered activities cost function which depends on start time of activities; the objective is to minimize sum of activities' costs, which may include costs of earliness and tardiness.

Dodin and Elimam (2001) considered minimization of project costs including cost of activities execution (the duration can be shortened at additional costs), material costs, inventory holding costs, and penalty costs for late project completion.

Nonobe and Ibaraki (2002) proposed a cost-based objective that consists of two parts, i.e., project execution costs proportional to project duration and consolidation cost of activities, in order to reduce project duration.

Zamani (2013) considered project cost as a non-renewable resource and is limited in association with project duration and tried to balance cost versus time by means of priority-ranking concept. Razavi Hajiagha et al. (Razavi Hajiagha, Mahdiraji and Hashemi 2013), Tareghian and Taheri (Tareghian and Taheri 2007) considered the relationship between project cost and duration in construction projects.

On the other hand, maximization of net present value is another important objective that can impact project objectives to a large extent. Maximizing net present value has been investigated for the MMRCPSP with minimal and maximal time lags (Neumann and Zimmermann (Neumann and Zimmermann 2002, Neumann and Zimmermann 2000), Ulusoy et al. (Ulusoy et al. 2001), Varma et al. (Varma et al. 2007)), (Najafi and Niaki (Najafi and Niaki 2006), Waligora (Waligóra 2008), and Tavana (Tavana et al. 2013)). Moreover, Delgoshaei et al. (Delgoshaei et al. 2014) maximized NPV in a MMRCPSP with preemptive activities.

Icmeli and Rom (Icmeli and Rom 1996) maximized NPV of problem with continuous activity durations and time-dependent resource capacities. Chen et al. (Chen et al. 2015) employed the NPV objectives in a problem where payments are done on activities completion time. A comparison between problems with cash flow optimization was carried out by Dayanand and Padman (Dayanand and Padman 1997).

Some research studies have been dedicated to different payment methods. Vanhoucke et al. (Vanhoucke, Demeulemeester and Herroelen 2001b) assumed the cash flow of an activity to be a linear and non-decreasing function of its completion time. On the other hand, Vanhoucke et al. (Vanhoucke, Demeulemeester and Herroelen 2003) considered progressive payments for activities. Najafi and Niaki (Najafi and Niaki 2006) mentioned that, in practice, payment of a subset of activities may proceed as soon as completion of the last activity in that subset.

Smith-Daniels et al. (Smith-Daniels, Padman and Smith-Daniels 1996) and Sung and Lim (Sung and Lim 1994) proposed maximizing discounted cash amount available in each period. Cash flows of each activity can influence available amount of cash in each period.

2-4-4. Quality-based objectives

Estimating and quantifying the impact of a given execution mode option on the quality of the project activity and, ultimately, the entire project is a challenging topic, which has attracted researchers. This subject can be attributed to two major challenges: (1) the difficulty of measuring and quantifying the impact of each execution mode on the quality of the project activity under consideration; (2) the complexity of aggregating quality levels at the activity level to provide an overall quality performance at the project level.

In this regard, Babu (Babu and Suresh 1996), El-Rayes (El-Rayes 2005), Khang and Myint (Khang and Myint 1996), Pollack-Johnson and Liberatore (Pollack-Johnson and Liberatore 2006), Khalili-Damghani et al. (Khalili-Damghani et al. 2015), and Tareghian and Taheri (Tareghian and Taheri 2007) proposed weighted mean quality of activities in order to aggregate quality performance of activities at the overall project level. Analogously, Tareghian and Taheri (Tareghian and Taheri 2006) suggested geometric mean of activities' qualities to provide the overall project quality performance.

Kim et al. (Kim, Kang and Hwang 2012), Tavana et al. (Tavana et al. 2013), and Zhang and Feng (Zhang and Xing 2010) calculated the overall level of project quality through the summation of quality performances at the level of activities.

Heravi (Heravi and Nezhad 2013) suggested a fuzzy simple additive weighting system for stochastic estimation of activities quality levels. Monghasemi et al. (2015) introduced fuzzy linguistic variables to quantify quality of activities; they suggested a fuzzy agglomeration function based on a convex relationship between minimum and average quality of all selected execution modes. Similarly, Hajiagha et al. (Razavi Hajiagha et al. 2013) utilized grey numbers to illustrate uncertainties in estimating activities quality level. Mokhtari and Bastan (Mokhtari, Salmasnia and Bastan 2012) assumed a continuous scale from zero to one in order to specify the quality attained by each individual activity; they also considered the minimum level of individual activities as the quality function.

