Resource Constrained Multi-Project Scheduling Using Priority Rules: Application in the Deep-Water Construction Industry

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Abstract

The resource constrained multi-project scheduling problem (RCMPSP) has predominately been addressed in deterministic environment. Yet, uncertainty is inherent to real-life problems and the rise in adopting projects and portfolios in managing business organizations has initiated growing interest in considering stochastic aspects when developing a resource schedule. Priority rules (PR) is a common approach to solving the RCMPSP avoiding its computational complexity. Since the performance of PRs is highly dependent on project context, it is necessary to study the performance of PRs with real-life cases. The current study presents an application of 17 priority rules to a portfolio of deep-water construction projects. The results confirm previous results obtained from the literature and gives project and portfolio managers insights about the adequacy of different PRs with respect to schedule quality and robustness.

Keywords
Construction, Priority rules, Project management, RCMPSP, and uncertainty.

1. Introduction

A common issue for contemporary enterprises is the simultaneous management of multiple projects in a portfolio through sharing limited resources. Hence, resource related decisions are one of the prominent aspects of multi-project environments (Beşikci, Bilge, & Ulusoy, 2015). On the top of those decisions is the determination of a schedule that satisfies the activities precedence and resource constraints while minimizing the projects duration (Z. Chen, Demeulemeester, Bai, & Guo, 2018). This problem is called Resource Constrained Multi-Project Scheduling Problem (RCMPSP).

Due to the dynamic nature of the real-world environment, project scheduling is subject to considerable uncertainties. For example, the project scope may change, weather conditions may cause delays to some activities (Z. Chen et al., 2018), activities may take longer or shorter than preliminarily expected, resources availability may vary, new activities or projects may have to be included or dropped (X. Wang, Chen, Mao, Chen, & Li, 2015), material may arrive behind schedule, due dates may have to be changed (Zheng, Shumin, Ze, & Yueni, 2013). Therefore, it's essential to include uncertainty when developing project schedule. Uncertainty in project management have been classified according to their sources as internal and external uncertainty (Hazır & Ulusoy, 2019). The former relate mainly to the project and are highly affected by the organization, while the latter are generated by uncertainties in logistics and procurement, environment, socio-political circumstances, market, and technology. This work mainly focuses on uncertainty internally generated.

When dealing with multiple projects, two approaches have been used: (1) a single-project approach, using dummy activities and precedence arcs to combine the projects into a single mega-project with a single start and finish node or (2) a multi-project approach, considering a separate critical path with a distinct start and finish node for each project. Based on literature analysis, it is obvious that the second approach is more realistic, has received less attention, and presents a greater opportunity for improvement (Browning & Yassine, 2010). Thus, the multi-project approach will be used in this research.

The RCMPSP is strongly NP-hard, meaning exact methods could hardly deal with it. Hence, most research has proposed different heuristics and meta-heuristics to solve the RCMPSP (P. H. Chen & Shahandashti, 2009; Confessore, Giordani, & Rismondo, 2007; Gonçalves, Mendes, & Resende, 2008; Homberger, 2007; Kim, Yun, Yoon, Gen, & Yamazaki, 2005; Kumanan, Jegan Jose, & Raja, 2006; Nozick, Turnquist, & Xu, 2004). Recently, Priority Rule (PR) heuristics are frequently suggested for their inexpensive computational requirements, ability to address large scale scheduling problems in stochastic environment, extensive usage by commercial project scheduling software, speed and simplicity in solving the RCMPSP, and most prominently for their importance in practice (Browning & Yassine, 2010; Chakrabortty, Sarker, & Essam, 2016; Vázquez, Calvo, & Ordóñez, 2013; Y. Wang, He, Kerkhove, & Vanhoucke, 2017). However, RCMPSP studies have disagreed about which priority rule performs the best and under which conditions, which is extremely relevant (Vázquez et al., 2013). Moreover, literature lacks real-life case studies where many researches used generated data sets to address the RCMPSP.
Therefore, the aim of this study is to investigate the impact of using different priority rules on the scheduling of a portfolio of concurrent projects in the deep-water construction industry considering uncertainty of activity duration. Historical data of three real-life concurrent projects are used. To measure the impact of the different PRs, two objectives were used: quality and robustness as suggested by (Y. Wang et al., 2017).
The remainder of the paper is organized as follows. Section 2 presents a literature review of the RCMPSP. Section 3 introduces the method used to solve the RCMPSP with different priority rules. Section 4 describes the case study. The results and analysis are reported in Section 5. Finally, Section 6 summarizes and concludes the paper.

