Sustainable Railway Solutions Using Goal Programming

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Abstract Project selection and the prioritization of activities are configured as classical optimization problems, and one of the most commonly used techniques to solve this kind of problem is Goal Programming (GP), a multi-criteria analysis technique. Problems related to the prioritization of railway investment selection or maintenance processes involve goals and constraints such as budget constraints, the availability of labour and resources, and the degradation of permanent track materials. This chapter presents two applications of Goal Programming in railways. The first model selects projects for a railway-sustaining investment portfolio. The second model allows for the prioritization of railway superstructure maintenance based on the maintenance demand for components and the geometric, environmental and demographic characteristics of a railway. Defining the best investment portfolio or a proper maintenance strategy are essential tasks for railway sustainability to achieve long-term goals involving multiple, often immeasurable and conflicting, objectives. The results show that these two proposed models allow for the prioritization of goals defined as the most important and proved useful in the presentation of scenarios that facilitate the choice of investment portfolio or superstructure maintenance strategy.

Keywords Project investments · Railway maintenance · Goal programming

1 Introduction

According to (Vargas 2010), one of the main challenges of organizations lies in their ability to make certain and consistent choices in line with their strategic direction. Thus, the contribution of investment funds to projects that bring positive returns becomes fundamental for the company that wants to succeed in its business and achieve its long-term goals. However, it is essential to use strategic planning to

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effectively allocate their resources. Strategic planning provides an environmental analysis of a company, identifying its opportunities, threats, strengths and weaknesses to get out of their current state (mission) and reach their expected state (vision) (Valle et al. 2007). Additionally, railway maintenance can be considered a strategic activity since the results are directly related to performance, reliability, transport safety and cost reduction. The maintenance activity is an important part of total railway costs.

The operation of a railway requires financial resources that can be divided into two categories: CAPEX (*Capital Expenditure*) and OPEX (*Operational Expenditure*). The CAPEX means that resources are used for investments that will bring future benefits. Within this last category, there are current investments that aim to maintain or increase the productivity of assets, improve the quality of products/services provided, preserve the environment and/or work conditions or even meet requirements imposed on the railway by external and internal authorities. The OPEX means that resources are used for the maintenance of assets and for the payment of staff.

Once the criteria for financial allocation resources have been defined, optimization models are excellent tools to help in making decisions. According to (Ahern and Anandarajah 2007), these models are developed to help decision making and select projects identified as possible investments. The selection of projects of railway investments presents itself as a problem of multiple objectives, and the development of a model for this purpose will use Goal Programming (GP) as a methodology. GP is a technique in which one or more goals are formulated as constraints, having an objective function that seeks to minimize the sum of the absolute deviations of these goals (Ahern and Anandarajah 2007). The same condition is found in railway maintenance. According to (Ferreira 2010), with robustness and high investment involved in the maintenance process, railways start to adopt maintenance investment strategies increasingly directed to critical problems that have been identified. However, a misconception in the railway maintenance process can result in defects concentrated in weak points that, if not properly identified and repaired, can create permanent and irreversible deformations in the railway, with the solution requiring complete replacement of components of the whole stretch with possible unwanted interruptions in train movements.

One of the ways to simplify decision making is through some method of optimization. The technique proposed by Charnes and Cooper (1961) to facilitate this process is Goal Programming (GP), an area of multi-objective programming that treats possible restrictions related to a problem that can be considered flexible to allow values close to those previously established as goals. This chapter will present two applications of the GP technique in railways. First, this chapter will present basic concepts of GP used to develop these two models, and in sequence, the applications will be described. The models were developed using the Solver Supplement of Microsoft Excel.

2 The Goal Programming

With the complexity existing in today's organizations, decision makers try to maximize generally not well-defined execution functions. The conflicts of interest and the lack of complete information make it virtually impossible to construct a reliable mathematical function that better represents decision-maker preferences. Thus, with the absence of an ideal decision-making environment, the decision maker tries and achieves a series of goals (or targets) as close as possible (Tamiz and Jones 1998).

Decision-making models with multiple objectives and goal programming (GP) are important tools for the fields of operational research and other management sciences, with extensive application in engineering and science investigations. The complexity that exists in most of the real problems is due to difficulties in modelling and solving problems with a single objective. GP is a method that optimizes multiple goals, minimizing the deviations of the objectives of the aspiration levels or goals sets by the decision maker. Deviations near zero show that the targets have been achieved. These deviations can also be positive or negative, which means that the targets were reached below or above a defined target (Colapinto et al. 2015).

The first application of GP was made by Charnes et al. (1955) and Charnes and Cooper (1961) in the context of executive remuneration. At that time, the term GP was not used, and the model was an adaptation of linear programming (Tamiz and Jones 1998). Since then, the GP became one of the methods of optimizing multiple goals that was more used considering the evolution of the number of articles published (Colapinto et al. 2015). The main important methods of GP are weighted GP, which allows for a trade-off analysis between the unwanted deviation variables, and lexicographic GP, which has different levels of priorities, each one containing several unwanted deviation variables to be minimized. In the sequence, the terminology and structure of weighted and lexicographic GP will be presented.

2.1 GP Basic Concepts and Classification

The concept of objectives and attributes is essential to any decision-making process. According to (Morais Neto 1988), an objective is essentially an expression that reflects the will of the decision-maker about a certain state of the system in question. An objective is an expression of decision-maker desire, and thus, it can be fully achieved or not. The author cites a decision problem with multiple objectives that is characterized by several goals, some well-defined, others poorly defined. A set of well-defined objectives often presents a hierarchical structure similar to the structure shown in Fig. 1.