Liberatore and Pollack-Johnson (Liberatore and Pollack-Johnson 2013) proposed a general quality function based on two basic properties where time and cost of activities are reasonable in the domain: (1) Holding time constant: quality is an increasing function of cost; thus, if time is fixed, allocating more budget to a task will increase the quality. (2) Holding cost constant: quality is an increasing function of time; thus, allocating more time to a task where the budget is constant will increase the quality of a task. Analogously, for a fixed quality level, the function would represent a standard time/cost tradeoff curve, which is decreasing and convex.

Mungle et al. (Mungle et al. 2013) proposed a quality measurement approach based on Analytical Hierarchy Process (AHP) to evaluate anticipated quality of work performed by subcontractors.

Ning and Lam (2007) first stated that the relation between quality and cost could be determined by reliability theory. Zhao and Hao (Zhao and Hao 2011) claimed that reliability must be considered for complex construction projects, and it should not be limited to activities level. Tao and Tam (Tao and Tam 2012, Tao and Tam 2013) provided a System Reliability Optimization approach in order to enhance quality of construction projects. They grouped main construction activities into work packages and defined the reliability structural function based on physical arrangement of work packages. Zhang et al. (Zhang, Du and Zhang 2013) presented a quality performance index based on a quality function which defines the relationship between quality of activities and their durations. Then, an agglomeration function based on reliability theory was proposed to estimate project quality level.

2-4-5. Multiple Objectives

The conventional MMRCPSP has a single objective function (e.g. make span minimization, cost minimization), and other problem properties, such as project budget or resource utilization, are controlled by means of constraints. Recently, several authors have considered multi-objective scheduling problem.

One basic approach to deal with multiple objectives is to aggregate all performance measures into one overall objective through weighted summation, in this regard, Nudtasomboon and Randhawa (Nudtasomboon and Randhawa 1997) and Voss and Witt (Voss and Witt 2007) considered an objective that contains make span, weighted tardiness, and setup costs. Al-Fawzan and Haouari (Al-Fawzan and Haouari 2005) combined make-span minimization and maximization of total free slack into one overall objective.

Hajiagha et al. (Razavi Hajiagha et al. 2013) introduced a fuzzy goal programming approach to aggregate different projects prospective into one objective function. Similarly, Zhang and Xing (Zhang and Xing 2010) employed a Multiple Attribute Utility (MAU) function in order to solve MMRCPSP with time, cost, and quality objectives. MAU is a measure of desirability of outcomes associated with alternative actions.

On the other hand, generating all Pareto-optimal solutions for a multiple objective MMRCPSP is another way to cope with this problem. Several authors followed this approach. Azimi et al. (Azimi, Aboutalebi and Najafi 2011) minimized project duration as well as project costs. Viana and De Sousa (Viana and de Sousa 2000) minimized the make span, overutilization of each renewable resource, and the mean weighted tardiness. Monghasemi et al. (2015) proposed a multi-criteria approach in order to optimize project time, cost, and quality simultaneously. Heravi and Faeghi Nezhad (2013) employed Borda-OWA method which is a group decision-making process to solve MMRCPSP with time, cost, and quality objectives.

For more information regarding multiple-objective MMRCPSP, one can refer to Khalili-Damghani et al. (Khalili-Damghani et al. 2015), Afruzi et al. (Afruzi et al. 2013), Peng and Wang (Peng and Wang 2009), Wuliang (Wuliang and Chengen 2009), Iranmanesh et al. (Iranmanesh, Skandar and Allahverdiloo 2008), Tiwari et al. (Tiwari et al. 2009), Ghoddousi et al. (Ghoddousi et al. 2013), and Abdel-Basset et al. (Abdel-Basset, Atef and Hussein 2018).