2. Literature Review

This review focuses on applying priority rules approach to the RCMPSP. Different aspects may be differentiated when adopting this approach regarding the type and number of objectives considered, the nature of the project parameters being deterministic or stochastic, the validation methodology using numerical instances or real-life case studies, and the type of priority rules. In the following paragraphs these aspects are investigated for the RCMPSP.
The main and original objective of the RCMPSP is to minimize the project duration. Although most of the studies have used duration as their main objective, it appeared in several ways. Examples include multi-project duration (Lova, Maroto, & Tormos, 2000), makespan of projects (P. H. Chen & Shahandashti, 2009), project and portfolio delay (Browning & Yassine, 2010), tardiness and makespan (Dalfard & Ranjbar, 2012), overall completion time and average percent delay (Vázquez et al., 2013), makespan (Zheng et al., 2013), individual projects' average percent delay and overall portfolio's percent delay (Browning & Yassine, 2016), average project delay and average portfolio delay (Chakrabortty et al., 2016), completion time and multi-project average project delay (González, Calderón, González, & Trujillo, 2017), quality; as the measure of the time needed to complete the projects (H. Chen, Ding, Zhang, & Qin, 2019; Y. Wang et al., 2017), and makespan; average project delay; and standard deviation of project delay (Villafáñez, Poza, López-Paredes, Pajares, & Olmo, 2019). Another objective is the expected total tardiness penalty suggested by (X. Wang et al., 2015). It is obvious that all the previously mentioned objectives, including the tardiness penalty, are duration based. The only other objective, that is not duration based, is robustness. It was suggested by (H. Chen et al., 2019; Y. Wang et al., 2017; Zheng et al., 2013) to measure the ability of a schedule to absorb uncertainty such as stochastic activity durations. Thus, there is a clear trade-off between robustness and any duration based objective. Moreover, it was observed that most of the literature has used multiple objectives with the exception of (P. H. Chen & Shahandashti, 2009; Lova et al., 2000; X. Wang et al., 2015).
The researchers addressed the RCMPSP in two different environments stochastic and deterministic regarding the activity durations of the project. However, stochastic environment is considered more realistic as it is better in terms of real-life representation. Hence, most of the studies used stochastic activity durations with the exception of (Chakrabortty et al., 2016; P. H. Chen & Shahandashti, 2009; Dalfard & Ranjbar, 2012; González et al., 2017) who used deterministic activity durations. Most of previous studies validate the methodology applied to the RCMPSP through generated numerical instances, while limited number of real-life case studies has been presented in the literature. To the best of the authors knowledge, (P. H. Chen & Shahandashti, 2009; Dalfard & Ranjbar, 2012; González et al., 2017) are the only papers that used a real-life case study to validate their work. In addition, most of the studies, that used generated data, recommended more validation for their results and a comparison with real-life data.
A myriad of PRs has been addressed in the literature of RCMPSP. These were originally designed for the single project case and have been extended to the multi-project environment. Kolisch (1994) suggested a three-class categorization of PRs: activity-based, project-based and resource-based rules. For the first category, a priority is set based on some characteristic of the activity itself as its slack or duration. The second class prioritizes activities based on project

characteristics as being the longest activity from the longest project (LALP). Resource-based PRs give priority based on activity and/or project's resource demands. The most commonly used twenty priority rules in the literature have been closely investigated by (Browning & Yassine, 2010) using a set of generated test instances covering different situations related to resource distribution and resource contention. The provided results present a decision aid for project and portfolio managers in solving the static RCMPSP. This same set of 20 PRs has also been used in several research (Browning & Yassine, 2016; H. Chen et al., 2019; Dalfard & Ranjbar, 2012; Y. Wang et al., 2017). (Browning & Yassine, 2016) added 11 rules to what they examined in 2010 that account for some basic characteristics of iterative projects, such as the likelihood of rework loops associated with an activity. The results in the literature indicate that there is no priority rule performing best for all project types. The performance of the PR is affected by several aspects related to project complexity and resource distribution and contention (Browning & Yassine, 2010). Hence, (Vázquez et al., 2013) presented a learning process to help managers select a PR in different situations when detailed information about project complexity and resource distribution and retention are lacking. They tested their algorithm using, 34 priority rules and 26 benchmark problems.

In this paper we address the RCMPSP for a real-life case study with uncertain activity duration. 17 priority rules taken from (Y. Wang et al., 2017) are adopted and tested under two kinds of objectives: quality measures and robustness measures.

