Priority Rules Performance Analysis as a GA Initial Population for RCMPSP

Germán Eduardo Giraldo González
Full Time Professor
Unidad de Proyectos
Escuela Colombiana de Ingeniería Julio Garavito
Bogotá, AK.45 No.205-59 (Autopista Norte), Colombia
german.giraldo@escuelaing.edu.co

César Miguel Ordóñez Calderón
Project Manager – Integrarq SAS
Graduate Student – Unidad de Proyectos
Escuela Colombiana de Ingeniería Julio Garavito
Bogotá, AK.45 No.205-59 (Autopista Norte), Colombia
cesar.ordonez-ca@mail.escuelaing.edu.co

Diego Camilo Aristizabal González
Project Management Consultant for Construction Companies – Freelance
Graduate Student – Unidad de Proyectos
Escuela Colombiana de Ingeniería Julio Garavito
Bogotá, AK.45 No.205-59 (Autopista Norte), Colombia
diego.aristizabal-g@mail.escuelaing.edu.co

Jonathan Xavier Castellanos Trujillo
IT Director – Technosoft Solutions SAS
Graduate Student – Unidad de Proyectos
Escuela Colombiana de Ingeniería Julio Garavito
Bogotá, AK.45 No.205-59 (Autopista Norte), Colombia
jonathan.castellanos@mail.escuelaing.edu.co

Abstract

Solutions to Resource Constrained Multi-Project Scheduling Problem (RCMPSP) were traditionally based on priority rules (PR) heuristics, and meta-heuristic approaches such as Genetic Algorithms (GA) and Evolutionary Strategies are recently proposed. In order to improve performance of these solutions, this paper solves the centralized RCMPSP using Priority Rules (PR) heuristics as best-case scenario for GA initial population. Using recently improved heuristics, this research analyze 12 well known priority rules on 14 different sets of simultaneously scheduled multi-projects commonly found in literature, with some generalized characteristics such as activity on node, deterministic durations, limited global resources and minimum Total Makespan (TMS) as objective. Furthermore, in order to evaluate the initial population performance, experimental results are compared, in terms of TMS and average project delay (APD). Analysis results shows that GA approach can lead to better solutions in some cases, in terms of TMS and APD, using an improved initial population.

Keywords
Resource constrained multi-project scheduling problem; RCMPSP; genetic algorithms; priority rules; metaheuristics

1. Introducción

The Resource Constrained Project Scheduling Problem (RCPSP) has been extensively studied in literature since the 1950s, mainly in the field of operations research and production systems (Okada et al., 2016). Likewise, as structures and organizational work by projects are more common, multiple applications have been made in modern project and production management, in construction, software, and operations and machine programming projects in production facilities (Wauters et al., 2012). However, the classic RCPSP model is not general enough to model real life aspects, so different extensions have been proposed (Wauters et al., 2016). In practice, organizations need to schedule multiple projects simultaneously, so one of the greatest interest extensions is the Resource Constrained Multi-Project Scheduling Problem (RCMPSP), which takes into account the global (or local) resources and precedence constraints, and as objective, performance measures related to time or cost, such as completion time (Makespan or Total Makespan TMS) or Average Delay (Average Project Delay APD or Total Project Delay TPD), or Reduction of the budget of each project or of the budget of the program (set of projects) or portfolio (set of projects and programs), among others. In general, the problem is to find the optimal Schedule of activities and projects that minimizes the objective performance measure under a set of constraints and assumptions.

It is well known that RCPSP is a combinatorial strongly NP-Hard optimization problem (Blazewicz et al., 1983), so RCMPSP is also strongly NP-Hard (Okada et al., 2016, Browning and Yassine, 2010). This means that there are no known algorithms that can solve the problem optimally in polynomial time (Lenstra and Kan, 1978). Therefore, heuristic and meta-heuristic solutions are proposed, typically, Priority-Rule (PR) Based, such as those studied by Browning and Yassine (2010), but recently improved by meta-heuristics such as genetic algorithms (GA) and other evolutionary methods (Okada et al., 2016). PR-based heuristics are important and necessary for several reasons: 1. They reduce computational time considerably, which makes it possible to treat larger problems, 2. They are fundamental to other local search and sampling based heuristics, being indispensable for The construction of initial solutions for metaheuristics, and 3. They are commonly used in commercial packages because of their simplicity, speed and ability to generate acceptable solutions (Kolisch, 1996a and 1996b; Hartmann and Kolisch, 2000). Likewise, the RCMPSP extension has been solved through two types of approach: simple and multi-project, as well as static and dynamic approaches. In the simple project, the entire schedule network is considered as a single project with a single critical path (reducing the problem to a RCPSP), while in the multi-project, each of the projects in the set is considered as a single project with an independent critical path (Kurtulus and Davis, 1982); In the static, the number of projects remains constant and the scheduling solution does not change over time, while in the dynamic, the number of projects changes over time, as other projects arrive at different dates, changing the program or portfolio schedule.

