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A COMPARISON OF DIFFERENT REDUNDANCY BASED METHODS TO SOLVE THE PROJECT SCHEDULING PROBLEM WITH PROBABILISTIC ACTIVIVIES DURATION

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Abstract

Redundancy based methods are proactive scheduling methods for solving the Project Scheduling Problem (PSP) with non-deterministic activities duration. The fundamental strategy of these methods is to estimate the activities duration by adding extra time to the original duration. The extra time allows to consider the risks that may affect the activities durations and to reduce the number of adjustments to the baseline generated for the project. In this article, four methods based on redundancies were proposed and compared from two robustness indicators. These indicators were calculated after running a simulation process. On the other hand, linear programming was applied as the solution technique to generate the baselines of 480 projects analyzed. Finally, the results obtained allowed to identify the most adequate method to solve the PSP with probabilistic activity duration and generate robust baselines.

Keywords

project scheduling; redundancy based methods; proactive scheduling; robustness measures; probabilistic duration.

Introduction

Traditionally, the Project Scheduling Problem (PSP) has been solved under the assumption that the input parameters are deterministic, and therefore the baseline of the project can be obtained directly by solving the corresponding optimization problem.

However, this approach is applicable only when parameters, such as the availability and quantity of resources to be used, the costs involved, or the duration of the activities are assumed as static values or have low margins of variation. Otherwise, a non-deterministic analysis will be required in order to attempt to model these parameters and provide reliable information for the project manager.

The non-deterministic approach implies that the parameters of the project must be analyzed in a probabilistic or uncertain context. In the first case employing probability functions, while in the second case, using fuzzy numbers or other types of representation.

In this article, the PSP was analyzed under a probabilistic context, since the activities duration and the impacts of possible risks were represented through normal probability distributions as in [1–3], among others. Therefore, the problem is called PSP with probabilistic activities duration. It's important to mention that the four proposed methods in section 5 allow to represent the activities duration from any probability distribution. The objective function of the problem analyzed seeks minimizes the project duration, the activity durations were incorporated as continuous parameters, and the model did not include resources requirements.

The proposed methods to solve the problem were procedures based on redundancies because included the addition of extra time to the original duration and the creation of a project baseline. Finally, each proposed method generated an alternative project baseline.

The main objective of this research was to select the best baseline of the four baselines generated. The selection was carried out using two indicators of robustness: the solution robustness and the quality robustness. It is important to remember that a baseline should be robust, in other words, the baseline should require few adjustments when the disruptions affect the estimated duration.

In order to analyze the possible disruptions, a Monte Carlo simulation process was carried out and 10,000 scenarios were generated for the same project. Then, the robustness of each baseline was evaluated, taking into account the differences between the activities start times of each baseline and the obtained start times in each simulated scenario. Additionally, the proposed analysis methodology was applied to the 480 problems of the j30 instance belonging to the PSPLIB library [4]. Finally, the results obtained allowed to identify the best method to obtain robust scheduling for the PSP with probabilistic activities duration.

In Sec. 2, the deterministic project scheduling problem is described and its mathematical formulation is explained. Section 3 presents useful academic contributions to understand the non-deterministic approach of the problem, specifically when the activities duration has a probabilistic behaviour. Then, in Sec. 4 a relevant literature review for the redundancy based methods is addressed. Section 5 presents four methods proposed in this research to solve the PSP with probabilistic activities duration. Afterwards, in Sec. 6 the computational experiment carried out to compare the different solution methods is described. Subsequently, in Sec. 7 the results obtained from the computational experiment are presented; and finally, the conclusions are given in Sec. 8.

The deterministic PSP

The PSP seeks to organize an optimal sequence of the project activities. The basic version of the optimization problem (PSP) only takes into account the precedence between activities. The associated mathematical model defines n activities, and each one is identified by a subscript (i or j) with values between 1 and n. For practical reasons of programming, the first and the last activities are represented as fictitious activities with zero duration.

The PSP objective function seeks to minimize the makespan or project duration (S_n). S_n indicates the start time of the fictitious activity n. The decision variables of the problem correspond to the optimal start times for each activity (S_i). The mathematical formulation for the PSP can be expressed as a linear program:

$$\text{Minimize} \quad S_n \tag{1}$$

with the following constraints:

$$S_j \geq p_{ij} \cdot (S_i + d_i) \quad \forall\,(i,j) \in E, \tag{2}$$

$$S_j \geq 0, \tag{3}$$

where the decision variable S_i represents the planned start time of activity i, d_i represents its duration, and p_{ij} corresponds to a binary parameter, which is equal to 1 if activity i precedes activity j, and equal to zero otherwise. Finally, E refers to the set of precedence between project activities.