3. RCMPSP Formulation

The RCMPSP considers the scheduling of activity *i* ($i = 1, 2, \ldots,$) in project *l* defined by a duration d_{il}, such that the precedence relationship is met within available resources shared by all projects. For each project *l* there is as set of K_l renewable resource types. Each activity *i* requires a renewable resource *k* ($k = 1, 2, \ldots, K_l$) by an amount r_{ilk} whose availability is expressed by R_k. Thus the problem is defined by the following precedence (Eq.1 and Eq. 2) and resource (Eq.3) constraints.

$$s_{il} + d_{il} \leq s_{jl}, \forall j \in S_{il}, \forall i \in N_l, \forall l \in L \qquad (1)$$

$$s_{0l} = 0, \forall l \in L \qquad (2)$$

$$\sum_{\forall l \in L} \sum_{\forall i \in A_t} r_{ilk} \leq R_k, \forall k \in K_l, \forall t \in T \qquad (3)$$

The first precedence constraint (Eq.1) defines the starting time of the successor task s_{jl} to be less than or equal the sum of the starting task of the preceding task in the same project *l* s_{il} and its duration d_{il}. Equation 2 indicates the starting time of the first task in project *l* which is a dummy activity. The resource *k* requirement of activity i in the set of ongoing activities A_t at time *t* in project *l* is restricted by resource type *k* availability (Eq.3).

3.1. Priority rules

In this study, we use 17 PRs out of 20 PRs used by (Y. Wang et al., 2017) and (Browning & Yassine, 2010). The 17 PRs have been selected based on discussion by management to match practical aspects and company policies. The PRs considered in this study are summarized in Table 1. Three rules are excluded in our study: WACRU, MINWCS and MAXSP.

Table 1. Deterministic priority rules (17 rules)

Priority rule	Description	Formula
FCFS	First come first serve	min(ES_{il}), where ES_{il} represent the earliest start time of activity *i* in project *l*
SOF	Shortest operation first	min(d_{il}), where d_{il} represent the duration of activity *i* in project *l*
MOF	Maximum operation first	max(d_{il}), where d_{il} represent the duration of activity *i* in project *l*
MINSLK	Minimum slack	min(SLK_{il}) with SLK_{il} = LS_{il}-max(ES_{il}, t), where LS_{il}represents latest start time of activity *i* in project *l* in time period t
MAXSLK	Maximum slack	max(SLK_{il})

Priority rule	Description	Formula
SASP	Shortest activity from shortest project	min(f_{il}), with $f_{il} = CP_l + d_{il}$
LALP	Longest activity from longest project	max(f_{il})
MINTWK	Minimum total work content	Minimum budgeted labor hour per activity
MAXTWK	Maximum total work content	Maximum budgeted labor hour per activity
RAN	Random	Random selection of activities
EDDF	Earliest due date first	min(LS_{il})
LCFS	Last come first serve	max(ES_{il})
MINLFT	Minimum late finish time	min(LF_{il})
TWK-LST	MAXTWK & earliest late start time (2-phase rule)	Use min (LS_{il}) as a tie breaker for the MAXTWK rule.
TWK-EST	MAXTWK & earliest early start time (2-phase rule)	Use min (ES_{il}) as a tie breaker for the MAXTWK rule.
MS	Maximum total successors	max (TS_{il}) with $TS_{il}$the total number of successors of the ith activity of project l.
MCS	Maximum critical successors	max (CS_{il}) with $CS_{il}$the number of critical successors of the ith activity of project l.

3.2. Objectives

This work considers the two objective types considered by (Y. Wang et al., 2017): quality and robustness. While the first evaluates the time needed to complete a project or set of projects, the second assesses the performance of solution method in terms of the deviation initiated when stochastic activity times are considered instead of deterministic activity duration. For each of these objectives two measures are used to reflect the viewpoint of project and portfolio manager, respectively. Specifically, one of the metrics is concerned about the quality/robustness of each individual project, while the other evaluates the quality/robustness of the set of projects constituting the portfolio.

Schedule quality measures

The quality measures for each individual project *l* and for the whole portfolio consisting of L projects are given by (Eq. 4) and (Eq. 5), respectively.

$$Q1 = \frac{1}{|L|} \sum_{l \in L} \frac{AD_l - CP_l}{CP_l} \quad (4) \qquad\qquad Q2 = \frac{max_{l \in L} AD_l - max_{l \in L} CP_l}{max_{l \in L} CP_l} \quad (5)$$

The measure Q_1 expresses the deviation between the critical path duration of project l CP_l and the actual project duration AD_l considering the allocation of resources according to the selected priority rule. This measure considers the average delay of all projects. The portfolio manager's viewpoint which focusses on the whole set of subprojects constituting the portfolio is given by measure Q_2. In this case only the project with longest critical path among the portfolio is represented.

Robustness measures

Similarly, the two robustness measures are expressed by (Eq. 6) and (Eq. 7). Here the deviation between project duration AD_l based on deterministic activity duration and project duration SAD_l using simulated stochastic activity duration is used.

$$R1 = \frac{1}{|L|} \sum_{l \in L} \frac{SAD_l - AD_l}{AD_l} \quad (6) \qquad\qquad R2 = \frac{max_{l \in L} SAD_l - max_{l \in L} AD_l}{max_{l \in L} AD_l} \quad (7)$$

As mentioned earlier for the quality measures, ($R1$) measure represents the project manager's perspective concerned with the performance of each individual project, while ($R2$) reflects portfolio manager viewpoint by considering the project with the longest project duration.