The terminology used in the GP varies widely in the literature. Among the various terms used in the GP issues, the basic definitions cited by (Morais Neto 1988) are as follows:

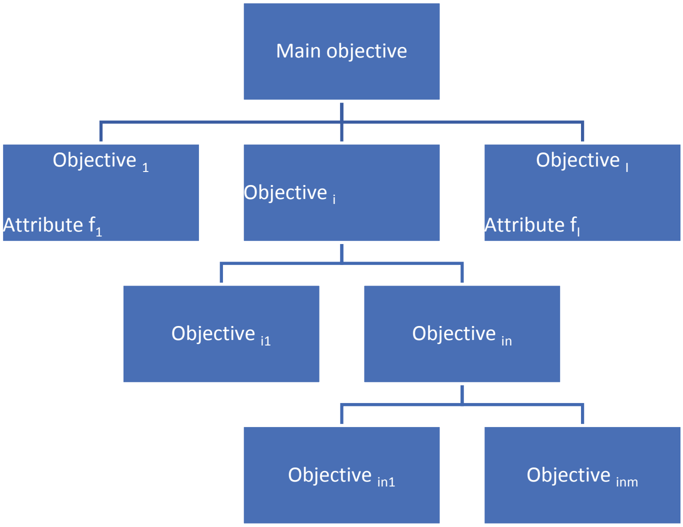

Fig. 1 Objective hierarchy. *Source* Morais Neto (1988)

- Objective: The expression (in a narrative or quantitative way) that reflects decision-maker desire, such as maximize profits or minimize costs.
- Level of achievement: A specific value that is associated with a desirable or affordable level of achievement of an objective, which is used as a measure for goal achievement;
- Goal: Every objective that has an achievement level is called a goal. Therefore, to reach a profit of at least \$Y or to reduce costs, a maximum of \$X are examples of goals;
- Goal deviation: The difference that may occur between the level of achievement attained for a goal and the level of achievement initially desired (aspiration level). A goal deviation can be "more" or "less" in relation to the aspiration level. In other words, you can have positive or negative deviations that occur when the goal is not reached.

According to (Tamiz and Jones 1998), GP models can be classified into two macro-groups. In the first group, the weighted GP, deviation variables receive weights according to their importance as established by the decision maker and have the following objective function:

$$\min Z = \sum_{i=1}^{I} (u_i n_i + v_i p_i) \tag{1}$$

Subject to:

$$f_i(x) + n_i - p_i = b_i, \quad i = 1 \ldots I \tag{2}$$

when

$f_i(x)$	linear function of x, for objective i;
x	decision variable;
b_i	desired value to reach each goal;
n_i and p_i	negative and positive deviation variables for a target value;
u_i and v_i	weights associated for deviation variable in Z function; and
I	total number of objectives.

The second group is classified as lexicographic GP. This group is based on optimizing goals according to their relative importance to the decision maker. The most important goals will be at the highest priority level, while the less important goals will be at the lowest levels. The deviation values obtained from a high priority level will be considered restrictions to its lower priority levels. In other words, the objectives of lower priority levels will play a secondary role in the decision-making process Aouni et al. (2014). The lexicographic GP is represented algebraically by the following objective function, and it is subject to the same previous restrictions (Morais Neto 1988):

$$Lex \min\ a = [g_1(n_i, p_i), (g_2(n_i, p_i), \ldots, g_L(n_i, p_i)] \tag{3}$$

subject to:

$$f_i(x) + n_i - p_i = b_i, \quad i = 1 \ldots I \tag{4}$$

where:

$f_i(x)$	linear function of x, for objective i;
x	decision variable;
a	ordered vector of priority levels;
b_i	desired value to reach each goal;
$g_L(ni, pi)$	linear function of deviation variables for priority level L;
L	priority levels; and
n_i and p_i	negative and positive deviation variables for a target value;
I	total number of objectives.

In summary, the main difference between weighted and lexicographic GP methods is that in the lexicographic method, the goals are optimized in sequence, according to the priority level that the decision-maker sets for each one of the goals. That is, the lexicographic GP model will only seek the optimization of the second priority goal after optimizing the first priority and so on. In weighted GP, the model is optimized, seeking the best result according to the objective function, respecting the weights assigned to the deviation variables of each objective. The decision maker may work with different trade-offs and can generate an analysis of different scenarios and choose the best to meet his/her needs.

The literature discusses the normalization techniques in GP problems several times, aiming to overcome the use of incommensurability, which occurs when goals have different units of measure. In these cases, the sum of deviation goals in an objective function could provoke incorrect results. The most popular normalization techniques are Euclidean normalization, scaling between ideal and nadir points and percentage normalization (Tamiz et al. 1995). The Percentage Normalization will be used in this chapter. This technique considers that each deviation from goal is divided by its goal value and then multiplied by 100. Then, these deviations come to represent the goal deviation percentage. The critical factor of this approach is the goal target value because the method only works well when target values are not equal to zero.

2.2 The Use of GP in Transports

According to Jones and Tamiz (2010), there is a tendency to use weighted GP rather than lexicographic GP because weighted GP provides greater flexibility by weighting constants and by the desire of decision makers to create more analysis of trade-offs and comparisons between the objectives. Niemeier et al. (1995) developed five optimization models for the selection of a set of projects with the objective of improving the performance of an entire hypothetical transport system. Among the models, one model used the weighted GP. Uliana (2010) used weighted GP associated with the utility method to solve the distribution problem of natural gas using trucks and/or pipelines. Yang et al. (2011) also used weighted GP to develop a freight optimization model of a Chinese intermodal network for the Indian Ocean, seeking to minimize transport costs, transit time and variation, ensuring a continuous flow and compatibility among railways, freeways, ships, airplanes and non-oceanic waterways.

Lexicographic GP (LGP) was used by (Morais Neto 1988) to develop a model of allocation of military cargo flows, seeking to rationalize the work of the military planner and the use of the available transport subsystems. Ramos (1995) applied LGP in deciding which mitigation alternatives or actions should be adopted in marine oil terminals to improve their operational performance. LGP was also used to develop a network design model for expanding a railway rapid transit network with a given number of new lines (López-Ramos et al. 2017).

Decisions considering transport investment projects were studied by Teng and Tzeng (1996) who developed a method of selecting independent transport investment alternatives through an efficient distance heuristic algorithm, seeking to maximize the objectives achieved, according to available resources. Additionally, Ahern and Anandarajah (2007) developed a weighted integer GP (WIGP) model for selection of new railroad investment projects in Ireland, where the core business is passenger transport. Subsequently, Ahern and Anandarajah (2008) developed a quadratic model that was applied in a similar situation, selecting new railway projects for passenger trains in Ireland, using the ideal solution concept, allowing more than one optimal solution to be identified as the first and the second and, thus, a potentially better solution, whereas the GP model presented only one optimal solution.