In this paper, we discuss the RCMPSP static problem with equal start times for all projects and a simple project approach, aiming to improve the completion time (TMS) and the multi-project Average Project Delay (APD). Each multi-project constitutes a single network, with a limited set of global resources, smaller than those required by the activities, so they cause constraints on their realization, and transfer times between projects equal to zero. The main objective is to distribute the scarce resources in the best way, finding a schedule that allows to minimize TMS and APD of multi-project. In order to improve the solution found by heuristics, the solution found by a priority rule (PR) is used as the initial population for a subsequent meta-heuristic based on Genetic Algorithms (AG). Using 14 sets of multi-projects, we analyzed the performance of 12 PRs commonly found in the literature, and then used the best 3 (in terms of TMS) as a starting point for GA. We found those PRs that may have greater potential to improve solutions found by AG and, in turn, may create future lines of research. Results are reported in terms of mean analysis for TMS and APD, as well as computational time.

The rest of this paper is organized in sections, as follows. In the second, the RCMPSP problem is described in its basic form. In the third, the related literature review is presented. In the fourth, the methodology is presented. In the fifth, the results for the 12 PRs and 14 groups of selected projects are showed. Finally, in the sixth, conclusions and future work are proposed.

2. Problem description

This article uses the Browning and Yassine (2010) definition of basic RCMPSP, which is form by a set of $l = 1, \dots, L$ projects, each with $i = 1, \dots, N_l$ activities with non-preemptable deterministic duration d_{il}, each of them having mandatory precedence relations *finish-to-start*, which prevent activity i from starting before all its predecessors are completed. Each activity will require a fixed amount of limited renewable resources r_{ik}, which are distributed in k types, where $k = 1, \dots K$ and the capacity of each one is R_k. If the resources capacity (availability) is exceeded, then the activity must wait until the resources are released. Each project has a due date determined by the critical path, while the multi-project has a delivery date equal to the critical path of the whole set. Finally, F_{il} is defined as the end date of activity i in the project l, $\boldsymbol{A_t}$ as the set of activities being processed at any time t, y P_{il} as the set of all the predecessor activities of an activity i in a project j. In this way, the problem formulation, according to Browning and Yassine (2010), can be established as follows:

Optimize : Performance measure $\left(\forall i \in N_l, l \in L : F_{1l}, \dots, F_{il}, \dots, F_{N_1 l}\right)$

Subject to : Precedence constraints: $\forall i \in N_l, \hat{\imath} \in P_{il}, l \in L : F_{il} \leq F_{il} - d_{il}$

Resources constraints, according to activities demands and capacities: $\forall i, l \in \boldsymbol{A_t} : \sum_{i,l \in A(t)} r_{ilk} \leq R_k k \in K,\ t \geq 0$

Non-negativity finish times: $\forall i \in N_l,\ l \in L : F_{il} \geq 0$

For the case analyzed in this paper, it is important to define several characteristics: 1. Single mode project scheduling approach, 2. Static environment with a set of pre-defined projects, without allowing the arrival of new projects, 3. All projects start in time zero, 4. Projects are independent and united by a dummy activity at the beginning and at the end, 5. Transfer Times are considered equal to zero, 6. Theoretical project completion date is the critical path (without considering resource constraints), 7. There are 4 different types of global resources, 8. Resources are limited and renewable, 9. Each activity has a predefined demand for resources, 10. No preemption is allowed for activities (once the activity starts, its progress is not interrupted), 11. The activity duration is deterministic, and 12. The dependencies are *finish-to-start* and obligatory.

3. Literature review

The literature on the simple project approach (RCPSP) is abundant. Revisions and analyzes such as those presented by Hartmann and Briskorn (2009), Herroelen (2005), Kolisch and Hartman (2005) and Browning and Yassine (2010) allows a close look to the problem and solutions presented. These are divided into two broad categories, exact methods (such as those presented by Chen, 1994 and Vercellis, 1994) that can only solve small problems, and heuristic procedures (including PR-based or X-pass heuristics, classical meta-heuristics, Non-standard meta-heuristics and miscellaneous heuristics) (Browning and Yassine, 2010) that can solve major problems. In terms of PR, also known as X-pass methods, these include simple and multiple methods. Simple, where a single PR is used or, multiple, where several PRs are used sequentially (Hartmann and Kolisch, 2000). In addition, they can be classified according to the information they use in 3 categories: (a) activity-related, (b) project-related, or (c) resource-related (Browning and Yassine, 2010).

