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# Project management under uncertainty: resource flexibility visualization in the schedule

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**Abstract**

Going from an idea to a result, using a series of well-defined techniques with deadlines and limited resources, is a skill that a project manager must have. In a rapidly changing environment like the present one, there are many factors that contribute to budget overruns and delays that occur in most major projects. To be successful, one must rely on techniques and tools that assist the project manager in the various stages of the project. Therefore, this paper presents an Add-In for MS Project®, based on a previously developed model for solving the Resource Constraint Project Scheduling Problem with Flexible Resource Management (RCPSP-FRM), which can help the project manager with regard to the scheduling of resources using flexibility, giving him relevant information to the decision making process in case of delays during the execution phase. The flexible chart and table format view allows project managers to easily and objectively identify the activities which can have their durations increased or shortened, impacting significantly on project execution time. This research contributes not only to the academic environment, but also to professional project management environments.



*Keywords:* RCPSP-FRM; resource flexibility; project management

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## 1. Introduction and motivation

Project management provides the ability to go from ideas to results by providing a range of tools and techniques that can make projects successful. Today, individuals, organizations and nations are interested in project management, becoming a distinct profession with excellent career opportunities, with undergraduate, master and certifications programs [1], [2].

In today's fast-changing environment, there are many factors that contribute to budget overruns and delays that occur in most large projects, as shown by the Standish Group [3], which reports that in 2015, 29% of projects achieved success, 52% were challenged and 19% failed. Despite the abundance of commercial tools for project management [4], the assistance provided to managers does not allow for adequate planning according to project progress, with effective risk management involved.

Some project management techniques were developed in the 1950s and 1960s as the Critical Path Method (CPM) [5], [6] and the Program Evaluation and Review Technique (PERT) [7], to work on project scheduling with unlimited resources. However, these methods have become of little use in responding to increasing complexity and resource requirements as projects grow and are more challenging [8], [9]. Goldratt [10] addresses the problems associated with these methods by introducing the concept of Critical Chain Project Management (CCPM), which aims to guarantee the delivery date of a project with the insertion of buffers.

The Resource-Constrained Project Scheduling Problem (RCPSP) [11] deals with the scheduling of projects with limited resources. In this case, for projects with greater number of activities, it is necessary to use heuristics and approximation algorithms; for small projects, it is possible to obtain exact solutions using branch-and-bound [12].

Following an innovative perspective for project management, which has been adopted in recent years [13]–[16], considering that project activities have a stochastic work content, allowing the development of project scheduling under uncertainty, coupled with proactive/reactive scheduling models [17]–[25], a model was developed that explores the flexibility of resources combining the two previously mentioned perspectives [26]. This new approach to the RCPSP problem, renamed Resource Constraint Project Scheduling Problem with Flexible Resource Management (RCPSP-FRM), takes into account the flexibility of limited resources. In this case, we intend to obtain effective solutions for the management of projects under uncertainty, resulting in a better control of the schedule, and consequently of the costs and deadlines [26]–[28]. The RCPSP-FRM approach proposed by Faria [26] allows us to explore the flexibility of resources to better cope with uncertainty. Given the slacks that typically exist on a schedule, this approach takes advantage of the flexibility of resources to absorb possible deviations from critical activities that could otherwise compromise project duration and cost. The proposed approach to RCPSP-FRM then allows a critical activity, which has no slack, to have its time reduced, adopting a strategy to decelerate non-critical activities, with slack, placing them in a reduced (slower) work mode, so critical activities, which are about to increase their duration, can still be executed on time, using its resources in an increased (faster) work mode. Considering the evolution of the methods used to solve this problem, it is understood that many studies still have to be done in order to improve the efficiency and effectiveness of projects. In this sense, and inspired by the work of Faria [26], a new project management tool to support project managers was created, following the RCPSP-FRM model. The main objective was then the implementation of the model, contributing to a future validation, by analyzing the influence of the flexibility of the resources in a schedule, making possible this academic contribution to be used in practice, to increase the knowledge in this area.