Some authors considered that usual GP methods for transport investment prioritization projects are not able to effectively deal with preferences and uncertainties of decision makers; therefore, they proposed the use of fuzzy set theory to deal with inaccurate information. As an example, Teng and Tzeng (1996) developed a method of selecting independent transport investment alternatives through an efficient distance heuristic algorithm, seeking to maximize objectives achieved, according to available resources. Teng and Tzeng (1998) also applied this theory and proposed a fuzzy GP 0-1 model, which was applied in a hypothetical situation for the selection of transport investment projects, considering 10 projects with resource constraints and objectives to be reached, which were qualitative and quantitative targets to be achieved. Kahraman and Büyüközkan (2008) combined the fuzzy GP with the fuzzy Analytic Hierarchy Process (AHP) to prioritize projects using the Six Sigma methodology. Chang et al. (2009) proposed an integrated model for selection of revitalization projects of the Alishan Forest Railway in Taiwan based on the fuzzy Delphi and Analytic Network Process (ANP) for qualitative evaluation of prioritization criteria of these projects. The results of this evaluation were incorporated into a GP 0-1 model to aid decision making. Wey and Wu (2007) proposed a methodology for the selection of transport infrastructure projects, combining the Delphi fuzzy method with ANP and GP 0-1. The authors applied the model to study transport infrastructure improvement in Taichung City, Taiwan.

This section presented some basic concepts and applications of GP in transport. In the next section, we present two applications of weighted GP in railways, referring to applications in forecasting new investments and in maintaining railway assets.

3 Applications

Weighted GP modelling was used for both: railway project selection and railway superstructure maintenance selection. These two case studies were validated using a heavy haul railway in Brazil.

3.1 Railway Project Selection

The general objective for this problem is to prioritize of current investment projects of a railway, according to strategic planning, financial indicators and sustainability. This objective needs to be decomposed into specific objectives to identify their attributes and measurement units, as described in Tables 1, 2 and 3, as follows.

Table 1 Specific objective details

ID	Goal	Attribute	Unit
1.1	To ensure projects that do not exceed the financial resources available for investment	Resources	R$*
1.2	To ensure financially viable projects (net present value)	VPL	R$
1.3	To ensure projects that contribute physical availability (PA) of railway increase	DF	%
1.4	To ensure projects that guarantee minimum conditions for sustainability requirements of the business	–	–

Note R$—Brazilian Real

Table 2 Decomposition of 1.4 objective

ID	Goal	Attribute	Unit
1.4.1	To ensure projects that contribute to reducing the rate of accidents (AC)	Accident rate decrease	Accident/MTkm[a]
1.4.2	To ensure projects that meet the expectations of external stakeholders	–	–

[a]Million tons per kilometres

Table 3 Attributes and Units – external stakeholders

ID	Goal	Attribute	Unit
1.4.2	To ensure projects that meet the expectations of external stakeholders		U_i
	– To meet environmental requirements	Environmental standards	U_{pj}
	– To meet ANTT requirements	ANTT Commitments	U_{pj}
	– To meet local community requirements	Commitments Communities	U_{pj}

The specific objective 1.4, listed above in Table 1, has neither an attribute association nor measures because it is described in a generic way. Therefore, this objective was decomposed to more specific objectives, as presented in Table 2.

Even after the second decomposition of objectives, objective 1.4.2 is still without an attribute and associated measure. Thus, for this objective, the following subobjectives can be identified, among others: (a) to comply with environmental requirements, (b) to comply with ANTT[1] requirements, and (c) to meet requirements of local communities. The association of attributes and measurement units in each subobjective uses an associated utility method to ensure that utilities of each attribute are mea-

[1]Brazilian Transport Agency (Agência Nacional de Transportes Terrestres – ANTT).

sured on a single numerical scale. In this case, quantification is performed by the association of an abstract value of usefulness for each possible situation. Therefore, an event that has no numeric or monetary correspondent can be transformed into a utility value (Margueron 2003). Table 3 shows the resulting attributes and units for subobjective 1.4.2:

Thus, the associated utility of external stakeholder objectives for each project can be calculated by the formula, and is defined as "Attendance to stakeholders":

$$U_p = \sum_{j=1}^{J} w_j u_{pj} \tag{5}$$

where

U_p total utility of p project ($p = 1,\ldots,$ P);
w_j associated weight of attribute j (j = 1,…, J); and
u_{pj} utility of attribute j.

The goal is achieved by the inclusion of negative and positive deviations in objective mathematical expressions and the attribution of its target or level of achievement. For the problem in question, the goals are:

$$\text{Budget} - \text{O} \quad (\sum_{p=1}^{P} X_P C_P) + n_i - p_i = M_O \tag{6}$$

$$\text{Net present value} - \text{NPL} \quad (\sum_{p=1}^{P} X_P VPL_P) + n_i - p_i = M_{VPL} \tag{7}$$

$$\text{Physical Availability} - \text{DF} \quad (\sum_{p=1}^{P} X_P DF_P) + n_{i-} p_i = M_{DF} \tag{8}$$

$$\text{Accident rate decrease} - \text{AC} \quad (\sum_{p=1}^{P} X_P AC_P) + n_{i-} p_i = M_{AC} \tag{9}$$

$$\text{Attendance to stakeholders} - \text{U} \quad (\sum_{p=1}^{P} X_P U_P) + n_i - p_i = M_U \tag{10}$$

where

x_i Binary variable for selection of projects (0 = no; 1 = yes) for p projects ($p = 1, \ldots P$);
n_i and p_i Negative and positive deviation variables of goal i ($i = O$, *VPL*, *DF*, *AC or U*);
C_p Investment required for project p implementation [R$];
VPL_p Net Present Value of project p [R$];
DF_p Impact on physical availability of the railway caused by project p [%];

AC_p	Annual reduction rate of railway accidents caused by the project *p*. [A/MTkm];
U_i	Total utility of project *p*;
M_i	Target values for each goal *i* (*i* = *O*, *VPL*, *DF*, *AC or U*); and
P	Number of projects considered.

3.1.1 Model Formulation

Once the goals are defined, an objective function is proposed that will seek to minimize the weighted sum of deviation variable percentage of goal values defined for each goal. Thus, the decision maker can prioritize the goals, normalized by percentage where deviations are lower for the most important goals. Thus, the model is composed of the execution function, and goals are defined as follows:

$$Minz = \sum_{i=1}^{I}\left(u_i\frac{n_i}{M_i} + v_i\frac{p_i}{M_i}\right) \quad (11)$$

Subject to:

$$(\sum_{p=1}^{P} X_P C_P) + n_i - p_i = M_O \quad (12)$$

$$(\sum_{p=1}^{P} X_P VPL_P) + n_i - p_i = M_{VPL} \quad (13)$$

$$(\sum_{p=1}^{P} X_P DF_P) + n_{i-} p_i = M_{DF} \quad (14)$$

$$(\sum_{p=1}^{P} X_P AC_P) + n_{i-} p_i = M_{AC} \quad (15)$$

$$(\sum_{p=1}^{P} X_P U_P) + n_i - p_i = M_U \quad (16)$$

where

$n_i, p_i \geq 0$ for all i
$M_i > 0$ for all i
x_p must be a binary value
$0 < u_i < 10$
$0 < v_i < 10$
u_i and v_i: positive and negative weighting deviations for goal i
M_i: Target value for the goal i.