2-5-Alternative solution procedures

2-5-1. Exact Methods

Among exact solving methods for MMRCPSP, Branch-and-Bound approach is the most preferred method addressed by authors. In this regard, Khang and Myint (Khang and Myint 1996), Sabzehparvar and Seyed-Hosseini (Sabzehparvar and Seyed-Hosseini 2008), Kyriakidis et al. (Kyriakidis, Kopanos and Georgiadis 2012), Buddhakulsomsiri and Kim (Buddhakulsomsiri and Kim 2006), Chen et al. (Chen et al. 2015), Kim et al. (Kim et al. 2012) solved their proposed MMRCPSP using branch-and-bound method. Sprecher and Drexl (Sprecher and Drexl 1998) enhanced the basic enumeration scheme of branch and bound method by searching tree reduction schemes, highly increasing the performance of algorithm. Heilmann (Heilmann 2003) made use of a branching strategy where the branching rule was selected dynamically. The solution approach is an integration approach where the modes and start times are determined simultaneously. Deblaere et al. (Deblaere, Demeulemeester and Herroelen 2010) proposed a branching procedure based on mode and delaying alternatives.

On the other hand, Tao and Tam (Tao and Tam 2012, Tao and Tam 2013) employed the Levenberg Marquardt plus Universal Global Optimization method in order to optimize MMRCPSP with time, cost, and quality objectives.

2-5-2. Heuristic Methods

Along with exact solving methods, several researchers have emphasized heuristic methods in order to decrease the computational time. These methods generally make use of simple priority rules to reduce some part of search area. Heilmann (Heilmann 2001), Lova et al. (Lova et al. 2006), and Buddhakulsomsiri and Kim (Buddhakulsomsiri and Kim 2007) utilized heuristics based on priority rules. Heilmann (Heilmann 2001) proposed a multi–pass priority rule method with back planning based on an integration approach, embedded in random sampling. Singh (Singh 2014) proposed a hybrid solving algorithm based on priority rules and AHP method to cope with MMRCPSP where the objective was to minimize project duration and penalty costs simultaneously. Gerhards et al. (Gerhards, Stürck and Fink 2017) combined an adaptive large neighborhood search algorithm with a mixed integer programming method to solve the MMRCPSP; they also showed that their proposed approach could compete with other heuristics.

2-5-3. Meta-Heuristic methods

Since each activity in the MMRCPSP can be executed in a particular mode with its specific time, cost, and quality, the MMRCPSP is known to be an NP-Hard problem from computational complexity point of view. Therefore, it is not possible to develop a polynomial time-order algorithm for medium- and large-sized instances of the MMRCPSP. Meta-Heuristic algorithms usually generate suitable solutions (qualified and low computational time) for NP-Hard problems.

Simulated Annealing (SA) is a well-known local search algorithm, which is able to solve hard combinatorial problems through a controlled randomization procedure. Application of SA on MMRCPSP was addressed by Seifi and Tavakoli-Moghaddam (2008), Delgoshaei et al. (2014), Mika et al. (2005), and Rahimi et al. (2013).

Deblaere et al. (2010), Atli and Kahraman (2014a), Ben Abdelaziz (2013), Najid and Arroub (2010), and Beşikci et al. (2015) employed Tabu Search (TS) on MMRCPSP. Muritiba et al. (2018) proposed a Path-Relinking (PR) for MMRCPSP and demonstrated the superiority of their proposed algorithm over most of competitive methods in the literature. Moreover, Tchao and Martins (2008) described a TS-based algorithm with path relinking. Path relinking was used as a post optimization strategy in order to explore paths that connect elite solutions found by TS algorithm.

Recently, different variants of Genetic Algorithms (GA) have been proposed to deal with MMRCPSP, e.g., Ulusoy et al. (2001), El-Rayes and Kandil (2005), Iranmannesh et al. (2008), Wuliang and Chengen (2009), Beşikci et al. (2015), Vartouni and Kanli (2014a), Alcaraz et al. (2003), and Lova et al. (2009), and Afruzi et al. (2013). Peteghem and Vanhoucke (Peteghem and Vanhoucke 2010) introduced a bi-population GA that makes use of two separate populations to generate new schedules. Pérez et al. (2014) introduced a GA complemented with different local search methods and a multi-objective management of evolution. Mungle et al. (2013) proposed a fuzzy decision-making and average linkage-based hierarchical clustering algorithm with GA to provide manageable Pareto-optimal front solutions in order to facilitate the decision-maker for a better decision-making. Barrios et al.

(2010) proposed a two-phase GA with different representation, fitness, crossover operator to deal with MMRCPSP with minimum and maximum time lags between activities.