4. Case Study

The case study addressed in this work is conducted in one of the biggest multi-national construction companies in the Middle East. The company is recognized as a leading regional Engineering, Procurement, and Construction (EPC) contractor with a strong portfolio covering various businesses like oil, gas, chemical, petrochemical, power, industrial and infrastructure projects. The company provides its services in the Middle East and North Africa. It employs a workforce of over 30,000 people, and owns a large fleet of construction equipment, high tech fabrication facilities for process equipment, and offshore fabrication yards.

This case study addresses a portfolio in the field of offshore construction. The portfolio consists of three concurrent deep-water construction projects. The scope of each project is the fabrication of deep-water structures which will be installed on gas wells under 1 km of sea-level with huge vessels and equipment. Figure 1 describes processes leading and succeeding the fabrication project, which is the scope of the current study. It is evident that ensuring that the portfolio will be accomplished without any tardiness is a big challenge in this type of projects. Any delay in the fabrication stage will delay the gas production that affects the national economy. Each activity needs a renewable (labor) and non-renewable (equipment and material) resources. The labor required in deep water projects must be highly-skilled and well-trained due to the customized specification required by the project client. Most of the material used in the construction phase is custom order material because each project has its own design. The following constraints are considered in our case study. First, no overtime is allowed for all resources. Second, no prefabrication is allowed outside the fabrication yard. Finally, no extension is allowed to target due dates.

All projects in the portfolio share the same resources at the same time. The problem occurs once the amount of required resources in a certain time exceeds the available resources. Solving this problem in an early stage will be helpful to avoid any delay penalties in the future.

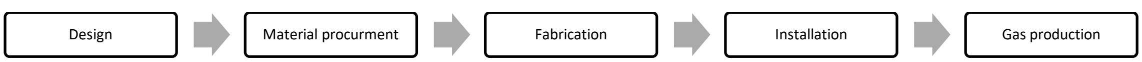

Figure 1. Deep water project process

The problem is solved by the project management team who is responsible for managing all resources in the project but under the umbrella of portfolio objectives. The main conflict between project managers and portfolio manager is the distribution of resources. Portfolio manager assigns a fixed number of resources for all projects, and each project manager considers resource requirements for individual project without any consideration to other projects. The solution to this problem is to prioritize the project activities to obtain the minimum possible duration of each project within available resources. In this research, we will study the performance of multi-project scheduling problems with a constrained resource under different priority rules which may be helpful for portfolio and project managers in the decision-making process.

5. Dataset

To examine the performance of the various priority rules, a dataset of one portfolio with three concurrent projects is used. Each of these projects consists of 34 activities. These are limited to fabrication activities without any considerations for procurement and design activities. Four different resource types are shared between all projects.

Each project needs a set of resources (labor, equipment and material). In this study, we will consider only labor resources as a constrained resource in the project. The study will focus on the most vital resources in construction project that lead sometimes to project delays. The four type of labor resources considered are Fitter, welder, grinder and welder piping.

Historical data of six projects have been used to identify the activity duration. Based on this data, the duration of each activity is presented by a triangular distribution defined by the three parameters a, b, and c presenting the optimistic, pessimistic and most likely value, respectively. The parameters have been estimated for each activity by the maximum, minimum and median duration of the activity in the 6 completed projects beside the current planned project. Table 2 summarizes the project duration and resource requirements for each of the planned 3 projects constituting the portfolio. When simulating stochastic activity durations to measure the robustness, we use the c value of the triangular distribution and random numbers to generate a set of uncertain durations for each activity. 200 Monte Carlo simulation runs are applied to obtain the simulated project duration SAD_l value to measure the robustness.

The software program used to analyze the data is Primavera (P6). It has been chosen because it is one of the most practical tools in project management. Most of priority rules already exist in the software while some priority rules need a customized calculation to be easily applied by the software.

Network complexity.

The performance of a PR is dependent on several factors, specifically, the performance measure selected, project network complexity, and resource distribution and contention (Browning & Yassine, 2010). The majority of research on RCMPS has been applied to numerical instances and benchmark problems to reflect different project and resource contexts. Thus it is necessary to identify the characteristics of the project addressed in the current case study to allow for results comparison with previous research work found in the literature.