The PSP with probabilistic activities duration

Algorithms to solve the PSP with probabilistic activities duration assume that this duration can be modeled from historical information, data of similar projects, or through the experience of expert personnel. The first model used to solve the PSP with probabilistic activities duration was the PERT network model, released in the late 1950s [5]. Subsequently, algorithms based on probability analysis [6] and simulation processes [7–9], were very useful. At the same time, new adaptations to the critical chain method and the generation of Buffers were developed [10, 11]. Other solution algorithms reported in scientific literature included probabilistic decision-making processes in multiple stages [13], Markov processes [14], Petri Nets [15], and the Dependent Structure Matrix [16].

The procedures to solve the PSP with probabilistic activities duration have been designed based on predictive, reactive or proactive strategies. According to [17], a predictive strategy takes the average activities duration as input data and creates a project baseline, a reactive strategy re-schedules the original schedule when an unexpected event takes place; and, finally, a proactive strategy takes into account the variation of the activities duration, generating a robust baseline for the project.

The proactive strategy seeks to generate a robust baseline, in order to support the disruptions that affect the estimated times, therefore the schedule will require few adjustments. Within this approach, three types of solution can be grouped [17]: robust scheduling methods, contingent scheduling methods, and redundancy based methods. The *robust scheduling methods* include an objective function that seeks to optimize some robustness measure. In project scheduling, the two most common robustness measures are: *Quality Robustness*, which evaluates if the baseline can support the disruptions that affect the project due date; and the *Solution Robustness*, which analyzes the ability to support the disruptions that affect the start times of each activity [10]. The *contingent scheduling methods* generate more than one baseline for the project, according to the different risk alternatives. In this case, the disruptions are previously analyzed and a baseline is created for each possibility, then, the project manager will have alternative action plans during the project execution. Finally, the *redundancy based methods* provide extra time to each activity of the project as a strategy to face the eventualities that may appear during its execution.

Relevant literature review on redundancy based methods

The redundancy based methods incorporate additional time to the activities of the project from two strategies: inserting buffers or extending the original duration of each activity. In the first case, we highlight the *Critical Chain* method, originally proposed by Goldrat [18]. This method purposed to insert extra time (buffers) in some strategic points within the project network. Traditionally, researchers have focused on the identification and quantification of key factors to determine the size and proper location of the project buffers. Rezaie, Manouchehrabadi and Shirkouhi [11] calculated the project buffers from the coefficient of variation of the probability distribution associated with the activities duration. Bie, Cui and Zhang [12] calculated the buffers size taking into account the dependence degree and the dependency factor among the tasks of the project. Yang, Fu, Li, Huang and Tao [19] determined the project buffers size taking into account the network size, the uncertainty of the activities duration and the flexibility to shift their start times.

Ash and Pittman [20] analyzed a variant of the PSP with probabilistic activities duration, known as the *Resource Constraint Project Scheduling Problem* (RCPSP). The problem was solved through PERT-based methods and it was possible to calculate the project duration and the buffer's size. Additionally, some researchers identified new factors that affect the size of the buffer. Shi and Gong [21] took into account components such as scarcity of resources, complexity of the network and the project manager's risk profile. Zhang, Cui, Bie, and Chai [22] concluded that there is a high degree of interaction between the size of the feeding buffer, the level of service, the uncertainty of the activities duration and the whole project duration. Liu, Chen, and Peng [23] used the entropy concept to calculate the buffer size from the resource utilization factor, the network complexity and the risk aversion. Yu, Xu, and Hu [24] incorporated in their analysis the probabilistic behavior of the activities duration, the multiple resources restriction and the impact factor of each one. Iranmanesh [25] designed a density factor that considers scarce resources, the location of activities in the network, the work environment risk and the activities risks.