Ghoddousi et al. (2013) presented a non-dominated-based genetic algorithm (NSGA-II) in order to find non-dominated solutions considering cost, time, and resource moment deviation as multiple project objectives.

Ant Colony (AC) optimization is also a met-heuristic method imitated from behavior of real ant colonies in communications and cooperation to find the shortest path between food and nest. Chiang et al. (2008) first proposed an AC algorithm to cope with MMRCPSP. Chen et al. (2012) employed AC on a stochastic MMRCPSP with probabilistic activity's cost and length; fitness of solutions is then examined via Monte Carlo simulation method. Zhang et al. (2012) presented an AC with two-level pheromones to guide the search course in the algorithm. Li and Zhang (2013) analogously considered two-level pheromones and an elitist-rank strategy to update pheromones. Wuliang et al. (2014) suggested an AC algorithm in order to determine the priority values of activities and their execution modes.

Particle Swarm Optimization (PSO) simulates a social behavior of colonies, such as flocking of birds, to a promising destination. Several researches have been dedicated to application of PSO algorithm to solve MMRCPSP. Jarboui et al. (2008) presented an alternative approach to solving MMRCPSP by utilizing PSO features. Zhang and Xing (2010), Rahimi and Iranmanesh (2008), and KHalili-Damghani et al. (2015) applied PSO algorithm to determine optimum schedule of activities as well as their execution mode considering cost, time, and quality objectives. Similarly, Azimi et al. (2011) provided a multi-objective PSO algorithm to provide a schedule of activities with minimum duration and maximum net cash flow. Kalilzadeh et al. (2012) introduced a PSO algorithm with a new displacement rule in order to improve intensification process by allowing each particle to visit two local positions before moving toward optimum solution.

In this regard, Szendrői (Szendroi 2010) and Csébfalvi (Csébfalvi and Szendroi 2012) applied Harmony Search Algorithm (HSA) to deal with MMRPSP. Peteghem and Vanhoucke (Van Peteghem and Vanhoucke 2011) and Baradaran et al. (Baradaran et al. 2012) suggested the application of Scatter Search (SS) in order to solve MMRCPSP. Afshar- Nadjafi et al. (2015), Nguyen and Kachitvichyanukul (2012), and Damak et al. (2009) adopted Deferential Evolution (DE) algorithm. Wang and Fang (2011) proposed a Shuffled Frog-Leaping Algorithm (SFLA) to provide schedules of activities as well as execution modes considering precedence relationships and resource scarceness constraints.

Vanhoucke and Coelho (2018) presented a much more diverse and comprehensive data set for MMRCPSP in order to enable the researchers to develop algorithms for solving a wider range of project scheduling problems.

2-6-Analysis

2-6-1. Deterministic

In general, most of research studies about MMRCPSP are quantitative in nature and rely on average or expected values of problem variables and parameters and, thus, are named as deterministic models. In this regard, Vanhoucke and Debels (Vanhoucke and Debels 2008), Voss and Witt (Voss and Witt 2007), Vanhoucke (Vanhoucke 2008), Bartels and Zimmermann (Bartels and Zimmermann 2009), Tavana et al. (Tavana et al. 2013), Pérez et al. (Pérez et al. 2014), and Cheng et al. (Cheng et al. 2015) are some important and recent studies on deterministic MMRCPSP.

2-6-2. Stochastic

Stochastic analysis involves distributions and confidence intervals around estimated values instead of average or expected values. Thus, stochastic methods incorporate a larger degree of variation in comparison with deterministic approaches. Chen and Zhang (2012) and Mokhtari and Bastan (2012), Afruzi et al. (2013), Eshtehardian et al. (2009), Godinho and Branco (2012), presented an stochastic optimization model in which activity durations and costs are given by random variables. Heravi and Nezhad (2013) and Monghasemi et al. (2015) utilized stochastic variables to represent uncertainty in activity duration, cost, and quality. Li and Womer (2015) captured stochastic resource supplies in MMRCPSP. On the other hand, Gutjahr (2015) considered stochastic multi-mode project scheduling under risk aversion.