To estimate the network complexity in our study, we use the same formula as mentioned in (Browning & Yassine, 2010) study. The input required is the number of non-redundant arcs (precedence relationships), A', and nodes (activities), N, that normalizes the complexity measure, C, over the range [0,1].

$$C = \frac{4A' - 4N + 4}{(N-2)^2} \qquad (8)$$

In the current study, the following characterizes the project network: $A' = 46,\ N = 34\ , and\ C = 0.05$; thus, $C = 0.05$ representing a low-complexity network.

Table 2. Activity durations (days) and resources requirements for the three projects

	Activity	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Project 1	Duration	24	18	23	6	153	90	31	21	61	8	1	5	12	13	2	1	4
	R_1	6	6	3	1	1	4	3	8			2	8	1	1	1	1	4
	R_2	12	12	6	1	1	8	6	16			4	16	2	2	2	2	8
	R_3	18	18	9	1	2	12	9	24			6	24	3	3	3	3	12
	R_4																	
Project 2	Duration	24	18	23	6	153	90	31	21	40	4	3	4	32	13	2	1	4
	R_1	6	6	3	1	1	4	3	8			2	8	1	1	1	1	4
	R_2	12	12	6	1	1	8	6	16			4	16	2	2	2	2	8
	R_3	18	18	9	1	2	12	9	24			6	24	3	3	3	3	12
	R_4																	
Project 3	Duration	26	70	69	5	90	76	26	21	12	4	3	6	8	4	2	1	4
	R_1	6	6	3	1	1	4	3	8			2	8	1	1	1	1	4
	R_2	12	12	6	1	1	8	6	16			4	16	2	2	2	2	8
	R_3	18	18	9	1	2	12	9	24			6	24	3	3	3	3	12
	R_4																	

	Activity	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH
Project 1	Duration	112	38	4	4	43	4	18	8	5	21	25	56	31	28	35	30	30
	R_1	1	1	1	1	1	1	1	1	1	1	2	1	2	1		2	1
	R_2																	
	R_3	1	2	2	2	2	2	2	1	1	1	4	3	4	2		5	1
	R_4	1	2	2	2	2	2	2	1	1	1	4	3	4	2		4	
Project 2	Duration	87	26	5	5	19	11	34	16	19	47	15	33	20	46	40	30	30
	R_1	1	1	1	1	1	1	1	1	1	1	2	1	2	1		2	1
	R_2																	
	R_3	1	2	2	2	2	2	2	1	1	1	4	3	4	2		5	1
	R_4	1	2	2	2	2	2	2	1	1	1	4	3	4	2		4	
Project 3	Duration	101	30	4	4	29	63	32	8	5	49	34	52	35	26	40	30	30
	R_1	1	1	1	1	1	1	1	1	1	1	2	1	2	1		2	1
	R_2																	
	R_3	1	2	2	2	2	2	2	1	1	1	4	3	4	2		5	1
	R_4	1	2	2	2	2	2	2	1	1	1	4	3	4	2		4	

Resource distribution.

Figure 2 presents the resource distribution curve for all four resources obtained from the Primavera software. The figure indicates that the bulk of resources is required at the first half of the project. This corresponds to the measures for resource distribution used by (Browning & Yassine, 2010) of the Normalized Average Resource Load Factor (NARLF) to be in the category of -3 & -2. The modified average utilization factor for resource (MAUF) is estimated as low, since the resources are fully utilized only in one month through the whole project duration as shown in Figure 2.