This article addresses the static RCMPSP with multiple independent projects using PR and AG, and literature review will focus on recent articles and PR-heuristic-based solutions and its use in meta-heuristics as AG. The studies are presented in chronological order as follows:

- Hanh Quang Le (2008) addresses the RCMPSP with resource transfer times and proposes a new RCMPS-RMT algorithm based on 9 most widely used PR heuristics. In a static environment, in the construction sector, the author proposes a new PR based on minimum resource transfer time (MinRMT) and performs computational experiments using PSPLIB project library (Kolish and Sprecher, 1996). The study shows that the resource moving increases by 29.3% the APD and by 26.6% the TMS. By applying the MinRMT priority rule, the total project delays to 7.34% can be reduced on average (among all cases analyzed).
- Kanagasabapathi et al. (2009), analyzes the PR performance for the RCMPSP static problem in terms of Mean Tardiness (MT) and Maximum Tardiness (MaxT). The author evaluates rules that consider project due-dates, operation / activity duration times, operation / activity due-dates, project slack and activity slack. The study analyzes 11 common PRs and proposes 14 modified rules, which in some cases constitute mixtures of the original PRs. By experimentation, using 8 multi-project networks (obtained from previous studies), results shows that W-TWKR-ODD, W-TWKR-OAS, W-TWKR-LST, W-TWKR-OPS and W-TWKR-DDD rules are the Best for Min (MT) and W-OPS-OAS, ODD, OAS, and OPS rules for min (MaxT).
- Browning and Yassine (2010), address a set of 20 well known PRs for the static RCMPSP with two objectives, project lateness and portfolio lateness. The study analyzed the PRs through a full factorial (ANOVA) with 12,320 instances and several levels "with project, activity and resource related

characteristics, including network complexity and resource distribution and contention", that are linked to local or global objectives of project and portfolio Managers. It stands out in the results that TWK-LST performed well under project manager (local) perspective and under high network complexity, while SASP performs well under low complexity under portfolio manager perspective. MINWCS performs well regardless of complexity. Based on the MAUF (modified average utilization factor for resource), NARLF (normalized average resource loading factor), and C (complexity level of project), project managers, depending on the objectives they pursue, may consider choosing a certain rule.

- Kanagasabapathi et al. (2010), addresses the RCMPSP with projects having different relative earliness and relative tardiness costs (or weights), and presents a set of scheduling rules in order to minimize weighted tardiness (WT) and sum of weighted earliness (WE) and weighted tardiness of projects.The authors use 12 well known PRs and propose 14 modified PRs. Results show that Wr-TWKR-ODD and the Wr-TWKR-LST rules perform very well with respect to the minimization of weighted mean weighted tardiness of projects. Wr-OPS-OAS and Wr(ODD) rules for minimization of maximum weighted tardiness. We,r-TWKR-ODD rule with respect to minimization of weighted mean sum of weighted earliness and tardiness of projects. We,r-TWKR-LST rule with respect to the minimization of weighted mean sum of weighted earliness and weighted tardiness. Finally, We,r-OPS-OAS and We,r(OPS) rules for minimization of maximum sum of weighted earliness and weighted tardiness of projects.
- Zhang and Sun (2011), presents a new way to solve the RCMPSP using a lower bound and an upper bound for resource requirements of each activity, so that the requirements can fluctuate within a certain level and improving the resource utilization and minimizing multi-project duration. The study use Maximum Total Work Content (MAXTWK) as priority rule.
- Pérez et al. (2015), address the question of which PR to use for each instance / type of project. The analysis use and classifies 34 popular priority rules in 26 benchmarking problems (RCMPSPLIB library), according to instance parameters (complexity, degree of resource contention, and resource distribution). However, results shows that every instance has its own best PR. The authors use two objectives functions, minimize the overall completion time, Cmax (TMS), and minimize the average percent delay.
- Suresh et al. (2015) analyze the RCMPSP with resource transfer times, and propose a GA where NPV (Net Present Value) of all projects is maximized subject to renewable resource constraints. This research also presents a heuristic approach using 60 two-phase PRs, and the proposed GA approach is compared to heuristic approach, showing that GA performs better that PR.
- Okada et al. (2016) solve the centralized RCMPSP with a GA approach, based on improved genetic operators, such as crossover and mutation, and local search. The authors compare computational results with 6 decentralized methods and centralized methods presented in the literature, including SASP (PR), with better results in terms of APD and TMS.

4. Methodology

This research begins with the search of the relevant literature regarding RCMPSP, in particular, the solution methods that use heuristic and PR-based metaheuristic procedures and whose purpose is to improve the solutions found when using them as initial population for AG.