3.1.2 Model Application

The model for selection of railway private company investment projects was used for a portfolio selection of 15 fictitious projects considering values equivalent to a real case, using the solver supplement of *Microsoft Excel* 2013®. The 15 fictitious projects considered for this application has the purpose to ensure the confidentiality information from real projects. The data used do not influence the application and results of the model. The total cost of all 15 projects is R$2418 $\times$ 10^6, and the available budget for project portfolio selection is equal to R$1800 $\times$ 10^6 (74.4% of project total cost). According to the decision maker strategy, the target values of the other goals will be equal to 85% of the total value of each attribute of the portfolio, as shown in Table 4. The budget was considered a goal and not a rigid constraint, so the decision maker can work with different trade-offs from a potential increase in the available budget. To analyse the different trade-offs several scenarios will be generated, changing the weight of each objective, so the decision maker is able to compare the projects selected by the model in each situation. The scenarios will be explained below. Thus, the GP model will indicate which of 15 projects will be selected, seeking to minimize the percentage deviation of target values per goal from decision variable X_i, which will be 1, if project i was selected and 0 otherwise. The values presented in Table 4 are equivalent to a real case.

According to the railway strategic planning the objectives considered in the project selection model have the following priorities: Budget (O), Net Present Value (VPL), Accident Rate Decrease (AC), Attendance to stakeholder (U) and physical availability (DF), as presented in Fig. 2.

It is noteworthy that the model will compose the portfolio of projects considering that the higher the value of the weights ($\boldsymbol{v}_\mathbf{i}$ and $\boldsymbol{u}_i$) of deviation variables of a goal, the higher the level of its priority because the objective function of the model will seek to minimize the weighted sum of the percentage deviation variables of the target values. With these assumptions, for the first scenario, the model selected 11 projects among the 15 proposed. Analysing Table 5, we observe that the budget objective was the only one with a non-zero $\boldsymbol{v}_\mathbf{i}$ value. The other $\boldsymbol{u}_i$ variable objectives received positive values since a burst in the available budget would not be acceptable by decision

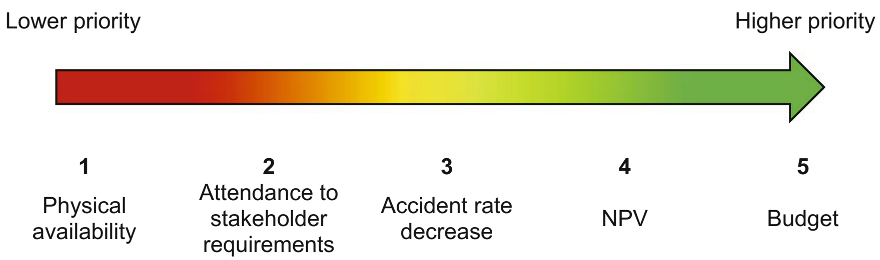

Fig. 2 Order of objective priority

Table 4 Railway projects portfolio

Project	Selector (Xi)	Budget (R$ $\times 10^6$)	NPV (R$ $\times 10^6$)	DF (%)	Accident rate decrease (A/MTkm)	Attendance to Stake-holder (U)
1		207	2557	0.206	0.000	3.000
2		132	0477	0.218	0.075	2.333
3		180	1942	0.436	0.009	2.000
4		199	2145	0.515	0.005	3.667
5		120	0921	0.060	0.011	3.667
6		156	1868	0.988	0.000	3.000
7		153	0612	0.735	0.001	2.667
8		189	2952	0.272	0.015	2.667
9		128	0444	0.220	0.031	1.667
10		180	0710	0.778	0.010	3.333
11		165	0037	0.007	0.000	2.000
12		150	2298	0.197	0.059	3.667
13		174	2324	0.487	0.008	2.333
14		105	1240	0.429	0.022	3.000
15		180	0533	0.057	0.004	2.333
Total		2418	21,060	5.605	0.250	41.333
Target value		1800	17,901	4.764	0.212	35.133
Target value/Total (%)		74.4	85	85	85	85

maker. For the other goals, the higher the values achieved the better, even if they eventually exceed their target values.

In this scenario, the objective function reached 35.6%, which shows that there may be an imbalance between the weights of the deviation variables or very high selection levels for the target values of some goals. As expected, the objectives of lower priority obtained negative deviations in relation to the values of their goals, and the sum of these deviations was equal to 11.2%, highlighting the deviations from the target of service to stakeholders (7.0%) and physical availability (3.7%). It is also noteworthy that the goal of net present value was exceeded by 8.6%.

The second scenario changed the priority order of reducing the rate of accidents (AC) and meeting the requirements of the objectives of the stakeholders (U), passing the weights of the variables of their negative deviations to 4 and 6, respectively (Table 6). From this change, the model again selected 11 projects; however, with the alteration of a project in relation to the initial situation, presenting an objective function equal to 42.3% and the following values and deviations was achieved.

Table 5 First scenario results

Objective	Values			Deviations		Weights	
	Target	Reached	Difference	ni (%)	pi (%)	ui	vi
O	1800.000	1792.000	−8.000	0.4	0.0	0	10
NPV	17.901	19.433	1.533	0.0	8.6	8	0
DF	4.764	4.586	−0.179	3.7	0.0	2	0
AC	0.212	0.214	0.001	0.0	0.7	6	0
U	35.133	32.667	−2.467	7.0	0.0	4	0
Total				11.2	9.2		

where O = Budget, NPV = Net Present Value, DF = Physical Availability, AC = Accident Rate, and U = Utility function for stakeholder requirements

Table 6 Second scenario results

Objective	Values			Deviations		Weights	
	Target	Reached	Difference	ni (%)	pi (%)	ui	vi
O	1800.000	1765.000	−35.000	1.9	0.0	0	10
NPV	17.901	18.104	0.203	0.0	1.1	8	0
DF	4.764	4.884	0.120	0.0	2.5	2	0
AC	0.212	0.206	−0.006	2.9	0.0	4	0
U	35.133	33.333	−1.800	5.1	0.0	6	0
Total				10.0	3.7		

where O = Budget, NPV = Net Present Value, DF = Physical Availability, AC = Accident Rate Decrease, and U = Utility function for Attendance to stakeholders

In this second scenario, the total value of the selected portfolio was R$27 million lower than in the previous one, and the sum of the negative deviations totalled 10.0%, which is 1.2% lower than the previous situation. If we compare the sums of negative deviations between the two scenarios, disregarding the budget deviations, there was a reduction of 2.7%, which explains the increase in the negative deviation of the budget target. Moreover, to compensate for this reduction, the positive deviations from the other targets were reduced from a total of 9.2 to 3.7%.