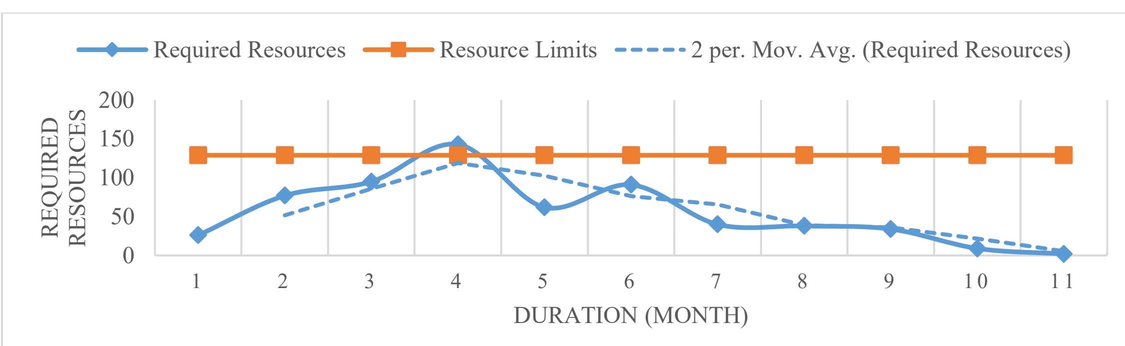

Figure 2. Total resource requirement for the three projects

6. Results and Discussion

The RCMPS problem has been solved using the Primavera software. Table 3 presents the summary of results for the performance of the studied 17 priority rules. The project manager's perspective is presented by the measures Q1 and R1, while the portfolio manager's perspective is reflected in the Q2 and R2 measures. In both cases, the managers seek to minimize the respective measure. The priority rules performing best are MS, MAXSLK, MCS, and SOF, for the Q1, Q2, R1, and R2, respectively. With reference to minimum project delay (Q1) the top four PRs are: MS, MAXSLK, MINTWK and RAN. Although MINSLK and MCS rules were expected to have a better performance, due to the fact that in the case study the activities requiring the highest resource level have high slack values, the MINSLK and MCS didn’t have a favorable performance. For robustness measure R1, the best priority rule is MCS. The MS rule performs the worst due to the fact that activities having maximum critical successors have relatively lower uncertainty level.

Table 3. Performance of the PRs on the objective measures

Priority rule	Q1	Q2	R1	R2
FCFS	5.9%	7.7%	32.8%	24.0%
SOF	13.1%	17.0%	24.9%	14.2%^{a}
MOF	13.5%	12.7%	24.6%	18.5%
MINSLK	9.8%	8.5%	28.5%	23.1%
MAXSLK	4.1%	0.8%^{a}	34.8%	32.6%
SASP	11.0%	16.2%	26.9%	15.0%
LALP	13.3%	12.7%	24.7%	18.5%
MINTWK	4.6%	7.3%	34.9%	24.5%
MAXTWK	12.9%	12.7%	25.2%	18.5%
RAN	5.2%	12.0%	34.4%	19.3%
EDDF	12.8%	12.7%	24.6%	18.5%
LCFS	9.8%	8.5%	28.5%	23.1%
MINLFT	9.8%	8.5%	28.5%	23.1%
TWK-LST	6.0%	16.2%	33.7%	15.0%
TWK-EST	6.0%	16.2%	33.7%	15.0%
MS	3.9%^{a}	10.0%	35.9%	21.4%
MCS	13.5%	11.2%	24.2%^{a}	20.1%

In order to minimize the portfolio delay (Q2) MAXSLK, MINTWK, FCFS and MINSLK are the top ranked PRs from portfolio manager’s perspective. For R2, the SOF is ranked first among the 17 priority rules and the MAXSLK delivers the worst results.

Table 3 highlights that no priority rule performs always the best or the worst for all measures, a fact that has been stated in the literature (Browning & Yassine, 2010). The delay and robustness measures for project and portfolio managers are graphically presented in Figure 3 and Figure 4, respectively. The symmetrical pattern depicted in both figures reflects the fact that delay and robustness measures behave differently, conforming the necessity for a trade-off. An improvement in one measure is accompanied with a deterioration in the other measure. For some portfolio measures exceptions are noticed as shown in Figure 4. The priority rules: SOF, SASP, TWK-LST, and TWK-EST have almost the same value of R2 and Q2.

In order to better investigate the trade-off between the delay and robustness measures, the robustness measure is plotted against the delay measure in Figure 5 and Figure 6 for the project and portfolio manager’s perspective, respectively. Figure 5 shows that the PRs may be categorized into three groups. The first group includes MS, MAXSLK, MINTWK, RAN, FCFS, TWK-LST and TWK-EST which have good performance in terms of Q1, yet a relatively high value for R1. The second category includes MINLFT, LCFS and SASP, which have improved R1 performance at the expense of almost doubling the Q1 measure. The third category encompasses SASP, MAXTWK, LALP, MOF, EDDF, MCS, and SOF which have relative lower and thus better R1 performance but a slightly higher Q1 values compared to the second category.

