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R&D and innovation project selection: can optimization methods be adequate?

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Abstract

This article proposes a comprehensive framework for R&D and innovation project selection under uncertainty and subject to real-world constraints applicable to the Brazilian electricity sector, using a combination of integer programming formulation and a PROMETHEE-based method. The objective is to contribute to this domain by offering an approach suitable for the challenges of this sector, but also applicable to other situations involving R&D and innovation investments under similar conditions. The manuscript presents applications using real data from an electricity company. It also compares the proposed method with similar approaches found in the literature such as PROMETHEE II and V. The application revealed the best performance of the proposed framework in dealing with the sector's regulatory constraints, which emphasize the companies' accomplishment with R&D and innovation expenditures obligations. In this way, although R&D and innovation project selection is not a typical case of optimization, under some particular regional, sector-based or organization boundaries this can be a better solution.

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1. Introduction

Project portfolio management is one of the main axes of management models of public and private organizations involved in research, development and innovation (RD&I) activities. Choosing and prioritizing the options in which the resources will be allocated based on their performance estimation is one of the major challenges in this field. The target is obtaining success by achieving good outputs and outcomes. The challenge is doing it under radical uncertainty. This "selection problem" is not a new one. There is an important amount of literature that has been dealing with this problem since the 1960s both conceptually, by discussing uncertainty and the degree of risk intrinsic to RD&I projects, and methodologically, by developing different

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approaches and tools to support decision making in this domain.

The article [10] argues that despite the importance of this field and the existence of several approaches to deal with the selection problem, the corporative use of research and development (R&D) project selection tools has been limited, precisely due to the fact that none of the available solutions has been able to capture the full range of particularities that exists in this kind of projects. The other possible reason is that the developed approaches are themselves so complex that it turns difficult for decision makers to systematically integrate them in their routines. The point is that additional efforts are still needed in this field, predominantly to deal with complexity in a less complex way.

Among the different application domains in which R&D project selection plays a role, the article [5] claims that the energy sector is a privileged one, mainly because of the several criteria that should be taken into account in planning and decision-making within the sector, e.g. economic, social, environmental and regulatory among others. In the Brazilian case, this importance can be reinforced since all electricity companies in the country have to invest part of their revenues in R&D activities as a legal obligation. As a consequence, the composition of a portfolio with an optimal resource allocation and also with a good strategic alignment based on future returns is crucial for the companies to obey the law and avoid fines as well as to develop scientific and technological competences that can help them to promote innovations and gain competitive advantages.

Bearing in mind the panorama exposed previously, this paper proposes a comprehensive framework for RD&I project selection under uncertainty and subject to real-world constraints applicable to the Brazilian electricity sector, using a combination of integer programming formulation and the PROMETHEE-based method. The objective is to contribute to the domain of R&D project selection by offering an approach suitable for the challenges of this sector, but also applicable to other situations involving RD&I investments under similar conditions. As a way to discuss the adequacy of the proposed framework, the manuscript also compares the chosen method with similar approaches found in the literature.

2. Combining Knapsack problem and Outranking methods

Given the particular conditions of the Brazilian electricity sector, the proposed framework for project selection considered a two-phase approach that begins by solving the knapsack problem by means of an integer programming formulation, incorporating different kinds of constraints, and then evaluate the projects with a multi-criteria basis, using the PROMETHEE outranking method [2]

Complementary, this choice opens the possibility of providing comparisons with other common approaches found in the literature review, such as those that apply just outranking methods or complement them by means of optimization efforts (in the inverse way of the one proposed here) [3].

Broadly speaking, the proposed framework seeks firstly for the best combination of project proposals to be chosen and then tries to order the best projects individually, in accordance with the different considered constraints. This framework is henceforth called KNAPSACK-OUTRANKING approach. The reason for the optimization effort in the model is given by the actual concerns of Brazilian electricity companies to effectively use the resources designated to R&D. The additional reason for complementing this optimization effort with an outranking method is to have a useful ordering to cope with changes in resources constraints that may occur in this sector. These changes can be particularly frequent in the case of human resource allocation due to the fact that most of the company's staff is not exclusively dedicated to R&D activities.

The input information for the model comprehends:

(a) The list of N candidate projects: p_i, i = 1, 2, …, N.

(b) The set of M strategic and operational criteria which will be employed to evaluate the set of N projects.