On the other hand, some authors purpose to add extra time to the original activities duration from the identification of potential risks and the quantification of their impacts. This focus has been proposed in some research works: Öztas and Ökmen [26] developed a risks analysis model called *Judgmental Risk Analysis Process.* This process is defined as a pessimistic risk analysis methodology because the extra time is obtained from the worst scenarios of a simulation process, which uses Monte Carlo techniques. Zafra-Cabeza, Ridao and Camacho [27] presented a model to assess the activities risks, to propose mitigation actions, to evaluate their impact in different scenarios, and to establish the project duration. The extra time of each activity was obtained from the risk occurence probability and its average impact. Mansoorzadeh and Mohd [28] proposed a framework based on the integration of risk management and Critical Chain Project Management. The extra time of each activity was estimated from the fuzzy failure mode and effect analysis. Zhang, Shi and Diaz [29] proposed a procedure for monitoring and controlling software projects. In this case, the extra time was based on the risk occurence probability, the estimated impact and the project manager's risk aversion. Recently, authors as Zhang and Qiao [30], Isaac, Su, Lucko and Dagan [31], and Izmailova, Kornevab and Kozhemiakin [32, 33], added extra time to the activities duration in order to face the unforeseen events in their schedule models.

Redundancy based methods designed to solve the PSP with probabilistic activities duration

The four methods proposed in this study took as reference the risk analysis applied by Ökmen and Öztaş [26, 34], Paz, Rozenboim, Cuadros, Cano, and Escobar [35], Zafra-Cabeza [27], Mahmoudi and Feylizadeh [36], and Mohammadipour and Sadjadi [37]. The process to calculate the *Estimated Duration* (d_i) of each method was different, however the information used in all cases was the same:

- *Basic Activity Duration* (b_i): This parameter expressed as a probability distribution, represented the activity duration under ideal conditions of operations. In other words, the external risks were not taken into account to estimate it;
- *Risk identification*: Changes in weather conditions, delays in delivery of materials or resignation of employees are typical examples of project risks. In this investigation, the risks were randomly generated and subsequently assigned to project activities;
- *Risk Occurrence Probability* (Pr_{ki}): For each risk k that affects the activity i, the *Risk Occurrence Probability* was defined. In this article, each risk was assumed as independent from each other;
- *Extra Task*: The extra task refers to an event that is executed when the risk occurs. In this work, the duration of each extra task was represented by a probability distribution and was denoted as h_{ki}. Here, k was associated to the risk, and i to the activity.

In order to organize the above information, a *Risk Activity Matrix* to relate both activities and risks was built. Table 1 presents an example created by the authors, where b_i and h_{ki} are represented by probability distributions. Additionally, Table 2 summarizes the notation introduced to the methods used.

Method A

In this method, d_i was selected after a simulation process which must randomly generate at least 1000 scenarios for the same project.

This method is based on a pessimistic risk analysis, where each activity duration corresponds to the maximum value obtained in the simulation process:

$$d_i = \mathrm{Max}[b_i + \sum_{1}^{k} (Pr_{ki} \cdot h_{ki}^{s})]. \tag{4}$$

In Eq. (4), b_i refers to the expected value of the b_i, Pr_{ki} indicates the probability that risk k appears in activity i, and h_{ki}^s is the simulated value for each h_{ki} associated with the risk k and the activity i. The h_{ki}^s values must be generated according to a previously defined probability distribution.

Once d_i is calculated, the project baseline can be obtained. In this research, the project baseline was found by solving the linear program presented in the deterministic PSP section.

Table 1
Risk Activity Matrix.

Activities	Basic Activity Duration (b_i)	Risk 1		Risk 2		Risk 3		Risk 4	
		Extra Task 1		Extra Task 2		Extra ask 3		Extra task 4	
		Risk occurrence probability (Pr_{ki})	Extra task duration (h_{ki})	Risk occurrence probability (Pr_{ki})	Extra task duration (h_{ki})	Risk occurrence probability (Pr_{ki})	Extra task duration (h_{ki})	Risk occurrence probability (Pr_{ki})	Extra task duration (h_{ki})
Activity 1	N(20,2.1)	0.1	N(4,1)	–	–	0.3	N(3,0.4)	–	–
Activity 2	N(12,1)	–	–	–	–	0.4	N(2,0.3)	0.3	N(3,0.6)
Activity 3	N(16,2)	–	–	0.51	N(3,0.2)	–	–	–	–

Table 2
Notation used to calculate the Estimated Duration (d_i).