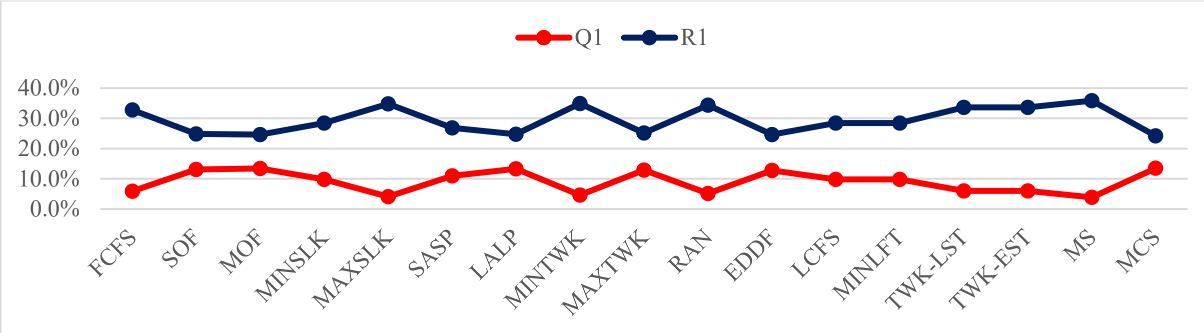

Figure 3. Quality and robustness performance measures for individual projects

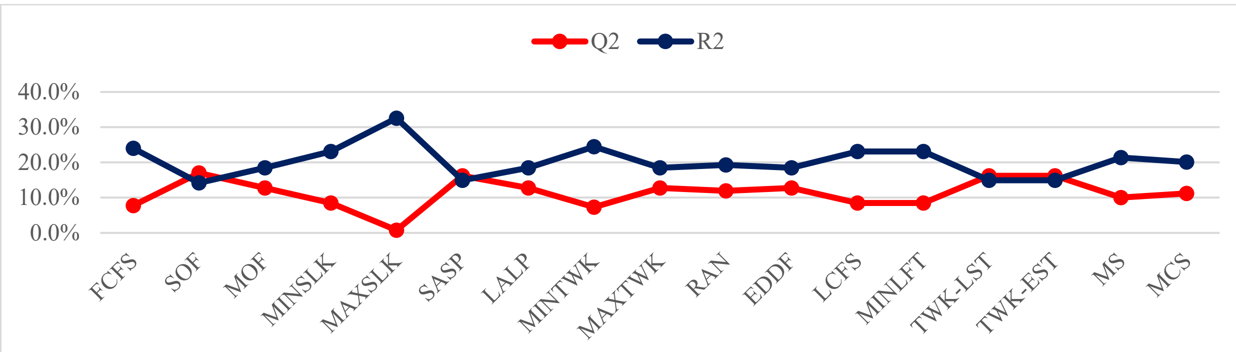

Figure 4. Quality and robustness measures for portfolio

With reference to portfolio manager's perspective, it is noticeable that a similar categorization is possible. MAXSLK is recognized to have the best performance in terms of Q2 and the worst for R2. On the other hand, TWK-LST, TWK-EST, SASP and SOF rules lead to higher value of Q2 and relative high improvement in performance in terms of R2 when compared to the MAXSLK rule. All the remaining PRs have average performance with respect to Q2 and R2 measures as depicted in Figure 4. It is also noteworthy as indicated in Table 3 that identical performance with respect to R2 and Q2 have been reported for several PRs indicating the insensitivity of the delay and robustness measures to the PRs. This is reflected in Figure 4 by the lower number of data points as compared to Figure 3.