(c) The value assignments for each criterion in each project. These values will be stored in the decision matrix C which each corresponding element will be: c_{ik}, i = 1, 2, …, N, k = 1, 2, …, M.

(d) The set of M criteria weights that specifies the importance of each criteria in the decision making process. Its corresponding values will be stored in w vector in which each element is represented by: w_k , k = 1, 2, …, M and the weights were set to w_k = 1/M.

(e) The set of R restriction criteria according to strategic and operational constraints of the company.

The first part of the proposed framework concerns the portfolio optimization approach, in which the objective function considers the maximization of knapsack total utility and it is expressed by the equations (1) and (2), respectively. The decision binary variable x_i has the value 1 if the project is selected and 0 if not.

Max $$\sum_{i=1}^{N} u_i x_i \qquad (1)$$

S.a.: $$\sum_{i=1}^{N} v_{ij} x_i \le b_j \text{, j=1, …, R.} \qquad (2)$$

$$x_i = 0 \text{ or } 1 \text{, i=1, …, N.} \qquad (3)$$

Where u_i is the utility of each project *i*, v_{ij} is the resources used by each project *i* in each constraint *j*, and b_j is the total of resources available for each constraint *j*, x_i is the variable that assumes value 1 if project *i* is selected to belongs the portfolio and 0 if not.

The total utility of the project *i* is given by:

$$u_i = \sum_{k=1}^{M} c_{ik} w_k \text{, i = 1, …, N.} \qquad (4)$$

On the other hand, the second part of the proposed framework concerns the use of the outranking method known as PROMETHEE II, which relates each project to a ranking index $\phi(p_i)$ calculated using Eqs. (5)-(7). After computing the ranking index for each project, the ranking is built by simply sorting the projects in decreasing order of their total flow.

$$\phi^+(p_i) = \frac{1}{N-1} \sum_{j=1}^{N} \sum_{k=1}^{M} P_k(c_{ik} - c_{jk}) w_k \text{, i = 1, …, N,} \qquad (5)$$

$$\phi^-(p_i) = \frac{1}{N-1} \sum_{j=1}^{N} \sum_{k=1}^{M} P_k(c_{jk} - c_{ik}) w_k \text{, i = 1, …, N,} \qquad (6)$$

$$\phi(p_i) = \phi^+(p_i) - \phi^-(p_i) \text{, i = 1, …, N,} \qquad (7)$$

where P_k (.) is usual preference degree function, $\phi^+(p_i)$, $\phi^-(p_i)$ and $\phi(p_i)$ correspond to the positive, negative and total flows, respectively.

For analytical purposes, the proposed KNAPSACK-OUTRANKING approach will be here compared with the simple use of PROMETHEE II, by means of selecting project proposals according to the generated ranking just before one constraint is violated. The portfolio composed in this way emphasizes the values formed from users' preferences and processed according to function degree preference.

The proposed approach will also be compared with PROMETHEE V, which combines the use of information from PROMETHEE II and the R portfolio constraints through Eq. (8)-(10) [2]. In this approach the objective function emphasizes not the selection of projects with higher position on the ranking, but the maximization of index $\phi(p_i)$.

$$\text{Max} \quad \sum_{i=1}^{N} \phi(p_i) x_i \tag{8}$$

$$\text{S.a.:} \quad \sum_{i=1}^{N} v_{ij} x_i \le b_j \text{, j=1, …, R.} \tag{9}$$

$$x_i = 0 \text{ or } 1 \text{, i=1, …, N.} \tag{10}$$

3. Numerical experiments: a simple example

Sample data from a Brazilian electricity company is used in this manuscript to evaluate and compare the solution given by KNAPSACK-OUTRANKING framework and the solutions from the PROMETHEE II and PROMETHEE V approaches. Companies from this sector continuously face the challenges of selecting RD&I project proposals defined internally or suggested by actual or potential partners, mainly universities.

The set of criteria employed in the selection of project proposals derived from an embracing sector-based study, mainly from innovation system approach proposed by [4] and the company's strategic goals, resulting in five main dimensions: Market; Corporate strategic objectives; Interactions and Partnerships; Regulation; and Technology. These results were thoroughly discussed with personal involved in the RD&I area of the company, generating a final 37 analytical criteria list, with their respective weights. As already seen, these criteria are well aligned with those commonly used in R&D project selection problems. A semantic scale ranging from 3 to 5 points was attributed to each analytical criterion of the list.