In summary, the methodology used for this study and approach of later stages is the following:

- Search, download and analysis of relevant RCMPSP and PRs literature in databases such as Scopus, Jstor, Scielo, ScienceDirect, Springerlink and Google Scholar (section 3).
- Definition of problem and its characteristics (section 2).
- Identification and selection of PRs to be used, and performance measures (objectives), based on the literature review. Each PR was used in case studies, and random rule was used as a tie breaker.
- Identification and selection of case studies (instances), in which PR will be applied.
- Programming and execution of PR and AG in JAVA language.
- Selection of the 3 best PR in terms of TMS performance measure and use of these sequences as the initial population for AG.
- Tabulation and analysis of the data collected.
- Conclusions, recommendations and proposals for future work.

5. Results

For this research, 12 PRs commonly used in the literature (Table 1) were selected, according to previous research results, such as those reported by Browning and Yassine (2010). Random rule was used as a tie breaker.

Table 1. 12 selected PRs

N.	NAME	INITIALS	DESCRIPTION	FORMULA
1	*First Come First Served*	FCFS	Activity Based Activity is scheduled first with minimum Early Start	Min (ES_{jl}) Where: ES_{jl} is the early start for activity j of project l
2	*Minimum Slack*	MINSLK	Activity Based The activity that has the minimum slack is scheduled first	Min (SLK_{jl}) Where: SLK_{jl} is the slack of the activity j of project l $SLK_{jl} = LS_{jl} - \max(ES_{jl}, t)$ LS_{jl} is the late start for activity j of project l t is the current period
3	*Shortest activity from shortest Project*	SASP	Based on activity and project Activity that has the minimum duration is scheduled first and belongs to the project that has the minimum critical path duration	Min (f_{il}) Where: $F_{il} = CP_l + d_{il}$ CP_l is the critical path of project l (without resource constraints) d_{ij} is the duration of activity j of project l
4	*Longest activity from longest Project*	LALP	Based on activity and project Activity that has the maximum duration is scheduled first and belongs to the project that has the maximum critical path duration	Max (f_{il})
5	*Earliest Due Date First*	EDDF	Activity Based Activity with the late start is scheduled first (for activity j of project l)	Min (LS_{jl})
6	*Minimum late finish time*	MINLFT	Activity Based Activity with the minimum late finish is scheduled first (for activity j of project l)	Min (FT_{jl})
7	*MAXTWK & earliest Late Start Time*	TWK-LST	Based on activity and resources Activity with total maximum work content is scheduled first In case of a tie, activity with a minimum late start is chosen	First: MAXTWK Tie breaker: Min (LS_{jl})
8	*MAXTWK & earliest early Start Time*	TWK-EST	Based on activity and resources Activity with total maximum work content is scheduled first In case of a tie, activity with a minimum early start is chosen	First: MAXTWK Tie breaker: Min (ES_{jl})
9	*Maximum total Successor*	MS	Activity Based	Max (TS_{jl}) Where:

N.	NAME	INITIALS	DESCRIPTION	FORMULA
			Activities that have the greatest number of successors are scheduled first	TS_{jl} is the total of successive activities of the activity *j* of project *l*
10	*Maximum critical successors*	MCS	Activity Based Activities that have the greatest number of critical successors are scheduled first (slack 0)	Max (CS_{jl}) Where: CS_{jl} is the total number of critical successor activities of the activity *j* of project *l*
11	*Weight activity priority*	WAP	User priority based The user prioritize the activities. Activities with the highest priority are scheduled first	
12	*Weight project priority*	WPP	User priority based The user prioritize projects. Activities with the highest project priority are scheduled first	

The selected performance measures (objectives) were TMS and APD. Additionally, computational time was recorded. Selected performance measures are shown in Table 2.

Table 2. Selected performance measures

PERFORMANCE MEASURE	FORMULA	DESCRIPTION
Tc Computational time	Seconds	Within the developed software, the total time consumed in resolving the instance is left as output data.
Total Makespan (TMS)	Max ($FT_{1,1}$, …$FT_{J,L}$)	*Finish time* (FT) of last finish activity *J* of last project *L*
Average Project Delay (APD)	$1/nt \sum_{l=1}^{L} \sum_{j=1}^{J} T\, j, l$	Average Project Delay of set of multi-projects Their calculation divides tardiness between the number of late activities

140 instances were found in the library MPSPLib (http://www.mpsplib.com/. Homberger, 2007; Kolisch, 2008 y 1996). Subsequently, its complexity was evaluated and the set of instances for this study were selected. A set of 14 multi-projects with 4 complexity ranges between 0 and 1 was conforming. The complexity was calculated based on Browning & Yassine, (2010), as follows:

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

Where : A : number of non-redundant precedence relationships or network arcs
N : number of nodes or network activities
C : multi-project complexity index

The instance selection was made based on the following parameters: 1. Number of projects (P), 2. Number of jobs per project (J), 3. Number of global resources per multi-project (G), and 4 Complexity of the network (C); With the following ranges: P [2, 5, 10, 20], J [30, 90, 120], G [1, 2, 3, 4], and C [0, 1]. Based on the number of projects, resources and complexity range, 14 instances were chosen randomly (Table 3).