## 2. Literature review

Society has become increasingly complex, which is the trigger to motivate the need to establish well-defined processes to address this complexity. The idea of well-defined and repetitive processes arose with the industrial revolution. However, at the end of the 1950s, methodologies were created to manage non-repetitive processes, that is, processes that had single execution tasks, thus creating models for managing non-repetitive tasks called projects. Increasingly, the paradigm of projects overlaps with the paradigm of repetitive processes or operations, and it is increasingly important to know how to manage change, translated into new projects [26], [29]. A project is a work that is planned, executed and controlled by people and conditioned by limited and specific resources, causing beneficial changes within a limited time frame. It is a temporary endeavor undertaken only once, with defined objectives, limited resources, and executed in the time available to create a product, service or outcome [2], [30]–[32]. The emergence of project management as a recognized area occurred between the 1930s and 1950s, for application in engineering projects, where standardized practices and tools were used, giving rise to project management models [33]. In the 1960s, the Project Management Institute (PMI) emerged, and since then they compile a set of achieved knowledge and good project management practices, serving as the basis for organizations to manage their projects more professionally. This compilation is called Project Management Body of Knowledge (PMBOK) [30]. PMI [30] defines project management as the application of knowledge, skills, tools, and techniques to project activities that meet the project requirements. During project management, several components interrelate and, when effectively managed, result in a successful completion. PMI divides the project management processes in groups: initiating; planning; executing; monitoring and controlling and; closing. This research will focus efforts on planning, executing and monitoring and controlling activities, to achieve efficient timelines and to absorb uncertainty so that, if necessary in the execution phase, these schedules are corrected by reorganizing resources to achieve successful project execution.

Many scheduling models have emerged, starting with the Critical Path Method (CPM), which allows estimating the minimum duration of a project, with activities with known fixed durations and infinite resources [5]. Program Evaluation and Review Technique (PERT), was created to coordinate activities in the development of the Polaris missile system in 1958 in the US Navy, where there was a great deal of uncertainty [34]. From the moment that the limited resources in the definition of the projects began to be considered, the classic models like the CPM, had to be replaced by models considering resource constraints, which gave rise to the Resource-Constrained Project Scheduling Problem (RCPSP). In the RCPSP, a project can be represented by an Activity-on-Node (AoN) network. The problem can be defined as finding the starting time for each activity, while respecting the precedence constraints and the resource constraints, in order to minimize the duration of the project [11]. It is a problem that considers deterministic durations for the activities which cannot be interrupted (non-preemption), and with precedence relations between activities of type FS (Finish-to-Start) = 0 i.e. the successor activity can start as soon as the predecessor activity ends. It is a formulation of a combinatorial problem being NP-hard in the strong sense, as proved by Blazewicz, Lenstra and Kan [35], with solutions that are exponentially time-consuming, depending on the number of project activities [26].

For projects with a greater number of activities, a solution for the RCPSP is more easily obtained using heuristics, such as constructive methods, which comprise two main components: the first is the scheduling scheme, which describes how the scheduling should be constructed, assigning start times of the activities in sequence, and; the second is the priority rule, which is applied consecutively to select the activity to be scheduled [36], [37]. Based on the network information obtained via CPM, these methods use the shorter activity duration, for the SPT rule, the earliest/latest starting time (EST/LST) and the earliest/latest finishing time (EFT/LFT), respectively. Other rules consider the number of resources of each activity, number of predecessor activities, number of successor activities, among others. Although RCPSP is a good approach for project scheduling, it is still based on the assumption that the duration of activities is deterministic. For projects where the duration is non-deterministic, the RCPSP does not apply directly, and additional models or variants are required to formulate and solve the planning problem considering uncertainty. The uncertainty in project scheduling can be minimized with methods such as FRCPSP [38] which is an extension of the RCPSP with resource profiles with flexibility, and more recently the RCPSP-FRM, an extension of the RCPSP with Flexible Resource Management [26]. The FRCPSP, initially approached by Kolisch and Meyer [39] to model the scheduling of pharmaceutical research projects, establishes the allocation of resources a priori without the need to be constant in the duration of the activities, but once assigned, they are kept fixed during the execution of the project. The RCPSP-FRM establishes that a project should begin with a stable and deterministic schedule, being able to deal with uncertainty at any time during project execution, exploring the flexibility of the resources and schedule [26]–[28]. The flexibility of the schedule is expressed as the time at which a noncritical activity can be completed late, without affecting the schedule. The flexibility of resources is associated with the daily working time that resources can spend, and can be variable, depending on the needs.