A set of four project proposals was then analyzed under the analytic set of criteria. This task was performed by the company's R&D staff by means of a questionnaire interface. A set of constraints related to budget (financial obligations), human resources and project time-consuming (measured in hours) was also defined. As a performance index, we shall consider the average resources consumption, which is is given by

$$\bar{r} = \left(\sum_{j=1}^{R} \frac{1}{b_j} \left(\sum_{i=1}^{N} v_{ij} x_i \right) \right) / R \tag{11}$$

The set of constraints that the portfolio solution must fulfil is described in Table 1. These constraints referrers to: financial resources (cost of the project); human resources (number of company's staff that should take part in the project); and hours (time-consumption per project).

Table 1: Project proposals, constraints and capacity

Project Proposals	Money ($)	Human (h)	Hours (o)
P_1	3.0	1	300
P_2	4.0	2	400
P_3	10.0	3	400
P_4	3.5	2	350
Capacity (b_i)	11.0	6	2500

From Table 1 the following portfolio constraints can be formulated by:

$$3.0\bullet x_1 + 4.0\bullet x_2 + 10.0\bullet x_3 + 3.5\bullet x_4 \leq 11.0$$

$$1.0\bullet x_1 + 2.0\bullet x_2 + 3.0\bullet x_3 + 2.0\bullet x_4 \leq 6$$

$$300\bullet x_1 + 400\bullet x_2 + 400\bullet x_3 + 350\bullet x_4 \leq 2500$$

Taking into account the criteria and the constraints sets, the three approaches were compared regarding their resource consumption for this is a critical issue under the electricity regulatory framework in Brazil. It is important to remember that companies are supposed to be finned if they do not accomplish with their R&D annual obligations, reinforcing the necessity of maximizing their financial resources consumption. This condition is a main concern for companies that face this kind of challenge and it is not properly considered in previous similar works found in literature such as [3, 6, 9].

The application of the KNAPSACK-OUTRANKING approach was made using Eqs. (1)-(4) which has been solved by a specially adapted Beam Search Method (BSM) from [7]. As presented before, the utility is used in this proposed approach as an objective function and this could lead to a different project portfolio composition when compared with other approaches such as PROMETHEE II and V.

It is worth noticing that given the projects utilities (u_1=94; u_2=115; u_3=133; and u_4=101) the best solution for the knapsack problem is $\{x_1, x_2, x_3, x_4\} = \{1, 1, 0, 1\}$ with corresponding best objective function value of 310. The corresponding ranking for these selected projects according to PROMETHEE II outranking using Eq. (5)-(7) is given in Table 2. It should be noted that projects 2 and 3 have negative $\phi(p_i)$ values, but were included in portfolio in order to acquire higher levels of resources consumption. This means that the final solution for the portfolio by applying KNAPSACK-OUTRANKING contains three projects, in the following order: P_2, P_4 and P_1.

As mentioned above, we apply the PROMETHEE II after solving the optimization in order to have a ranking of projects in case of future changes in the constraints. Under the regulatory conditions of the electricity sector in Brazil this procedure can be useful for the allocation of resources is extremely sensitive.

Table 2: Ranking values obtained after PROMETHEE II computation with prior optimization

Project	Utility (u_i)	$\phi^+(p_i)$	$\phi^-(p_i)$	$\phi(p_i)$	PROMETHEE II Ranking	Selected to Portfolio
P_1	94	0.1890	0.5805	-0.3915	3	Yes
P_2	115	0.6479	0.2160	0.4319	1	Yes
P_4	101	0.4050	0.4455	-0.0405	2	Yes

The PROMETHEE II method can also be applied as an alternative and comparable approach. This can be done by selecting projects until one constraint is violated, using Eq. (5)-(7). The resulting ranking and the solution is given in Table 3. Using PROMETHEE II ranking leads to the solution $\{x_1, x_2, x_3, x_4\} = \{0, 0, 1, 0\}$

and related total $\phi(p_i)$ is 0.6569.