Table 3. Selected Instances

Instance	**Projects**	**Resources**	**Activities (without dummy's)**
3	10	2	30
12	20	1	30
24	10	3	90
34	20	3	90
38	5	2	90
45	10	1	120
49	2	3	120
53	20	2	120
57	5	1	120
59	5	3	120
99	5	4	92
108	10	4	120
113	20	4	120
128	2	4	120

The PRs were programmed in JAVA language and executed on a LENOVO laptop, with an Intel® Core i5-4200U processor and 5 GB of RAM. The collected data are shown in Table 4 and Figures 1, 2 and 3.

Table 4. Compiled data for each instance and PR

PR	**Tc (sec) (average)**	**TMS (average)**	**APD (average)**
MS	22,80	202,00	55,02
MINLFT	20,48	202,29	53,58
EDD	21,12	203,86	55,29
MCS	19,96	204,71	57,83
FCFS	19,87	209,14	58,02
MINSLK.MINWCS	18,96	209,50	56,52
LALP	19,59	210,43	59,43
WAP	18,60	210,64	57,31
TWF.EST	18,06	211,71	59,15
SASP	18,57	211,86	57,21
TWK.LST	18,75	211,86	58,29
WPP	18,33	214,64	57,85

For the data analysis and using the Analysis of Means (ANOM) for each performance measures and all instances (average), a ranking was elaborated, which is presented in Figures 1, 2 and 3.

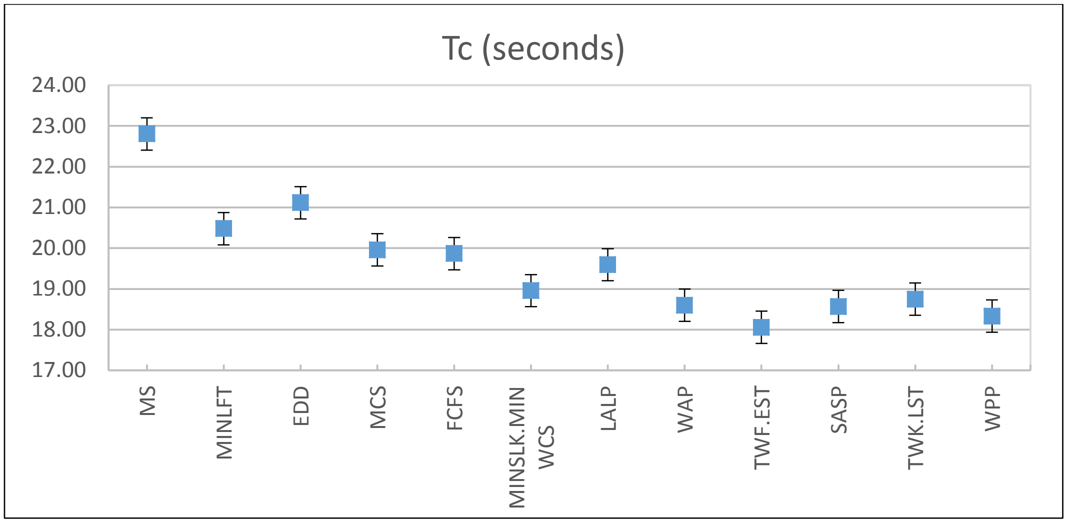

Figure 1. Tc (seconds) for all instances (average)