Going further into the RCPSP-FRM methodology, it can be considered as a proactive-reactive scheduling approach. Generally, in the proactive phase (before the beginning of the execution) a schedule is determined, protected against uncertainties and according to the parameters of the project and the organization, being the flexibility of the schedule calculated, generating the best solutions. Then, in the reactive phase, the project execution is monitored, reacting against deviations, with the increase or decrease in the pace of execution of the activities within the calculated intervals (in the proactive phase). If schedule flexibility limits are not sufficient to deal with deviations, additional actions are usually required which will normally lead to rescheduling [17], [26]. The procedure used is as follows [26]:

- STEP -1 (before project start): Set resource flexibility parameters $(\alpha_k^-, \alpha_k^+)$
  $a_k^{nom}$ is the nominal availability of resource type $k$ (usually referred to as $a_k$ having a constant value per project); $\alpha_k^-$ the negative resource flexibility (maximum percentage decrease of $a_k$ in relation to nominal); $\alpha_k^+$ the positive resource flexibility (maximum percentage increase of $a_k$ in relation to nominal); $a_k^-$ the minimum resource availability of type $k$; $a_k^+$ the maximum resource availability of type $k$.
  $$a_k^{nom}(1-\alpha_k^-) \le a_k \le a_k^{nom}(1+\alpha_k^+)$$
- STEP 0 (before scheduling): Define the project data and determine the possible durations $(d_i^{min}, d_i^{max})$. Assuming the flexibility of the resource delimited, for example, by $\alpha_k^- = \alpha_k^+ = 25\%$, these values can be applied to the duration of the activity to determine the possible intervals for the durations for each activity where:
  - $d_i^{nom} = d_i$: The nominal duration is equal to the initial (deterministic) duration $d_i$;
  - $\overline{d_i} = d_i^{nom}/(1-\alpha_k^-)$: The maximum duration of the activity is its duration when executed at the slowest rate (unitary minimum resource availability). In this case, the minimum rate is 75%;
  - $\underline{d_i} = d_i^{nom}/(1+\alpha_k^+)$: The minimum duration of the activity is its duration when executed at the fastest rate (maximum availability of unit resources). In this case, the maximum rate is 125%;
  - $\overline{d_i}$ and $\underline{d_i}$ can assume non-integer values that are not values commonly used for activity durations. Therefore, the corresponding limit values are considered;
  - $d_i^{max} = \lfloor \overline{d_i} \rfloor$: Integer maximum duration of the activity;
  - $d_i^{min} = \lceil \underline{d_i} \rceil$: Integer minimum duration of the activity.
- STEP 1 (within the project planning stage): Establish the base schedule $S^B$ using a suitable scheduling technique and determine the $(\mathrm{slack}_i)$, the maximum possible durations $(d_{iS}^{max})$, and the schedule flexibility $(\mathrm{balance}_k^+)$. Define the initial balance of the project as $\mathrm{balance}_k^+$ and establish a work schedule $S^w$, with the same start times as $S^B$, but with end times defined in the intervals resulting from the possible durations of the activities.
- STEP 2 (during project execution): If deviations occur, check that they can be absorbed by the flexibility of the schedule and that sufficient balance is left. If this is possible, update the work schedule accordingly. If not, rescheduling is required.