2-6-3. Fuzzy

Fuzzy techniques are used when problem parameters/variables are not only imprecise, but also vague. When problem parameters are not known and historical data are not sufficient to extract distribution functions, fuzzy methods can be used. In this regard, Zhang and Xing (2010), Baradaran et al. (2012), Khalilzadeh et al. (2012), Zhang and Xu (2014), Nguyen and Kachitvichyanukul (2012), Atli and Kaharman (2014b), Ben Abdelaziz (2013), Vartouni and Khanli (2014b) Ghoddousi et al. (2013), Hao et al. (2014), and Sajadi et al. (2017) applied fuzzy variables in order to estimate activity durations and cost.

Xu et al. (2012) considered environmental impacts of large construction projects by means of fuzzy linguistic variables. Zheng et al. (2013) also utilized fuzzy linguistic variables in order to prioritize activities with uncertain durations.

2. Future Research

This section is dedicated to identification of current gaps and possible trends, which could shape future research in MMRCPSP. In this regard, Algorithm 1 demonstrates the proposed sequential steps which are applied to distill potential trends and gaps in the literature. The proposed procedure is mainly derived from Willems and Vanhoucke (2015); however, it is enhanced by considering the effect of publication date on trend identification process. Generally, three areas of further research can be recommended: (i) considering other objective functions except cost and time such as quality simultaneously; (ii) developing new models which are able to cope with uncertainties encountered in problem parameters; (iii) extending existing solving procedures in order to handle real-world problems.

3-1. Trend and gap identification

3-1-1. Step 1: single class analysis

As Algorithm 1 indicates, the first step for gap identification is to find those subclasses, which have gained very little attention, in comparison to other subclasses among each individual class. This stage is dedicated to a preliminary search for gaps in order to save those subclasses containing a few papers from being overlooked at the next levels. A threshold equal to 1 was recommended by Willems and Vanhoucke (2015) in order to identify potential gaps. As a result, 6 potential Gaps were identified in the first step: setup time, time switching constraints, multiple objectives and objective based on quality, and finally fuzzy and stochastic analysis.

Tab. 1. Demonstrates classification framework defined by six classes and related subclasses.

Notations

K: number of classes that have been combined, k=1,…,6

P: number of publications that have been considered

$combination_k$: a specific combination of k subclasses from k different classes

$N_r(combination_k)$: number of occurrences of $combination_k$

$N_r(subclass_j)$: number of papers assigned to $subclass_j$

Y_0**:** Initial year which forms the bassline of publication scoring method (2000)

Y_p: Year of publication of paper p

Y_c: current year of study (2016)

S_p: score of publication p($\frac{[(Y_c - Y_0) - (Y_c - Y_p) + 1] \times 2}{(Y_c - Y_0)[(Y_c - Y_0) + 1]}$)

$S(combination_k)$: sum of scores of all publications matching with $combination_k$

Step 1: Single class analysis

$k \leftarrow 1$

for each $subclass_j$ in $class_i$ **Do**

if $\frac{Max_x Nr(subclass_x) - Nr(Subclass_j)}{Nr(Papers) / Nr(subclasses)} > 1$ **then** save as possible gap

end if

end for

$k \leftarrow$ k + 1

Step 2: Recursive Procedure

For each $combination_k$ of k classes **do**

If $S(combination_k) \geq$ threshold **then**

Save as possible trend

$k \leftarrow$ k + 1

if $k \leq 4$ **then** go to step 2

end if

else if $k \geq 3$ **then** save as possible gap

end if

end for
Step 3: Qualitative analysis
for all saved possible trends and gaps do check relevance
end for

Algorithm 1 Trends and gap identification procedure

3-1-2. Step 2: recursive analysis

The recursive analysis is aimed at finding a combination of subclasses that regularly and recently has occurred. Trends that are more detailed can be identified if higher levels of *k* are experimented; however, in this study, level of *k* is limited to 4. Moreover, as level of *k* increases, the number of occurrences per combination decreases.

As 3-1 demonstrates, a scoring scheme is utilized which puts more emphasis on recent publications rather than older ones. This scheme includes scores of the papers published during year 2000 till now. For example, score of a paper published in 2005 is equal to $\frac{[(Y_c-Y_0)-(Y_c-Y_p)+1]\times 2}{(Y_c-Y_0)[(Y_c-Y_0)+1]} = \frac{[(2016-2000)-(2016-2005)+1]\times 2}{(2016-2000)[(2016-2000)+1]} = 0.08$, respectively; score of a publication in 2016 is equal to 0.12. Thus, the search will start from a combination of two subclasses belonging to two different classes; if a summation of publications' scores relating to the combination is above a certain threshold, the combination is saved as a possible trend and *k* is raised by one unit. This action continues while *K* is smaller than 4. A combination is recorded as a potential gap if only the combination score of level *k* falls below threshold, while it exceeds the threshold at level *k*-1. On the other hand, potential gaps are not selected based on a combination with too little or no research. Instead, those combinations with a significant or very recent occurrence at level *k*-1 are emphasized.