To evaluate the necessary increase in the budget so that the negative deviations of the targets were the smallest possible, one can opt for a new scenario, reducing the priority of the budget target and maintaining the priority of the first scenario, which reflects the priorities of objectives according to the strategic planning of the organization. The budget is still a priority but is less important since the weight of its deviation variable received the smallest nonzero value in relation to the other goals. Thus, for the third scenario, the model selected 12 projects, with a burst of R$93 million in the budget target, but with the negative deviation of only 0.4% in the target of meeting the requirements of the stakeholders and with objective function equal to 12.6%. The other goals had positive deviations, as shown in Table 7.

Table 7 Third scenario results

Objective	Values			Deviations		Weights	
	Target	Reached	Difference	ni (%)	pi (%)	ui	vi
O	1800.000	1893.000	93.000	0.0	5.2	0	2
NPV	17.901	18.548	0.647	0.0	3.6	10	0
DF	4.764	5.105	0.340	0.0	7.1	4	0
AC	0.212	0.237	0.025	0.0	11.7	8	0
U	35.133	35.000	−0.133	0.4	0.0	6	0
Total				0.4	27.6		

where O = Budget, NPV = Net Present Value, DF = Physical Availability, AC = Accident Rate Decrease, and U Attendance to stakeholders

Table 8 Fourth scenario results

Objective	Values			Deviations		Weights	
	Target	Reached	Difference	ni (%)	pi (%)	ui	vi
O	1800.000	2083.000	283.000	0.0	15.7	0	0
NPV	17.901	18.059	0.158	0.0	0.9	10	0
DF	4.764	5.178	0.414	0.0	8.7	4	0
AC	0.212	0.219	0.006	0.0	3.0	8	0
U	35.133	36.667	1.533	0.0	4.4	6	0
Total				0.0	32.7		

where O = Budget, NPV = Net Present Value, DF = Physical Availability, AC = Accident Rate Decrease, and U = Attendance to stakeholders

Even with a significant reduction of negative deviations in third scenario, how much more budget would be needed for all negative deviations to be equal to zero? This would mean that all target values of the objectives were achieved or were larger than that established by the decision maker. To evaluate this trade-off, a new scenario was carried out, with the weights of the deviation variables maintained in relation to the previous situation, except for the positive deviation variable of the budget, which went from 2 to zero, showing that this deviation ceased to be a priority and became indifferent to the decider. The results of this scenario will consider no budget restriction and will show how much more budget would be necessary, so the decision maker could reach at least the target level of all the other objectives. In these conditions of the fourth scenario, the model selected 13 projects, with an overflow of R$283 million in the budget target, and an objective function equal to 0.0% and no negative deviation, as shown in Table 8.

In the analysis of the results in the first scenario (Table 5), priorities were defined according to the strategic planning and available budget, and from the results achieved, there were reversed priorities of the two objectives for the second scenario, where the model selected a portfolio with lower negative deviations from the

Table 9 Selected projects for each scenario

Project	SC1	SC2	SC3	SC4
1	1	1	1	
2	1	1	1	1
3	1			1
4	1	1	1	1
5	1	1	1	1
6	1	1	1	1
7		1	1	1
8	1	1	1	1
9			1	
10	1	1	1	1
11				1
12	1	1	1	1
13	1	1	1	1
14	1	1	1	1
15				1
Total	**11**	**11**	**12**	**13**
Objective (%)	**35.6**	**42.3**	**12.6**	**0.0**

where SC1 to SC4 presents the projects selected in scenarios 1 to 4

proposed targets, using fewer resources in relation to the previous situation, though it was still within budget. Aiming at a greater reduction of deviations, in the third scenario, the positive deviation of the budget target began to have a lower priority in relation to other priorities. This scenario resulted in the lowest total negative deviation of the portfolio but with a budget overflow. Finally, in the last scenario, the question of how much more budget would be needed for non-negative deviation in other goals was evaluated.

The comparison among the four situations allows for evaluating and choosing the best selection of proposed projects. The trade-offs performed among each of the four situations assist in decision making since the decision maker can evaluate the reduction of deviation of a goal to the detriment of the increase or reduction of the deviations of others. Clearly, there is no better situation among the four presented, and the choice of best is in the hands of the decider based on his/her needs and availabilities. The relationships of projects selected by the model in the four evaluated situations is presented in Table 9, indicating the total of the selected projects and the value obtained for the objective function.

Figure 3 shows deviations of the goals of each objective in the 4 scenarios. To facilitate the presentation of these deviations, it was agreed that positive deviations of the goals would be expressed above the figure axis and negative deviations of

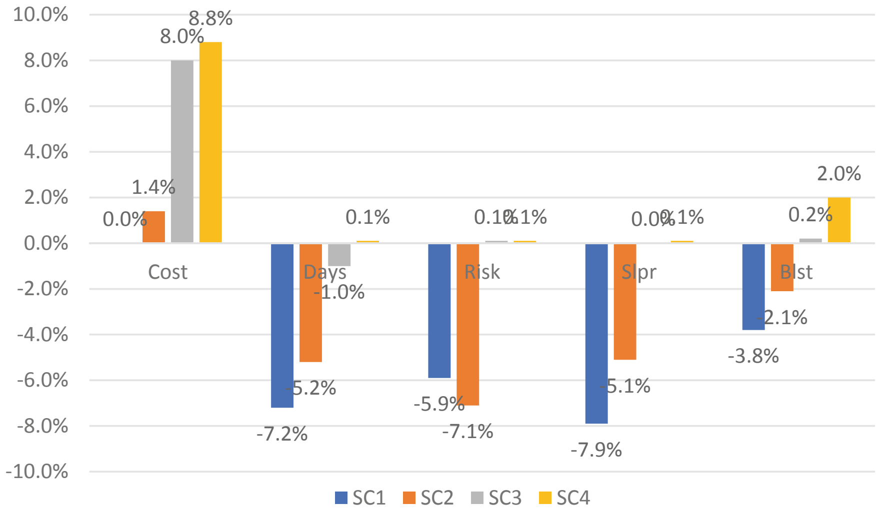

Fig. 3 Deviation goals per objective and scenario. Where O = Budget, NPV = Net Present Value, DF = Physical Availability, AC = Accident Rate Decrease and U = Attendance to stakeholders

targets would be represented below the figure axis. However, all the deviations have positive values.