This approach to the flexibility of the resources in a schedule is the basis of this work. Project managers need the information about the flexibility to take actions, so a tool was developed to provide this information to them. The process (research methodology) and the resulting tool will be presented in the following sections.

## 3. Experimental methodology

According to Simon [40], design science involves a paradigm of pragmatic research that seeks to create innovative artifacts to solve real-world problems. In this sense, the methodology adopted was Design Science Research (DSR) following the steps proposed by Vaishnavi, Kuechler & Petter [41]: problem awareness, suggestion, development, evaluation and conclusion.

In problem awareness phase, the analysis of a set of concepts, theories and relationships verified and tested, being useful to explain organizational processes and results, are necessary to identify and understand the problem under study and for which a solution is sought [41]. The problem identified was the need to develop a tool that allows project managers to visualize, analyze and consequently react to possible slippage of the project using the flexible resource management model proposed by Faria [26].

In the suggestion phase, a prototype was suggested with the requirements previously identified. The proposal was to create an Add-In for MS Project® (MSP), with a friendly user interface, which presents results about the flexibility of the resources in a table format and resource profile graphs.

In the development phase, the tool construction was performed, giving shape and form to the proposed artifact (tool for visualization and management of resource flexibility) incorporated with a set of algorithms, models and automated methods. In the development step, the C# programming language was used in the implementation of an Add-In for MS Project 2016® focusing on simple installation, ease of use and good visualization of the information.

A validation strategy (evaluation phase) with quantitative data was used. The experiments were carried out in a transversal time horizon. Experiments were conducted using the developed tool, with data generated as shown in section 4, as well as data from PSPLIB, namely the 480 instances from J30 [42], with 10% and 20% of negative and positive flexibility. From the scientific point of view, the conclusion phase presents the main results of the study. It is at this stage that the importance of the work done, usefulness, rigor and the innovation it provides are presented.

## 4. Results

This chapter describes the steps developed to successfully achieve the general objective of this work: the development of a tool based on the RCPSP-FRM method, which allows the visualization of the flexibility of the resources in a schedule. This tool will also help validate the model proposed by Faria [26]. The developed interface will be shown next, in the sequence of the execution of the tool, after visualization of the generated information, namely the flexibility of the resources after the use of the RCPSP-FRM method.

The initial interface of the tool is simple, as shown in Figure 1, and the priority rule, scheduling schema and scheduling direction, for the constructive heuristic used for the generation of the initial solution, are already predefined, being changed as required. The resource flexibility information must be entered, other than zero, so that the RCPSP-FRM is calculated. If it is zero the flexibility view will not be displayed. As referred before, there is also the possibility of importing PSPLib files with '.rcp' extension [42]. Finally the RCPSP-FRM calculations can be performed. After the initial interface of the tool, the visualization of the information is presented, namely the flexibility of the resources. It will be arranged sequentially as in execution.

For illustrative purposes, a simple project 12 non-dummy activities was used. After importing the file to the MSP, its layout in the Gantt chart is shown in Figure 2. After the introduction of the network that has information about the activities, precedences and resources, the schedule is automatically evaluated by MSP using CPM, so as can be seen in the information column, there are several resources over-allocated.

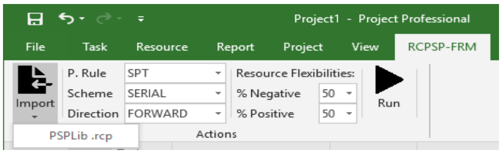
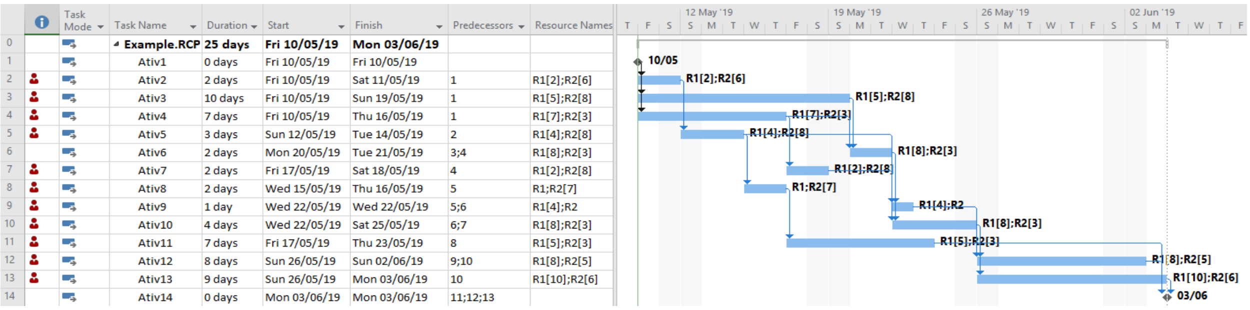