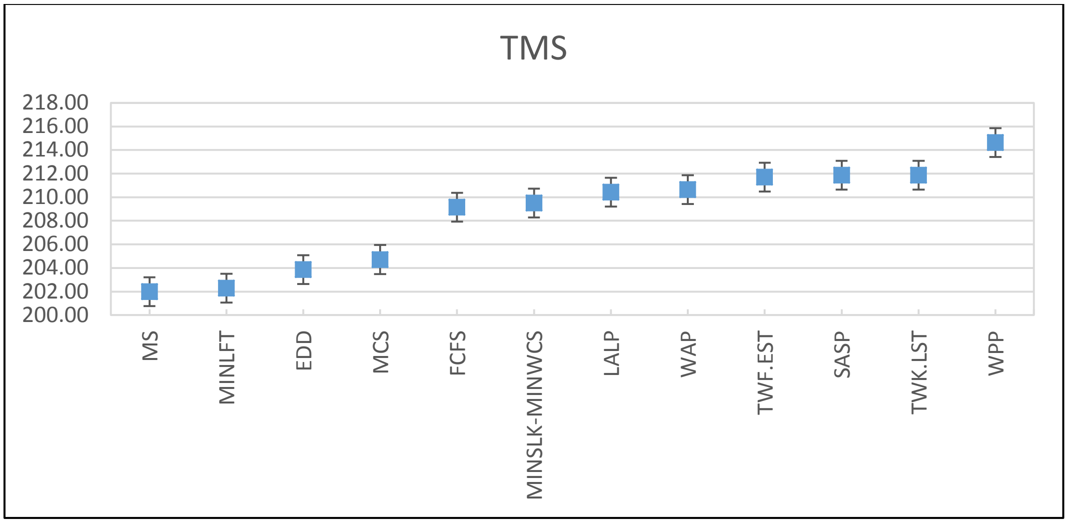

Figure 2. TMS for all instances (average)

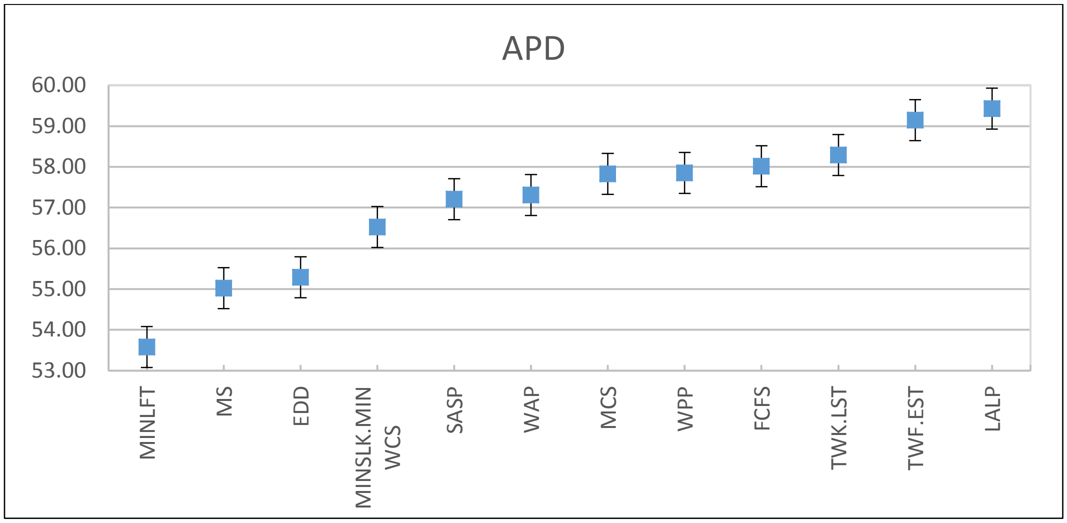

Figure 3. APD for all instances (average)

The best PRs in terms of TMS, are: MS, MINLFT and EDD. The initial populations of these PRs were used to execute AG with the following parameters: 1. Initial population: sequences obtained from each PR, 2. Number of generations: 500, 3. Number of children per generation: 10, 4. Crossover: 30 %, 5. Inversion: 30%, and 6. Mutation: 40%. However, only the first 3 instances for identified PR could be reported, because this is an ongoing research. The results for instances 34, 53 and 113 are shown in Table 5.

Table 5. Results for MS, MINLFT and EDD as initial population for AG

Method / Instance		**AG**		**PR**		**DIFFERENCE**	
PR	Instance	TMS	APD	TMS	APD	TMS (AG-PR)	APD (AG-PR)
MS	34	193,00	47,16	193,00	43,56	0,00	3,60
MS	53	173,00	35,97	173,00	34,01	0,00	1,96
MS	113	302,00	89,51	302,00	92,15	0,00	-2,64
MINLFT	34	190,00	78,25	190,00	43,24	0,00	35,01
MINLFT	53	183,00	36,70	183,00	33,42	0,00	3,28
MINLFT	113	313,00	89,21	313,00	91,36	0,00	-2,15
EDD	34	197,00	45,97	197,00	43,45	0,00	2,52
EDD	53	187,00	37,19	187,00	35,47	0,00	1,72
EDD	113	305,00	90,86	307,00	94,38	**-2,00**	-3,52
					AVG	-0,22	4,42

6. Conclusions, recommendations and future work

6.1 Conclusions

This study deals with the Constrained Multi-Project Scheduling Problem (RCMPSP) and the use of initial populations for AG, using solutions commonly found in literature (PR heuristics). In order to improve performance of these solutions, this research analyze 12 well known PRs on 14 different sets of simultaneously scheduled multi-projects, with some generalized characteristics such as activity on node, deterministic durations, total global resources and minimum Total Makespan (TMS) And average project delay (APD) as objectives.