3.2 Railway Superstructure Maintenance Selection

Maintenance activity is an important part of the total cost of railway business. In this context, maintenance of the railway system can be considered a strategic activity inherent in the transportation of cargoes since results are directly related to performance, reliability, transport safety and cost reduction. Problems related to the prioritization of activities are usually part of the railway maintenance process and involve goals and constraints such as budget constraints, the availability of labour and resources, and the degradation of permanent track materials.

Railway maintenance interventions are essentially divided into three unique operations: preventive maintenance, one-off interventions and track renewals. In the first situation, deteriorated track components are checked, followed by repairs and/or replacement. However, punctual interventions are corrective maintenance related to some fault of a track component that compromises train circulation, such as rail fracture fixes, the repair of geometric deformations, and the replacement of screws. Finally, railway renovation is a process in which all elements are replaced due to the inability of the railway to function or to increase transport capacity, considering traffic conditions that are higher than those existing.

In general, railway maintenance is a process of organizing the maintenance of a permanent track to keep railway superstructure in good operating condition. According to (Ferreira 2010), with robustness and high investment involved in the maintenance process, railroads started to adopt maintenance investment strategies increasingly directed to critical problems that were identified. However, a misconception in the railway maintenance process can result in defects concentrated in weak points that, if not properly identified and repaired, can create permanent and irreversible deformations in the railway. The solution demands the complete replacement of components of a whole stretch with possible unwanted interruptions in the movement of trains. The choice of location that requires maintenance intervention is usually performed due to the degradation of permanent track components that occur mainly due to fatigue and the wear actions of material together with the speed of train circulation in the stretch, type of component material, track geometry, and geographic and climatic conditions, etc.

3.2.1 Definition of Model Objectives

The definition of objectives is based on a general objective, which, in turn, is broken down into specific objectives until each can be measured by some attribute. Therefore, the proposed general objective (first level) of this application is "To prioritize maintenance of railway superstructure according to available resources, workforce, risks and maintenance indicators". The general objective can be broken down into the following specific objectives in the second level (Table 10).

Objective 1.3 does not have a unit that describes the risk associated with the region or location where the defect is due to be a qualitative objective, and it is necessary to use the Associated Utility Method for a better description in terms of a numerical scale. Thus, the following environmental, demographic and geometric factors are considered:

- Proximity to water courses or environmental preservation areas;
- Proximity to urban centres or towns;
- Railway Geometry (straight or curved).

Table 10 Specific objectives of the second level

ID	Objective	Attribute	Unit
1.1	Do not exceed limit of financial resources available for maintenance of railway	Resource	R$
1.2	Do not exceed work capacity available for maintenance activities	Labour	days
1.3	To reduce risks of road defects associated with defect localization	Risk index	ur
1.4	To improve current track condition according to maintenance indicators	–	–

Table 11 Specific objectives of the third level

ID	Objective	Attribute	Unit
1.4.1	To replace insufferable sleepers	Sleeper	un
1.4.2	To replace rails below tolerance levels	Rail	m
1.4.3	To apply ballast to sections with insufficient materials	Ballast	m

The estimation of risk index involves the relationship between measurement and criticality of defects (in sleeper, ballast and rail) and severity represented by location of these defects. The equation for estimation of risk index, measured in units of risk, is represented as follows:

$$R_i = \sum_{m=1}^{M}(u_m \cdot \delta_{im}) \sum_{n=1}^{N}\left(g_n \cdot \lambda_{in}\right) \tag{17}$$

where

- i each section or division of railway in I equal parts (i = 1, 2, 3,…, I);
- m type of defect analysed: sleeper (m = 1), ballast (m = 2), rail (m = 3);
- n criterion referring to defect locality: environmental, geometric (n = 1, 2, 3,…, N);
- u_m criticality factor or urgency factor of defect m;
- g_n weight for each of *n* evaluation criteria of locality;
- δ_{im} measure or extent of defect m in section *i*;
- λ_{in} factor of severity of locality referring to criterion n in section *i*.

The value of the severity factor associated with locality λ_{in} is represented by the numerical scale reported from 1 to 5.

Objective 1.4, described in a generic way in Table 10, needs more detail so that it can have a form of measurement. Thus, this item is broken down into more third level specific objectives (Table 11), as follows:

3.2.2 Transformation of Objectives into Goals

Once objectives are defined, they must be transformed into goals. The goal is achieved by including negative and positive deviations in mathematical expressions that represent the goal and also by attribution of its target or level of attainment. For the problem in question, the following goals are formulated:

$$\text{Cost} \quad \sum_{i=1}^{I}(x_i \cdot C_i) + \eta_1 - \rho_1 = M_1 \tag{18}$$

$$\text{Labour} \quad \sum_{i=1}^{I}(x_i \cdot W_i) + \eta_2 - \rho_2 = M_2 \tag{19}$$

$$\text{Risk reduction} \quad \sum_{i=1}^{I}(x_i \cdot R_i) + \eta_3 - \rho_3 = M_3 \tag{20}$$

$$\text{Sleeper replacement} \quad \sum_{i=1}^{I}(x_i \cdot S_i) + \eta_4 - \rho_4 = M_4 \tag{21}$$

$$\text{Rail replacement} \quad \sum_{i=1}^{I}(x_i \cdot T_i) + \eta_5 - \rho_5 = M_5 \tag{22}$$

$$\text{Ballast application} \quad \sum_{i=1}^{I}(x_i \cdot B_i) + \eta_6 - \rho_6 = M_6 \tag{23}$$

where

i	each section or division of railway in I equal parts (i = 1, 2, 3,…, I);
j	numerical identification of each goal (j = 1, 2, 3,…, J);
η_j and ρ_j	variables of negative and positive deviation of goal j;
M_j	target values for each goal j;
x_i	binary variable of decision for each section i;
C_i	investment or cost required to perform maintenance in each section i [R$];
W_i	labour or workforce required to maintain each section i [days];
R_i	risk index associated with defects in each section i [ur];
S_i	number of sleepers to be applied in each section i [und];
T_i	extension of rails to be replaced in each section i [m];
B_i	extension of ballast to be replaced in each section i [m].