Fig. 1. Add-In RCPSP-FRM.

In order to show the flexibility of the resources according to the RCPSP-FRM method, it is necessary to obtain the project schedule, considering the RCPSP, using constructive heuristics, with a priority rule, following a schedule scheme and a schedule direction. After that, the RCPSP-FRM method is applied, using the positive and negative flexibility initially inserted (Figure 1). As a result, activities with positive and negative score are identified, as shown in Figure 3 on the RCPSP-FRM tab. The first column of the table displays the list generated by the chosen priority rule. The activities with positive score are identified with green color. The ones with negative score are identified with orange color and the others with white color. This color coding facilitates the quick identification of activities with different characteristics in relation to flexibility.

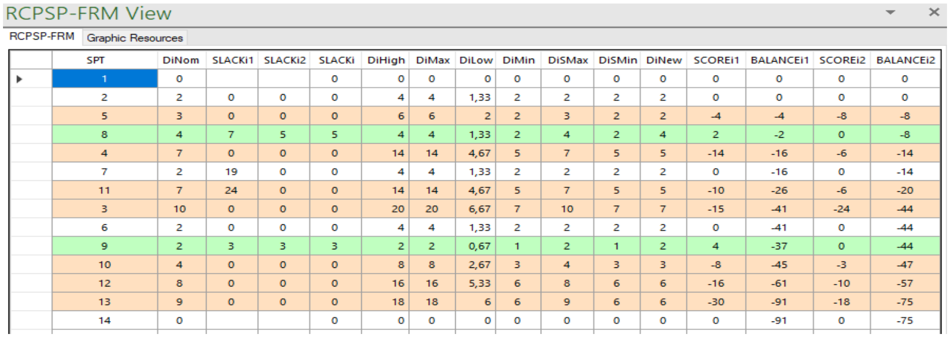
With the flexibility identified displayed in the form of a table it is possible to identify how the resources can be scheduled following the RCPSP-FRM method. For this, the resource graphs are shown in the Resource Graph tab, as shown in Figure 4.



| | | Task Mode | Task Name | Duration | Start | Finish | Predecessors | Resource Names |
|---|---|---|---|---|---|---|---|---|
| 0 | | | Example.RCP | 25 days | Fri 10/05/19 | Mon 03/06/19 | | |
| 1 | | | Ativ1 | 0 days | Fri 10/05/19 | Fri 10/05/19 | | |
| 2 | | | Ativ2 | 2 days | Fri 10/05/19 | Sat 11/05/19 | 1 | R1[2];R2[6] |
| 3 | | | Ativ3 | 10 days | Fri 10/05/19 | Sun 19/05/19 | 1 | R1[5];R2[8] |
| 4 | | | Ativ4 | 7 days | Fri 10/05/19 | Thu 16/05/19 | 1 | R1[7];R2[3] |
| 5 | | | Ativ5 | 3 days | Sun 12/05/19 | Tue 14/05/19 | 2 | R1[4];R2[8] |
| 6 | | | Ativ6 | 2 days | Mon 20/05/19 | Tue 21/05/19 | 3;4 | R1[8];R2[3] |
| 7 | | | Ativ7 | 2 days | Fri 17/05/19 | Sat 18/05/19 | 4 | R1[2];R2[8] |
| 8 | | | Ativ8 | 2 days | Wed 15/05/19 | Thu 16/05/19 | 5 | R1;R2[7] |
| 9 | | | Ativ9 | 1 day | Wed 22/05/19 | Wed 22/05/19 | 5;6 | R1[4];R2 |
| 10 | | | Ativ10 | 4 days | Wed 22/05/19 | Sat 25/05/19 | 6;7 | R1[8];R2[3] |
| 11 | | | Ativ11 | 7 days | Fri 17/05/19 | Thu 23/05/19 | 8 | R1[5];R2[3] |
| 12 | | | Ativ12 | 8 days | Sun 26/05/19 | Sun 02/06/19 | 9;10 | R1[8];R2[5] |
| 13 | | | Ativ13 | 9 days | Sun 26/05/19 | Mon 03/06/19 | 10 | R1[10];R2[6] |
| 14 | | | Ativ14 | 0 days | Mon 03/06/19 | Mon 03/06/19 | 11;12;13 | |