Tab. 2. Classification framework and result of analysis per individual class

Class	Abbreviation	Sub Class	#	Score
Generalized activity concepts (GAC)			31	
	Pree	Preemptive scheduling	15	0.00
	Res Supp	Varying resource supply and demand	13	0.19
	Setup	Setup time	3	1.16
Generalized temporal constraints (GTC)			27	
	Lags	Time lags	14	0.00
	Deadline	Release date and deadline	10	0.44
	Time-Switch	Time-switch constraints	3	1.22
Generalized resource constraints (GRC)			31	
	Renew Res	Nonrenewable and doubly constrained resources	13	0.00
	Cum Res	Cumulative and continues resources	10	0.29
	Var Res Cap	Resource capacities varying with time	8	0.48
Alternative objectives (AO)			186	
	Time Obj	Time-based objectives	72	0.00
	Res Obj	Objectives based on resources	36	0.97

	Mul Obj	Multiple Objectives	17	1.48
Alternative solution procedures (ASP)			86	
	Exact	Exact Methods	35	0.17
	Heuristic	Heuristic Methods	11	1.01
	Meta	Meta-Heuristic methods	40	0.00
Analysis (ANL)			155	
	Det	Deterministic	129	0.00
	Fuz	Fuzzy	17	2.17
	Stoch	Stochastic	9	2.32

3-1-3. Step 3: qualitative analysis

Not all potential gaps and trends can be considered as a relevant research gap or trend. In this stage, a qualitative analysis is investigated if the recorded gap or trend can be interpreted logically.

3-2. Potential trends and gaps for future research

summarizes identified trends and gaps resulting from applying the proposed algorithm. Gaps resulting from individual class analysis are identified with (*k*=1). Column 1 indicates the level of *k* at which the trend or gap is identified. Columns 2-7 show the combination of subclasses which form trends and gaps; the next column is dedicated to combination score; finally, the last two columns provide the sum of additional information regarding trends and gaps.

3-2.1. Stochastic analysis

Approximately 18% ($\frac{26}{155}$) of all papers present some degree of uncertainty in MMRCPSP. Almost 34% ($\frac{9}{26}$) of these papers deal with uncertainty of problem data and have been published after 2009. Stochastic analysis is mainly used in order to cope with multiple objectives of problem or to deal with uncertainty of problem parameters, where this kind of historical data exists.

Tab. 2. Current trends and potential areas of future improvements

K	GAC	GTC	GRC	AO	ASP	ANL	Grade	Trend	Gap
1	Setup	-	-	-	-	-	0.14	-	Considering setup time for activities in different modes
2	Setup	-	-	Time Obj	-	-	0.13	Considering activities setup time	-
3	Setup	Time-Switch	-	Time Obj	-	-	0.01	Activities Setup times, forbidden working periods	-
1	-	Time-Switch	-	-	-	-	0.04	-	Indication of periods in which activities can be performed
2	–	Time-Switch	-	Time Obj	-	-	0.04	Forbidden working periods	
1	-	-	-	Qual Obj	-	-	1.16	-	Optimizing quality of project through improving quality of individual activities
2	-	-	-	Qual Obj	-	Fuz	0.27	Using fuzzy linguistic variables to estimate level of quality of activities	
2	-	-	-	Qual Obj	-	Stoch	0.29	Using stochastic approaches to estimate quality of project	
2	-	-	-	Qual Obj	-	Det	0.31	Estimating Project quality through mean of quality of activates	
3	-	-	-	Qual Obj	Meta	Det	0.28	Meta-heuristics, mean of quality of activities	
1	-	-	-	Mul Obj	-	-	1.70		Considering multiple objectives simultaneously
2	-	-	-	Mul Obj	-	Fuz	0.19	Fuzzy multi-objective methods	
2	-	-	-	Mul Obj	-	Stoch	0.19	Stochastic methods for solving multi-objective problems	