For TMS, the best PRs are MS, MINLFT and EDD, with TMS averages of 202.00, 202.29 and 203.86 for all 14 instances. For APD the best PR were MINLFT, MS and EDD with averages of 53.58, 55.02 and 55.29 respectively. Finally, for the computational time Tc, the best rules were TWF.EST, WPP and SASP, with 18.06, 18.33 and 18.57 seconds respectively.

In general, the best PR, with which all performance measures can be minimized, is MS (Maximum Successors). This PR is activity-based, that is, it takes into account the attributes of the activities and not their use of resources. The good behavior of this PR in all performance measures is due to the fact that by prioritizing activities with the greatest number of successors, it is indirectly given a "transitivity" priority to all the activities below the network, reducing the possibility of delays.

As for AG, the results showed a better solution for instance 113, both for MS method and TMS performance measure, as for APD and MS, MINLFT and EDD methods. This proves that it is possible to achieve better solutions starting from a previous improved initial population, obtained by the best PR according to the goal sought by the portfolio or program manager.

6.2 Future work

The scope of the study is to improve and analyze the solution performance of different PRs as the initial population for GA. However, there are numerous possibilities to analyze that could improve the solutions found. Here are some possible future research lines:

- In case of a tie, the criterion used as a tie breaker is random, but different PRs may be used as a second or third rule. These results can then be used to run AG and try to get better solutions.

- This study used random as a tie breaker (second PR). This case should be analyzed with a larger number of runs (eg 5,000) to evaluate the variability. These results can be used later to execute AG and improving the solutions when comparing random as initial population versus the best solution found by PR as initial population.
- The analysis was performed with respect to Tc, TMS and APD. It is also important to evaluate the behavior of PR and AG with respect to other performance measures, such as mean flowtime, number of tardy projects and number of tardy jobs, as well as the use and distribution of resources.
- Static models do not represent reality in the best way, so it is necessary to analyze cases that allow times of transfer of resources, use of local resources, preemption in activities, priorities for activities and projects, stochastic durations, other types of dependencies, multiple modes, multiple skills, dynamic environments with different activities and projects arrival dates, and other variants that allow better representation of reality, developing new heuristics and metaheuristics for them.
- The parameters used for AG were obtained based on researchers experience, but in order to improve results, it is necessary to analyze better GA parameters combinations. Likewise, only 3 instances were tried and it is necessary to continue with 14 instances experimentation.
- Similarly, and in line with the aforementioned research lines, the impact on the project and program / portfolio cost (budget) should be analyzed.

Acknowledgements
The authors would like to thank Escuela Colombiana de Ingeniería Julio Garavito for financial support of this research.

References
Blazewicz, J., Lenstra, J.K. and Rinnooy Kan, A. H. G. Scheduling subject to resource constraints: classification and complexity. *Discrete Applied Mathematics*, vol. 5, pp. 11–24, 1983.

Browning, T. R. and Yassine, A. Resource-constrained multi-project scheduling: Priority rule performance revisited. *International Journal of Production Economics*, vol. 126(2010), pp. 212–228, 2010. Doi:10.1016/j.ijpe.2010.03.009.

Chen, V.Y.X. A0-1 programming model for scheduling multiple maintenance projects at a copper mine. *European Journal of Operational Research*, vol. 76, no. 1, pp. 176–191, 1994.

Goncalves, J. F., Mendes, J. J. M. and Resende, M. G. C. A genetic algorithm for the resource constrained multi-project scheduling problem. *European Journal of Operational Research*, vol. 189, pp. 1171–1190, 2008.

Hanh Quang Le. Resource-Constrained Multi-Project Scheduling with Resource Moving Time for Construction Projects in Vietnam. *First International Conference on Construction in Developing Countries (ICCIDC–I)*, 2008.

Hartmann, S. and Briskorn,D. A survey of variants and extensions of the resource-constrained project scheduling problem. *European Journal of Operational Research*, vol. 207, no. 1, 16 November 2010, pp. 1-14, 2010.

Hartmann, S. and Kolisch, R. Experimental evaluation of state-of-the-art heuristics for the resource-constrained project scheduling problem. *European Journal of Operational Research*, vol. 127, no. 2, pp. 394–407, 2000.

Herroelen, W.S. Project scheduling—theory and practice. *Production and Operations Management*, vol. 14, no. 4, pp. 413–432, 2005.

Homberger, J. A multi-agent system for the decentralized resource-constrained multi-project scheduling problem. *International Transactions in Operational Research*, vol. 14, no. 6, pp. 565-589, 2007.

Kanagasabapathi, B., Rajendran, C. and Ananthanarayanan, K. Performance analysis of scheduling rules in resource-constrained multiple projects. *International Journal of Industrial and Systems Engineering*, vol. 4, no. 5, 2009.