Fig. 2. Gantt Chart.



RCPSP-FRM View

RCPSP-FRM | Graphic Resources

| SPT | DiNom | SLACKi1 | SLACKi2 | SLACKi | DiHigh | DiMax | DiLow | DiMin | DiSMax | DiSMin | DiNew | SCOREi1 | BALANCEi1 | SCOREi2 | BALANCEi2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 2 | 0 | 0 | 0 | 4 | 4 | 1,33 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 |
| 5 | 3 | 0 | 0 | 0 | 6 | 6 | 2 | 2 | 3 | 2 | 2 | -4 | -4 | -8 | -8 |
| 8 | 4 | 7 | 5 | 5 | 4 | 4 | 1,33 | 2 | 4 | 2 | 4 | 2 | -2 | 0 | -8 |
| 4 | 7 | 0 | 0 | 0 | 14 | 14 | 4,67 | 5 | 7 | 5 | 5 | -14 | -16 | -6 | -14 |
| 7 | 2 | 19 | 0 | 0 | 4 | 4 | 1,33 | 2 | 2 | 2 | 2 | 0 | -16 | 0 | -14 |
| 11 | 7 | 24 | 0 | 0 | 14 | 14 | 4,67 | 5 | 7 | 5 | 5 | -10 | -26 | -6 | -20 |
| 3 | 10 | 0 | 0 | 0 | 20 | 20 | 6,67 | 7 | 10 | 7 | 7 | -15 | -41 | -24 | -44 |
| 6 | 2 | 0 | 0 | 0 | 4 | 4 | 1,33 | 2 | 2 | 2 | 2 | 0 | -41 | 0 | -44 |
| 9 | 2 | 3 | 3 | 3 | 2 | 2 | 0,67 | 1 | 2 | 1 | 2 | 4 | -37 | 0 | -44 |
| 10 | 4 | 0 | 0 | 0 | 8 | 8 | 2,67 | 3 | 4 | 3 | 3 | -8 | -45 | -3 | -47 |
| 12 | 8 | 0 | 0 | 0 | 16 | 16 | 5,33 | 6 | 8 | 6 | 6 | -16 | -61 | -10 | -57 |
| 13 | 9 | 0 | 0 | 0 | 18 | 18 | 6 | 6 | 9 | 6 | 6 | -30 | -91 | -18 | -75 |
| 14 | 0 | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -91 | 0 | -75 |

Fig. 3. Flexibility table.

Users can also view all features by sliding the scroll bar to the right of the chart. In the graph it is possible to observe that the activities that have flexibility to delay, are followed by a dash blue immediately after the end of the original duration of the activity, as in activities 8 and 9, with the translucent background. For activities that may need to accelerate their execution, the dash is black in color, being within the duration’s limitation of the activity, which means that it may shorten its duration. The other activities are presented without any dashes. The resource usage limit is shown as a red line. It shows the maximum amount of a resource that can be used. The model allows to work with multiple resources, thus, the graph is repeated for each resource, giving better support to the project manager. For J30 PSPLIB, using the same Priority Rule, Scheme and Direction of Figure 1, with 10% of positive and negative flexibility, 359 instances presented at least one activity with the possibility of delay in its duration and no activity with the possibility of accelerating its duration. Nevertheless with 20% of positive and negative flexibility all 480 instances presented activities with the possibility of accelerating or delaying their durations.