2	-	-	-	Mul Obj	-	Det	0.39		
2	-	-	-	Mul Obj	Meta	-	0.52	Using meta heuristic methods in order to solve multi-objective problems	
3	-	-	-	Mul Obj	Heuristic	Fuz	0.10		Heuristic solving procedures for fuzzy multi-objective problems
1	-	-	-	-	Heuristic	-	0.31		In contrast to the exact methods, heuristics provides a near-optimum solution in a shorter amount of time
3	-	-	-	Cost Obj	Heuristic	Det	0.10	Heuristic approaches to minimize project costs	
4	Pree	-	-	Cost Obj	Heuristic	Det	0.06	Heuristic approaches to minimize project costs + Preemptive activities	
4	-	Lags	-	Res Obj	Heuristic	Det	0.09	Optimizing resource utilization + time lags between activities	
4	-	-	Renew Res	Time Obj	Heuristic	Det	0.06	minimize project duration + renewable resources	
1	-	-	-	-	-	Fuz	1.35		Incorporating vague information into optimization models
2	Pree	-	-	-	-	Fuz	0.28	Fuzzy parameters of problem + preemptive activities	
2	-	-	Var Res Cap	-	-	Fuz	0.20	Fuzzy parameters of problem + resources with varying capacity	
1	-	-	-	-	-	Stoch	0.95		Incorporating probabilistic estimations of problem parameters
2	-	-	-	Cost Obj	-	Stoch	0.37	Minimizing project costs + probabilistic definition of problem parameters	
3	-	-	-	Res Obj	Meta	Stoch	0.09	Optimizing resource utilization + probabilistic definition of problem parameters + meta heuristics	

3-2-2. Fuzzy analysis

Besides stochastic methods, fuzzy approaches are also used in order to represent vague nature of problem data. Approximately, 66% $(\frac{17}{26})$ all papers dealing with some sort of uncertainty have applied fuzzy approaches. Fuzzy approaches have been mainly used to aggregate multiple objectives of problem into one single objective, or to represent soft problem constraints. It is also applied in situations where there are not any clear historical data of the behavior of problem parameters.

3-2-3. Multiple objective functions

MMRCPSP problem tries to optimize project schedules from a different perspective, which includes time, cost, resource, and quality. Meanwhile, almost 10% of the papers try to consider different objective functions simultaneously. This trend has attracted many researchers during the last 7 years.

3-2-4. Objective based on quality

Among various objective functions, quality-based function is one of those areas which has gained little attention $7\%(\frac{12}{194})$; however, all of the papers in this area are published after year 2012. These researches are mainly focused on two topics: (i) methods to evaluate quality of activities; (ii) approaches to aggregate quality of activities at the project level.

3-2-5. Multiple objectives and Meta-Heuristic methods

Combination of multiple objectives and meta-heuristic approaches has shown a recent trend in the literature. Since MMRCPSP is naturally an Np-Hard problem, the application of Meta heuristic approaches has always attracted of meta-heuristic approaches. Moreover, recently, multiple objective meta-heuristic methods, which are able to provide pareto-optimal solutions, are becoming highlighted among the literature in a way that there are several papers on this matter published in recent years.

4. Conclusions

This research is dedicated to the classification of the multi-mode resource constraint project scheduling problem (MMRCPSP) literature and to the identification of potential gaps and trends in this area. In this regard, first, a wide literature search was performed using well-known academic databases naming Scopus, Web of Science, and Google Scholar (471 were initially found). The search result was then reduced to 172 items by applying a journal selection procedure. The gathered papers were arranged based on the following six classes: (i) generalized activity concept, (ii) generalized temporal constraints, (iii) generalized resource constraints, (iv) alternative objectives, (v) alternative solution procedures, and (vi) analysis. Moreover, a novel procedure was proposed in order to reveal potential gaps and trends in the literature.

This studies showed that application of MMRCSPS with all its variants was not limited to its original purposes, scheduling projects with respect to other aspects of project management such as quality besides traditional objectives such as cost, and time would be one of areas of future improvements. In addition, a shift from deterministic approaches to stochastic and fuzzy methods may improve the applicability of such scheduling models to the real-world problems. At last, this research reveals that besides focusing on modeling different aspects of MMRCPSP, solving procedures can be of particular importance, especially those approaches which deal with multi-objective problems.

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