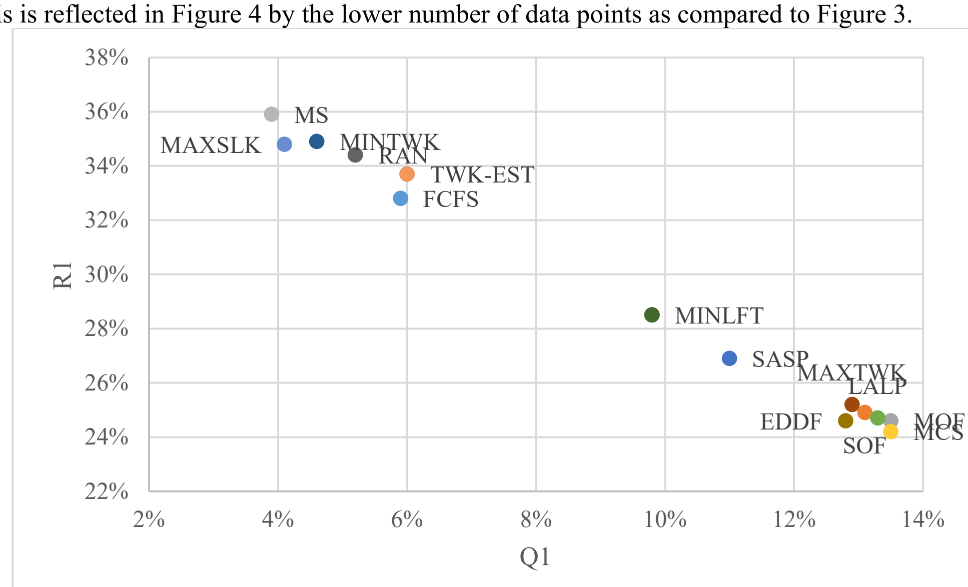

Figure 5. Performance of quality and robustness measures Q1 and R1

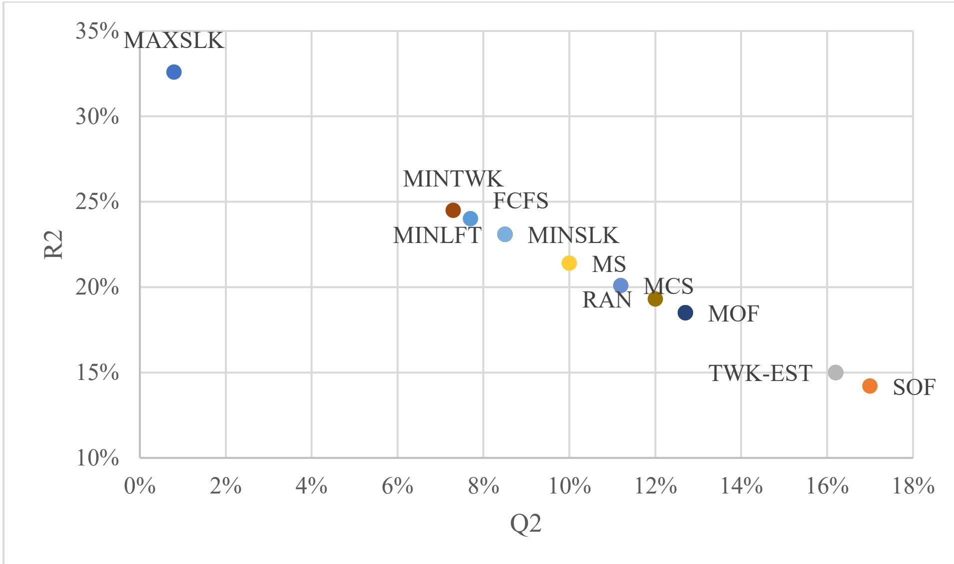

Figure 6. Performance of quality and robustness measures Q2 and R2

The current results have been compared to the results obtained by (Browning & Yassine, 2010). In their work only one objective related to delay has been considered to reflect project manager and portfolio manager perspectives. Thus only results from quality measures Q1 and Q2 can be compared. For a project configuration similar to the current case study related to network low complexity and front-loaded resource distribution and low resource contention, they identified the following PRs as performing best in terms of project delay: MINWCS, MAXSP, TWK-LST, MINSLK, MINLFT, EDDF, MAXTWK, and MOF. In terms of portfolio delay the following PRs have been identified for best performance: LALP, MS, MCS, MINSLK, and MINWCS. It is noticed that similar results are obtained. Furthermore, results have been compared to (Y. Wang et al., 2017). It is observed that values for R1 and R2 in the current study are generally higher than those reported by (Y. Wang et al., 2017). This is due to two reasons. First, the higher uncertainty level in the considered case study; in fact, the average deviation from planned value reached +148% and -43% on average. Second, while the activity duration in (Y. Wang et al., 2017) were generated by a random number ranging from 1 to 9, the activity duration in the current case study show a high variation level (Table 2). This high variation in activity duration among project activities is one of the most influencing parameters on the obtained result with reference to Q1 & Q2.

Therefore, a rule that performs well under most cases is recommended. Thus, MAXSLK and MINTWK are recommended for both project and portfolio level.

In conclusion MS wins for Q1, which seems to be acceptable because each activity has a relatively higher number of successors, while MAXSLK dominates for Q2. The unexpectedly good performance for this rule is due to the activities with high slack need more resources than the critical activities which not required a lot of resources. For robustness measures, MCS performs well for R1, whereas SOF delivers the best for R2. In addition, MAXSLK and MINTWK considered as the preferable rules with respect to Q1 and Q2. These results show that the performance of priority rules differs significantly according to the desirable objective.

7. Conclusion

This work presented a case study for applying PRs to solve the RCMPSP considering uncertainty in activity duration. A set of 17 PRs have been compared to test the performance of the individual project and portfolio in terms of schedule quality and robustness. In order to identify the PR performing best, a trade-off has to be made. An evident conflict may be identified between the selected objectives as well as the viewpoints of project and portfolio managers. The presentation of results and analysis for the specific case study for the company gives managers insights about the performance of the different PRs and allows to arrive at a compromise satisfying both objectives and viewpoints within the defined company strategy. Since, no PR is ranked best under different circumstances related to project and resource characteristics, such a case study is vital to help managers solve the RCMPSP under uncertainty inherent to

the real-life cases. The applied approach is advantageous due its simplicity, low computational requirement and the application of commercial project management software.
Finally, this study is subject to the following limitations. First, we considered a relatively small set of projects (three projects), and each project consists of only 34 activities. In real-life cases project size and the number of projects included in the portfolio may be larger. Second, the study does not consider the dynamic arrival of projects. Finally, the resources are constant and uniformly distributed during the total portfolio execution duration.
Recommendations for future work include the consideration of other sources of uncertainty related to resource availability and dynamic project arrival. Additionally, other priority rules designed for the stochastic environment may be further analyzed and compared to the performance of the 17 PRs presented in this work.

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