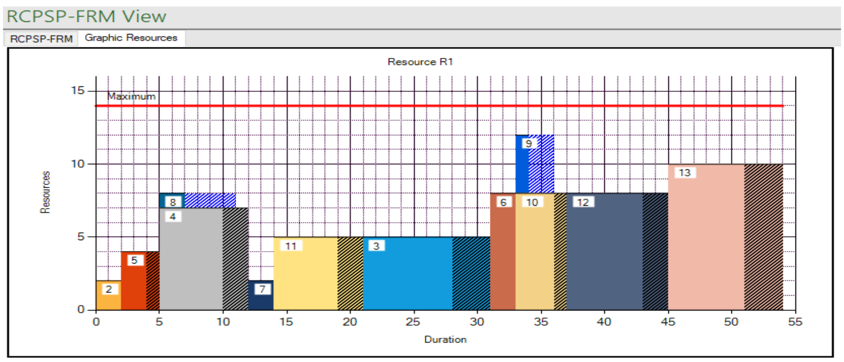




Fig. 4. Resource Profile.

## 5. Conclusions and future research

This work presents the development of a tool to visualize the flexibility of resources in a schedule to assist the project manager. The flexibility is an ally of the project manager and with a tool to manage it properly it is easier to ensure project success in terms of time and resources usage. The tool presents the flexibility of the resources in both table and graph format. It has a simple interface with easy to understand results. It is based on the RCPSP-FRM model [26], which proposes to identify the activities capable of accelerating or decelerating their duration, based on the flexibility of the resources. In the planning phase, the durations of activities are estimated so that a schedule can be established. Depending on the case, these estimates may be appropriately modeled by a deterministic value or may be subject to deviations. The RCPSP-FRM model presents a solution in handling these deviations using the flexibility of the resources that are limited, allowing the fulfillment of the project deadlines [26]. This model is inspired on two lines of research: the allocation of resources with stochastic work content [13]–[16], [43] and proactive/reactive scheduling techniques [18], [23]–[25]. It considers the ability of the resources to be flexible, varying the work content within the time unit of the project, where the activities with slack and positive score can decelerate the duration to meet the needs of the critical activities, accelerating their duration. In runtime, if a critical activity shows tendency to delay, we can decelerate the ones with slack, putting them in a slower mode, with fewer resources, therefore, and use that slack to end the critical activity still on time. As a result, by using the RCPSP-FRM method in project management, it is possible to align project planning with the flexibility of resources, in a proactive way, allowing to react in case of skidding, preventing delays in project due date. Thus, this research contributes to the academic and professional environment, in the scope of the management of projects related to the scheduling of resources with flexibility, positively impacting on what involves project execution time.

As limitations of this model we can point out that this model only applies in cases where the work content of an activity is fixed, and therefore, the duration of the activity can be longer or smaller depending on the number of resources allocated. For example, an activity that requires 10 men*days (Work content) can be done in 10 days with a man or 5 days with 2 men (W=d*r). Not all resources/activities are of this type. There are activities that have fixed duration, for example, a meeting lasting one hour is not done in half an hour when there are twice as many people. Also a linear relationship between the duration of the activity and amount of resources allocated is considered, however, in a more realistic model, it would be necessary to consider the law of diminishing marginal productivity when adding more resources.

Extensions of the tool will be made in the future, namely to explore flexibility to change the schedule in the planning phase. Also, a future work would be to calculate individualized flexibility or by categories of resources. Another way of exploring flexibility is the possibility of rearranging the schedule at planning time. This will also be explored in the future.

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