3.2.3 Model Formulation

Once goals are defined, an objective function is proposed that will seek to minimize the weighted sum of the percentage deviation variables of the target values defined for each of the goals. In this way, the decision maker can prioritize goals, normalized in percentage, which will be weighted so that deviations are smaller for most important goals. The percentage treatment of deviation weights becomes important because it allows for a comparison of deviations at the same level of magnitude. Therefore, according to Rehman and Romero (1984), the execution function and its goals are defined as follows:

$$\min \sum_{j=1}^{6}\left(\alpha_j \frac{\eta_j}{M_j} + \beta_j \frac{\rho_j}{M_j}\right) \tag{24}$$

Subject to:

$$\sum_{i=1}^{I}(x_i \cdot C_i) + \eta_1 - \rho_1 = M_1$$
$$\sum_{i=1}^{I}(x_i \cdot W_i) + \eta_2 - \rho_2 = M_2$$
$$\sum_{i=1}^{I}(x_i \cdot R_i) + \eta_3 - \rho_3 = M_3$$
$$\sum_{i=1}^{I}(x_i \cdot S_i) + \eta_4 - \rho_4 = M_4$$
$$\sum_{i=1}^{I}(x_i \cdot T_i) + \eta_5 - \rho_5 = M_5$$
$$\sum_{i=1}^{I}(x_i \cdot B_i) + \eta_6 - \rho_6 = M_6$$

where

$\eta_j, \rho_j \geq 0$ for all j
$M_j > 0$ for all j
$0 < \alpha_j \leq 10$
$0 < \beta_j \leq 10$
$x_i = 0$ or $x_i = 1$
where α_j and β_j weights are negative and positive deviations of goal j

The proposed model was implemented in Microsoft Excel solver due to the ease in formulating and changing data for generations of different scenarios and because it is a commercially distributed software.

3.2.4 Model Application

The proposed model for prioritization of railway sections that will undergo maintenance intervention is then applied to a 100-km-long fictitious railroad, which is divided into 100 stretches of 1 km each, and the number of defects of randomly simulated superstructure materials with values is presented in Table 12.

The GP model considers the division of the railway into equal parts and seeks to indicate, from decision variables, which sections should have maintenance prioritized to minimize percentage deviations of target values for each goal. Each division has a necessary amount of material, labour (in working days) and investment, as well as respective risk associated with the need for maintenance and factors inherent in location of defects.

Table 12 Simulated railroad parameters

Item	Amount
Total extension (km)	100
Sequences of insufferable sleepers (unid)	60,885
Extension of rails below tolerance levels (m)	28,566
Extension of insufficient ballast (m)	36,995

Table 13 Proposed model targets

	Sections (unit)	Investment (BzR$)	Work Days	Risk Reduc-tion	Sleepers (unit)	Ballast (m)	Rails (m)
Required	100	27,257,332	555	681,150	60,885	36,995	28,566
Target	–	20,442,999	472	578,978	51,753	31,446	24,281
Target (%)		75	85	85	85	85	85

As in practical situations, there are budget constraints. It is considered a strategy of the decision maker that the available budget for selection of stretches to be worked is approximately 75% of the real need and that target values of other goals are equal to 85% of the value total of each attribute (Table 13); it is the responsibility of the decision maker to carry out trade-offs to evaluate possible extrapolations of the available budget.

To analyse different trade-offs, from possible changes in priorities of objectives carried out by the decision maker, different scenarios are generated to be analysed. For the First Scenario, according to the strategic planning for railroad maintenance, objectives contained in the project selection model have the following priority levels:

- Priority 1: Investment;
- Priority 2: Working days;
- Priority 3: Risk reduction;
- Priority 4: Sleepers application;
- Priority 5: Ballast application;
- Priority 6: Replacing rails.

In this way, the model will select the segment that will receive investment intervention considering that the greater the value of the weights of deviation variables of a goal, the higher the level of its priority because the objective function of the model will seek to minimize the weighted sum of percentage deviation variables of target values.

Using these assumptions, for the First Scenario, the model selected 76 stretch from the existing 100, which are presented in Table 14. In this case, the only goal that did not present a deviation was one of investment, considering that its overflow would be acceptable and receive maximum weight. All other goals had a deviation below their target values.

Table 14 First maintenance scenario results

Objective	Required	Target	Amount reached	Difference	+Deviation (%)	−Deviation (%)	Weight above	Weight below
COST	12,243,418	20,442,999	20,444,856	1857	0.0	0.0	10	0
DAYS	276	472	438	−34	0.0	7.2	0	1
RISK	284,067	578,978	544,744	−34,234	0.0	5.9	0	5
SLPR	33,000	51,753	47,675	−4078	0.0	7.9	0	3
BLST	16,800	31,446	30,252	−1194	0.0	3.8	0	3
RAIL	11,000	24,281	20,470	−3811	0.0	15.7	0	3

In a second scenario, with inversion of orders of priority of material application and risk reduction objectives, while maintaining restrictions to exceed available investment, it is possible to note that the solution found is a 1% overflow in the budget that generated a lower reduction in existing risk and greater application of materials. From this change, the model selected 77 stretches compared to 76 from the first scenario (Table 15).

The third scenario (Table 16) prioritized the application of materials and risk reduction, making the investment goal more flexible. In this way, the reduction of deviations from this goal was quite pronounced, resulting in an 8% overflow in budget and prioritizing maintenance in 82 sections.

The fourth scenario (Table 17), considered as a priority optimization of available labour, increases the weight of working days and reduces investment priority and risk, maintaining some importance of the application of materials. Thus, the model selected prioritization of maintenance in 83 stretches, zeroing deviations of the goal of days worked and presenting applications of sleepers with deviations close to zero and applications of ballast superior to that established as the goal. The number of rails to be replaced presented a deviation of less than 8%, which can be explained by its high unit value.

3.2.5 Results Analysis

The first scenario (Table 14) was the object of mainly available budget consultation and, from results achieved, was reversed as direct from other objectives for the generation of a second scenario (Table 15), a variation of 1.4% in positive deviation of target budget. Most of the deviations are not found in the third scenario (Table 16); a positive deviation from budget target became less important in relation to others. There is nothing less than this negative in total portfolio, but without budget. Finally, the maximum available labour force was evaluated in the last scenario (Table 17).