Symbol	Description
i	Subindex to identify each project activity
k	Subscript to identify each project risk
d_i	Estimated duration of activity i
b_i	Expected value for activity duration i when the risks don't appear
h_{ki}	Expected value for the extra task duration caused by the risk k and associated with the activity i
h_{ki}^s	Simulated value for the extra task duration caused by the risk k and associated with the activity i
Pr_{ki}	Probability that the risk k appears when the activity i is executed
PR	Average value of the occurrences probabilities of all the risks

Method B

According to this method, d_i depends on the average value of the risks occurrence probabilities (PR).

The PR value could also be interpreted as the level of risk aversion: if the project manager assumes that any risk will affect the project ($PR = 0$) then d_i corresponds exactly to the expected value of the b_i, but, if the project manager assumes that all risks will appear ($PR = 1$), then d_i includes not only the expected value of b_i but also the extra tasks durations. Equation (5) can be used to calculate the d_i, even if PR values belong to interval [0,1]:

$$d_i = b_i + PR \cdot \sum_{1}^{k} h_{ki}. \tag{5}$$

Here, b_i refers to the expected value of the b_i, PR corresponds to the average probability of risks occurrence in the project, and h_{ki} is the expected value of the extra task durations associated with the risk k and the activity i.

Once d_i is calculated, the project baseline is obtained by solving the same linear program presented in the deterministic PSP section. In this research, all the proposed methods use the same linear program.

Method C

In this case, d_i can be interpreted as the total expected duration for activity i, because it depends on the expected value of the b_i, Pr_{ki}, and the value expected of the extra tasks:

$$d_i = b_i + \sum_{1}^{k} (Pr_{ki} \cdot h_{ki})]. \tag{6}$$

A new baseline is obtained from d_i using the same linear program presented in the deterministic PSP section.

Method D

This method assumes that when an activity is executed, the occurrence of all identified risks is unlikely. Therefore, the risk that generates the greatest impact should be considered the only parameter to calculate the extra time associated with activity i.

Then, the impact of each risk is calculated taking into account Pr_{ki} and the expected value of h_{ki}:

$$d_i = b_i + \mathrm{Max}[Pr_{ki} \cdot h_{ki}]. \tag{7}$$

According to (7), d_i is selected from the maximum value obtained by multiplying Pr_{ki} and h_{ki}.

Finally, the baseline is obtained from d_i solving the same linear program.

Computational experiment

In order to evaluate the performance of the four redundancy based methods presented in the previous section, some tests were applied to the 480 problems of the j30 instance belonging to the PSPLIB library [4].

The original j30 instance is a deterministic instance, therefore it was adapted to the particular characteristics of the PSP with probabilistic activities duration. The adjustments made were the following:

- b_i was assumed as a normal probability distribution, with mean equal to the deterministic duration of the original problem.

The standard deviation was generated randomly from a uniform distribution defined in a range between 10% and 20% of the deterministic duration. This interval allows to create scenarios with low variability, then it is coherent with the behavior of activities free of external risks.

- h_{ki} was assumed as normal probability distributions with means generated randomly (uniform distribution) in a range that oscillates between 1% and 33% of the deterministic duration.

The standard deviations were also generated randomly (uniform distribution) and their values oscillated between 10% and 20% of the mean obtained for each Extra Task.

- The number of risks assigned to each project network was defined randomly between 40 and 50.

In turn, the number of risks assigned to each activity was defined between 0 and 3.

- The occurrence probability of each risk was generated randomly through a uniform distribution that oscillated between 0.05 and 0.35.

The problem analyzed did not include the project resources requirements, therefore the problem to solve, is the PSP without resources restriction.

Each method presented in the previous section was used to solve the 480 problems of j30 instance.

The linear program created for each problem was programmed in GAMS and the baseline obtained was compared with the sequences obtained for 10000 scenarios generated in a simulation process.

Robustness indicators

The comparison between the project baselines was made through two concepts: *Solution Robustness* and *Quality Robustness*.

The *Solution Robustness* analyze the ability to support the disruptions that affect the activities start times, and the *Quality Robustness* analyze the capacity to support the disruptions that affect the deadline project [10, 38].

The first step to obtain the *Solution Robustness* indicator (*SR*) was to calculate the average deviation for each project activity (ΔS_i) using (8):

$$\Delta S_i = \frac{\sum_1^m \left| S_i^{LB} - S_i^R \right|}{m}, \tag{8}$$

where S_i^{LB} corresponded to the planned start time in the project baseline for each activity i ($i = 1, 2, ..., n$), and S_i^R represented the start time executed for each activity i (obtained through a simulation process with $m = 10000$ scenarios).