Kanagasabapathi, B., Rajendran, C. and Ananthanarayanan, K. Scheduling in resource-constrained multiple projects to minimise the weighted tardiness and weighted earliness of projects. *International Journal of Operational Research*, vol. 7, no. 3, 2010.

Kolisch, R. and A. Sprecher. "PSPLIB - A project scheduling library". *European Journal of Operational Research*, vol. 96, pp. 205–216, 1996.

Kolisch, R. and Hartmann,S. Experimental investigation of heuristics for resource-constrained project scheduling: an update. *European Journal of Operational Research*, vol. 174, no. 1, pp. 23–37, 2005.

Kolisch, R. Efficient priority rules for the resource-constrained project scheduling problem. *Journal of Operations Management*, vol. 14, no. 3, pp. 179–192, 1996(a).

Kolisch, R. Serial and parallel resource-constrained project scheduling methods revisited: theory and computation. *European Journal of Operational Research*, vol. 90, no.2, pp. 320–333, 1996(b).

Kolisch, R. Library for project scheduling problems. http://129.187.106.231/psplib/ accessed January 15, 2008.

Kurtulus, I. and Davis, E. W. Multi-project scheduling: categorization of heuristic rules performance. *Management Science*, vol. 28, no. 2, pp. 161–172, 1982.

Lenstra, J. K. and Kan, A. H. G. R. Complexity of scheduling under precedence constraints. *Operations Research*, vol. 26, no. 1, pp. 22–35, 1978.

Okada, I., Weng, W., Yang, W. and Fujimura, S. A Genetic Algorithm with Local Search using Activity List Characteristics for Solving Resource-Constrained Multiproject Scheduling Problem. *IEEJ Transactions on Electrical and Electronic Engineering*. IEEJ Trans 2016, vol 11(S2), pp. S34–S43, 2016. DOI:10.1002/tee.22324.

Pérez, E., Posada, M. and Martín, P. Learning process on priority rules to solve the RCMPSP. *Journal of Intelligent Manufacturing*, February 2015, vol. 26, no. 1, pp. 123–138, 2015.

Suresh, M., Dutta, P. and Jain, K. Resource Constrained Multi-Project Scheduling Problem with Resource Transfer Times. *Asia-Pacific Journal of Operational Research*, vol. 32, no. 6 (2015) 1550048, 2015.

Vercellis, C. Constrained multi-project planning problems: a Lagrangean decomposition approach. European *Journal of Operational Research*, vol. 78, no. 2, no. 267–275, 1994.

Wauters, T., Kinable, J., Smet, P., Vancroonenburg, W., Vanden Berghe, G. and Verstichel, J. (2016). The Multi-Mode Resource-Constrained Multi-Project Scheduling Problem - The MISTA 2013 challenge. *Journal of Scheduling*, June 2016, vol. 19, no. 3, pp. 271–28, 2016. DOI 10.1007/s10951-014-0402-0.

Wauters, T., Verbeeck, K., Verstraete, P., and De Causmaecker, P. Real-world production scheduling for the food industry: An integrated approach. *Engineering Applications of Artificial Intelligence*, vol. 25, no. 2, pp. 222–228, 2012. Doi:10.1016/j.engappai.2011.05.002.

Zhang, L. and Sun, R. An improvement of resource-constrained multi-project scheduling model based on priority-rule based heuristics. *8th International Conference on Service Systems and Service Management (ICSSSM)*, 25-27 June, 2011. DOI: 10.1109/ICSSSM.2011.5959321.

Biography

Germán Eduardo Giraldo González, PMP, is an industrial engineer, holds a master's of science degree in industrial engineering, and is a member of the Institute of Industrial Engineers (IIE) and Project Management Institute (PMI). He is a Project Management Professional (PMP)® credential holder with experience in implementing quality management systems and is a full time professor and research group director in project management of the Escuela Colombiana de Ingeniería Julio Garavito (Colombian School of Engineering Julio Garavito).

César Miguel Ordóñez Calderón is a civil engineer from Universidad Industrial de Santander, Specialist in economics from Escuela Colombiana de Ingenieria Julio Garavito and candidate to master's degree on Project Development and Project Management from Escuela Colombiana de Ingeniería Julio Garavito. Currently working as project manager at Integrarq SAS Company dedicated to consulting of construction projects.

Diego Camilo Aristizábal González, is a civil engineer from Universidad Nacional de Colombia, candidate to master's degree on Project Development and Project Management from Escuela Colombiana de Ingeniería Julio Garavito. Currently working as a Project Management Consultant of several companies in the construction sector in Colombia.

Jonathan Xavier Castellanos Trujillo, is an economist, holds an executive management degree in finance and accounting from University of La Verne, candidate to master's degree on Project Development and Project Management from Escuela Colombiana de Ingeniería Julio Garavito. Currently working as IT Director for implementation and support of ERP/CRM projects.