Table 3: Ranking values obtained after PROMETHEE II computation without prior optimization

Project	Utility (u_i)	$\phi^+(p_i)$	$\phi^-(p_i)$	$\phi(p_i)$	PROMETHEE II Ranking	Selected to Portfolio
P_1	94	0.1620	0.6569	-0.4949	4	No
P_2	115	0.4589	0.3420	0.1169	2	No
P_3	133	0.7379	0.0810	0.6569	1	Yes
P_4	101	0.2880	0.5669	-0.2789	3	No

Other alternative is the use of PROMETHEE V, which employs the PROMETHEE II data (in this case study presented in Table 3) and incorporates constraints, as described in this section. As in the KNAPSACK-OUTRANKING application, the BSM was also employed, but using Eqs. (8)-(10). It should be observed that in the PROMETHEE V the objective function emphasizes the maximization of index $\phi(p_i)$, which means that the difference from KNAPSACK-OUTRANKING is caused not only from its combinatorial nature, but also by its problem formulation. Using PROMETHEE V method leads to the solution $\{x_1, x_2, x_3, x_4\} = \{0, 0, 1, 0\}$ which corresponding best objective function value is 0.6569 (the same solution of PROMETHEE II by itself).

Table 4 presents the solutions found for the different frameworks. Clearly, the different solutions found from PROMETHEE II and V and KNAPSACK-OUTRANKING happen because its objective functions are not equivalent. This means that these solutions will lead to different portfolios and resources consumption.

Table 4: Comparing the solutions found from different frameworks

Method	Solution $\{x_1, x_2, x_3, x_4\}$	Strategic and Operational Criteria		Mean consumption (%)
		Total $\phi(p_i)$	Total Utility	
PROMETHEE II/V	{0, 0, 1, 0}	0.6569	133	53.30
KNAPSACK-OUTRANKING	{1, 1, 0, 1}	-0.6569	310	73.50

Table 4 shows that the solution provided by KNAPSACK-OUTRANKING has best values of resources consumption. Nevertheless this result cannot be extended for all values of resource availability, which means that modifying the available resources can lead to other solutions in the proposed framework and comparable methods.

Tables 5 and 6 show the possible solutions provided by PROMETHEE II/V and KNAPSACK-OUTRANKING under certain values of financial constraint availability. The decision of selecting this kind of constraint to test the approaches is due to its importance for the Brazilian electricity sector problem addressed in this manuscript.

A comparison between the Tables brings the conclusion that the solutions generated from PROMETHEE II/V are especially sensitive to resource constraints changes. This is a key factor for decision makers interested in RD&I project selection under restrictive circumstances and also to those that have to deal with risks associated with resource allocation – such as the Brazilian electricity sector – as well as with risks of project discontinuation due to some kind of resource shortage.

As a consequence, the KNAPSACK-OUTRANKING preference for low cost projects leads to a portfolio in which a resource shortage will smoothly influence its contents, since there are more possible combinations of projects that could fulfil different ranges of financial constraints.

Table 5: Possible solutions for the PROMETHEE II/V methods according to financial constraints

Financial Constraint Ranges	Solutions $\{x_1, x_2, x_3, x_4\}$	Objective Function Total $\phi(p_i)$	Objective Function Total Utility
20.5 ≥	{0, 1, 1, 0}	0.7738	248
[17.5, 20.5)			
[14.0, 17.5)			
[10.5, 14.0)	{0, 0, 1, 0}	0.6569	133
[10.0, 10.5)			
[7.5, 10.0)	{0, 1, 0, 0}	0.1169	115
[7.0, 7.5)			
[6.5, 7.0)			
[4.0, 6.5)			
[3.5, 4.0)	{0, 0, 0, 0}	0.0000	0
[3.0, 3.5)			
[0.0, 3.0)			

Table 6: Possible solutions for the KNAPSACK-OUTRANKING according to financial constraints

Financial Constraint Ranges	Solutions $\{x_1, x_2, x_3, x_4\}$	Objective Function Total $\phi(p_i)$	Objective Function Total Utility
20.5 ≥	{1, 1, 1, 1}	0.0000	443
[17.5, 20.5)	{0, 1, 1, 1}	0.4949	349
[14.0, 17.5)	{1, 1, 0, 1}	-0.6569	310
[10.5, 14.0)			
[10.0, 10.5)	{0, 1, 0, 1}	-0.1620	216
[7.5, 10.0)			
[7.0, 7.5)	{1, 1, 0, 0}	-0.3780	209
[6.5, 7.0)	{1, 0, 0, 1}	-0.7738	195
[4.0, 6.5)	{0, 1, 0, 0}	0.1169	115
[3.5, 4.0)	{0, 0, 0, 1}	-0.2789	101
[3.0, 3.5)	{1, 0, 0, 0}	-0.4949	94
[0.0, 3.0)	{0, 0, 0, 0}	0.0000	0

Tables 6 and 7 showed a common pattern between PROMETHEE II/V and KNAPSACK-OUTRANKING methods: as the financial resource availability increases, there is a corresponding increase in the objective function. This means an increase of the total value of $\phi(p_i)$ (third column in Table 5) for PROMETHEE II/V and for total utility (fourth column in Table 6) for KNAPSACK-OUTRANKING.