Subsequently, each value ΔS_i was used to obtain *SR* by using (9):

$$SR = \sum_1^n \Delta S_i. \tag{9}$$

On the other hand, *QR* refers to the average deviation for the last project activity (ΔS_n). Therefore, (10) simply reflects that $QR = \Delta S_n$:

$$QR = \frac{\sum_1^m \left| S_n^{LB} - S_n^R \right|}{m}. \tag{10}$$

The robustness indicators (*SR* and *QR*) were the fundamental measures to select the method with the best project baseline.

A robust baseline tries to support all foreseen scenarios during the simulation, therefore, the robustness analysis was focused on identifying the baseline with the least deviation between the start times (planned and executed).

Results obtained

The redundancy based method with the most robust baseline for each problem was selected from the lowest values of the robustness indicators (*SR* and *QR*).

Table 3 shows each method used and the number of times that they obtained the most robust project baseline.

Table 3
Performance of applied methods.

	Best Solution (SR)	Best Solution (QR)
Method A	120	149
Method B	54	91
Method C	279	225
Method D	27	16
Total	480	480

According to Table 1, method C obtained a higher performance than the others since it had lower *SR* and *QR* values for the most of the problems analyzed (279/480 = 58.12% and 225/480 = 46.87%, respectively).

Additionally, when the method C did not show the best performance, its robustness indicators were close to those obtained by the methods with the best baseline.

To estimate the proximity between the solutions of method C and the methods with the best baseline, the maximum difference (*MaxD*) between their indicators was calculated according to (11)

$$MaxD = 100 \cdot \left[\frac{a^*}{\text{Robustness indicator}_{\text{best}}} \right], \tag{11}$$

where

$$a^* = \text{Robustnes indicator}_{\text{method C}} \\ -\text{Robustness indicator}_{\text{best}}.$$

The results can be seen in the Tables 4 and 5.

When the SR of method C was compared with the best value obtained for each problem (see Table 4), the difference never exceeded 8.86%. Additionally, for the 98% of the cases (469 out of 480 problems) the SR obtained for method C had a percentual difference of less than 5%.

Table 5 presents similar results between the QR and the SR. In this case, although the maximum difference reached 24.77%, the method C provides QR values with small percentual differences (less than 5%) for 82% of the cases analyzed (393 of 480 problems).

Table 4
Proximity between the *SR* indicator of method C and the best *SR* indicator.

	Best Solution (SR)	Maximum difference in percentage (*maxD*)	Number of cases with differences less than 5%	Percentage of cases with differences less than 5%
Method A	120	8.86%	111	93%
Method B	54	6.74%	52	96%
Method C	279	0%	279	100%
Method D	27	3.17%	27	100%
Total	480		469	98%

Table 5
Proximity between the QR indicator of method C and the best QR indicator.

	Best Solution (SR)	Maximum difference in percentage ($maxD$)	Number of cases with differences less than 5%	Percentage of cases with differences less than 5%
Method A	149	24.77%	67	45%
Method B	91	17.40%	85	93%
Method C	225	0%	225	100%
Method D	16	3.29%	16	100%
Total	480		393	82%

Therefore, method C had a better performance compared to the other methods presented in this article.

It is important to indicate that this method has practical applicability in any project with high vulnerability to the risks. Then, it's possible highlight the projects of high-technology new product development, the construction projects with high dependence on geological studies, or the software development projects where the duration of the activities is associated with the skills of the computer programmers, among others.

Conclusions

In this article, a comparative analysis of four redundancy based methods proposed to solve the PSP with probabilistic activities durations was presented. Those methods required basic information related to identification of risks, the estimation of the occurrence probability and the impact on the activities duration.

A computational experiment was carried out and two robustness indicators were used to evaluate the performance of each method. The j30 instance belonging to the PSPLIB library was used as a reference to apply the methods of solution.

One of the methods presented, method C, is the better procedure since it generates baselines with lowers robustness indicators. Additionally, method C provides a simple procedure to calculate the estimated duration of each project activity.

The design of new solution methods to generate robust solutions based on the identification of risks will be a topic to explore in future research projects.

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