A comparison between four series allows us to evaluate and choose a better selection of proposed maintenance strategies. Trade-offs in one of four situations help in decision making since the decision maker can evaluate the reduction of the deviation of one goal in detriment of high or the reduction of deviations of others. It is important that its opinions be more rigorous, improved and assessed for priority.

Finally, Fig. 4 shows the deviation goals of each of the 4 scenarios. The most important of these are for status of representative of axis. However, all deviations have positive values.

Table 15 Second maintenance scenario results

Objective	Required	Target	Amount reached	Difference	+Deviation (%)	−Deviation (%)	Weight above	Weight below
COST	12,243,418	20,442,999	20,729,629	286,630	1.4	0.0	10	0
DAYS	276	472	447	−25	0.0	5.2	0	1
RISK	284,067	578,978	537,862	−41,116	0.0	7.1	0	2
SLPR	33,000	51,753	49,108	−2645	0.0	5.1	0	5
BLST	16,800	31,446	30,777	−669	0.0	2.1	0	5
RAIL	11,000	24,281	20,496	−3785	0.0	15.6	0	5

Table 16 Third maintenance scenario results

Objective	Required	Target	Amount reached	Difference	+Deviation (%)	−Deviation (%)	Weight above	Weight below
COST	12,243,418	20,442,999	22,087,474	1,644,475	8.8	0.0	2	0
DAYS	276	472	467	−5	0.0	1	0	1
RISK	284,067	578,978	579,558	580	0.1	0.0	0	5
SLPR	33,000	51,753	51,742	−10	0.0	0.0	0	5
BLST	16,800	31,446	31,495	49	0.2	0.0	0	5
RAIL	11,000	24,281	22,188	−2093	0.0	8.6	0	5

Table 17 Fourth maintenance scenario results

Objective	Required	Target	Amount reached	Difference	+Deviation (%)	−Deviation (%)	Weight above	Weight below
COST	12,243,418	20,442,999	22,234,093	1,791,094	8.8	0.0	1	0
DAYS	276	472	472	0	0.1	0.0	0	5
RISK	284,067	578,978	579,625	648	0.1	0.0	0	1
SLPR	33,000	51,753	51,787	34	0.1	0.0	0	3
BLST	16,800	31,446	32,090	644	2.0	0.0	0	3
RAIL	11,000	24,281	22,382	−1899	0.0	7.8	0	3

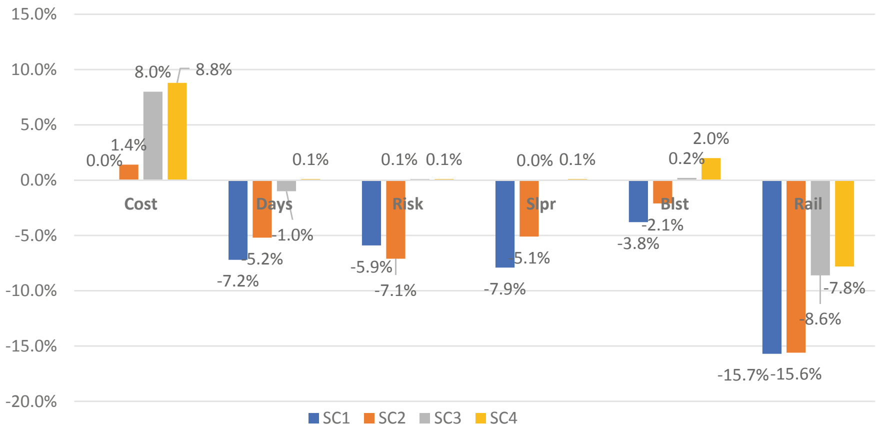

Fig. 4 Percentage deviation goals in each scenario

4 Conclusions

The use of optimization techniques by multiple criteria has grown every year in various fields of application. Among these techniques, programming by goals (GP) stands out. In the GP approach, goals are formulated by the association of targets to be achieved in each objective, having an objective function that seeks to minimize the sum of absolute deviations of these goals.

Based on the GP methodology, a model of the selection of current investment projects was developed, seeking the composition of a project portfolio focussing on strategic-level financial and sustainability indicators, which was applied to the selection of a portfolio of 15 fictitious projects. To evaluate the trade-offs carried out with a change in the priority of the objectives, 4 selection scenarios were generated from the same project portfolio, varying the weights of the variable deviations of the targets, which directly influences programming results. The scenarios were generated in sequence, from an analysis of the variables of the deviation of the targets and not the value obtained by the objective function of each previous scenario since each change of the weights of the deviation variables in each scenario results in different situations.

The developed model proved useful in the selection of railway investment projects, but it is only a tool to assist the decision maker, who needs to define which goals need to be prioritized according to business needs. The target values of each goal must be defined according to the strategy of the organization, and the change of these values directly influences the results achieved by the model. In addition to prioritizing the most important goals, based on model results, the decision maker can also redefine the target values of their goals, seeking harmony with the possible results against existing objectives.

Special attention should be given to returns that each project will achieve in the view of specific objectives, if selected and implemented, since this selection stage deals with values estimated by the decision maker or by project owners. Often, this information is presented at low maturity levels; therefore, it is important that there is a previous stage of maturity evaluation of the projects that will compete in the selection by the model. Thus, the results achieved by the model should serve as a reference, not only a source for decision making. The recommendation for the development for future work, with the possibility of the prioritization of the projects selected from the Portfolio ranking best scored for worst, means that the decision maker can analyse which project should be cut if there is a reduction in the available resources.

The model proposed for prioritizing the maintenance of railway sections seeks the best application of superstructure materials focussing on maintenance, financial and risk reduction indicators, which was applied in a railway with an extension of 100 km. The model that was developed proved to be useful in the choice of the sites of the application of the superstructure materials as a tool to assist the decision maker.

For these two applications, the decision maker must define the prioritization of the goals according to the strategy of the organization. The change of these values directly influences the results achieved by the models.

The software used proved to be very friendly and suitable for implementation of the model. However, the software can present limitations in more robust applications due to the complexity of the problem to be modelled, such as additions of variables or goals, as well as the greater number of subdivisions of model.

The models developed were used to select projects for railway investments and maintenance strategies, but they could be applied in other applications if the specific objectives and target values of the goals are duly redefined.

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