Nevertheless these objectives functions are conflicting. PROMETHEE II/V methods did not propose a project portfolio for financial values in range [0,0, 4.0) while KNAPSACK-OUTRANKING proposed two different allocations. In this range, all proposed solutions from KNAPSACK-OUTRANKING have a negative value for total $\phi(p_i)$ what will always be avoided by PROMETHEE II/V scheme, limiting the possibilities of resource reallocations under different scenarios of financial availability. The KNAPSACK-OUTRANKING never limits the possibilities of portfolio since its decision is based on total utility, which is always positive.

This is important since the most critical target in the Brazilian electricity sector is to guarantee the highest financial resource consumption to accomplish with the regulatory framework. On the other hand, PROMETHEE II/V scheme will not allocate projects that produce negative values of total $\phi(p_i)$.

The stronger evidence of this principle is showed in the range where the financial availability is [10.5, 14.0). In this case, KNAPSACK-OUTRANKING proposes a portfolio composed by projects 1, 2 and 4 with total utility of 310 and total $\phi(p_i)$ value of -0.6569. But, PROMETHEE II/V scheme proposes exactly the opposite of this: a portfolio composed just by project 3 with total utility of 133 and total $\phi(p_i)$ value of 0.6569.

Another interesting effect is the difference between the proposed approach and PROMETHEE II/V as financial availability increases. In Table 5, for financial availability higher than 14.0, only projects 2 and 3 are selected and this will not change, even there is enough money to execute more projects. This happens because the inclusion of other projects will lead to a portfolio with a lower level of total $\phi(p_i)$. In other words, there is a kind of saturation point where the next project to be included has a negative value of $\phi(p_i)$. In Table 6, the fulfilment of financial constraint is accomplished with the inclusion of more projects that leads to portfolio with higher utility.

The composition of portfolio considering a much greater number of projects should be a good solution for the Brazilian electricity sector problem considering the amount of financial resources available for RD&I projects that must be consumed by the companies. Future works will provide the evaluation and comparisons among the three approaches simulating large-scale instances.

4. Conclusions

RD&I project selection problem is a complex one, mainly due to its inherent uncertainty nature. The literature review shows a great variety of approaches and tools to deal with this problem.

MCDM and its association with mathematical programming seem to be an interesting path to be explored when the problem has to do both with multiple (and even contradictory) strategic and operational criteria and resource constraints.

However, in the present case – the Brazilian electricity regulatory framework towards R&D – there is a somewhat inverse situation. As a sort of policy contradiction, the main interest of companies is protecting themselves against the so-called regulatory-risk, which means being punished for not accomplishing with the obligations of R&D expenditures (companies normally would invest much less if there were no such obligations).

Having this situation in mind, we proposed an adapted two-stage approach, starting with optimization (knapsack problem) and then applying outranking methods. We tried to evaluate the proposed approach by using real data from a Brazilian electricity company and a Monte Carlo simulation and also by comparing it with similar approaches from literature (PROMETHEE II and V).

The main finding is the best performance of KNAPSACK-OUTRANKING framework in dealing with the sector's regulatory constraints, since the resource consumption is always better in this approach. The application and comparison of the three approaches also reveal a trade-off between dealing with resources consumption and achieving strategic and operational alignment based on preferences, such as used by outranking methods like PROMETHEE.

In this way, although RD&I project selection is not a typical case of optimization as seen in the prior literature review, in the case discussed in this manuscript it is and the proposed framework seems to suit really well as a solution for this kind of problem. As observed by [8] the methods that use utility as an objective function tend to select projects of low cost, which, on the one hand, do not guarantee the selection of strategic projects but, on the other hand, is a guaranty of better "filling the knapsack".

One important policy implication is that the Brazilian regulatory framework towards RD&I in the electricity sector pushes firms in direction of being more concerned with "filling the knapsack" than looking for projects that will really bring them positive returns. This situation is coherent with that found by [1] when studying the minimalist RD&I management models adopted by the electricity companies in Brazil.

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