Development of an aggregated risk index for the management of investment in safety measures on the Belgian rail network

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Abstract: In order to take up new challenges regarding the management of a wide range of parameters impacting the risk of accidents at rail crossings on the Belgian railway network, we have developed an innovative multicriteria decision making framework based upon the pairwise comparison PROMETHEE (Preference Ranking METHod for Enrichment and Evaluation). The framework allows the evaluation of a global risk index based upon a wide range of indicators thanks to a “two-steps” aggregation process including the definition of sensitivity parameters. Around 50 indicators are classified into three main clusters related to three specific risk sources, namely: the road network, the rail network and the town planning related aspects. These three clusters are then aggregated into the final risk index. Within the frame of the Belgian rail network, this index provides the responsible public body with an actual strategic investment handbook regarding the most risky locations. An user friendly excel tool has been developed in order to make that new decision framework easily understandable by the final users.

Keywords: Decision-making, safety, rail, management

Introduction

Within the context of a mission for the Belgian railway infrastructure manager, a fully new and innovative methodology is developed to improve the way of identifying and quantifying the risk of accidents at railway crossings. It is the task of the research as discussed in this paper to provide an integrated and aggregated framework in order to be able to assess that new global risk index on the basis of around 50 key performance indicators (KPIs).

First a brief literature review is presented regarding the choice of the multicriteria method used for designing the two-steps aggregation framework. The global risk index is then presented including the mathematical modelling of the selected multi criteria decision aiding method. Before the conclusion, a use case based upon a sub-set of rail crossings is then demonstrated.

Literature review

In order to design the aggregation framework used for evaluating the new risk index, the main literature source is [13] where Rigo et al. develop a two-steps aggregation framework in order to design a new global transport performance macro indicator. As discussed in [13], the methodology PROMETHEE stating for Preference Ranking Organization METHod for Enrichment and Evaluation seems to be very efficient for the purpose of this paper. More precisely, [21] in which Roy and Bouyssou detail a non negligible set of multicriteria decision aiding methods; and [22] in which Roy develops the concept of decision process and gives an overview of multicriteria decision aiding methods demonstrate again the interest of this outranking method for its perfect understanding by end users, namely the manager of the rail network infrastructure. As previously confirmed by [13], other references demonstrate the appropriateness of the selected methodology within the frame of this paper.

Global Risk Index

Introduction

As briefly discussed in the introduction, the global risk index consists in an innovative aggregated score describing the overall risk level of a rail crossing based upon a wide range of KPIs. These KPIs are firstly clustered and
aggregated into three major types of risk namely the road network, the rail network and the town planning related aspects. Then, these three macro risks are aggregated into the global risk index allowing the ranking of all Belgian rail crossings. This ranking can be used by the infrastructure manager in order to prioritize investments in terms of safety measures.

**Methodology**

As previously mentioned, a two-steps aggregation process is designed to quantify the risk index. Figure 1 highlights the pyramidal aggregation structure developed within this framework. It has to be noted that only some KPIs among a total of 50 are presented on Figure 1 since some confidentiality agreements govern the communication and dissemination on KPIs used in the Belgian context. This paper focuses on the way of aggregating KPIs more than on KPIs themselves.

![Figure 1 Schematic overview of the global risk index framework](image)

It is of key importance for the readers to note that such a wide range of KPIs are necessarily characterized by different measure units. While some KPIs such as “Bycicle path” or “Safety gates” can be evaluated thanks to a two-levels linguistic scale “Yes-No”, KPIs such as “Max. Speed” or “Density of schools” are quantified thanks to specific measure units such as km/h and absolute number. This demonstrates the importance of choosing a methodology such as PROMETHEE which allows the user to simultaneously consider quantifiable (including various evaluation scales) and non quantifiable KPIs into one unique approach. On top of that, the main objective is to provide the infrastructure manager with a ranking of rail crossings so that an outranking method based upon pairwise comparisons like PROMETHEE is definitely the most convenient way to meet the expectations.

As highlighted on Figure 1, KPIs are firstly clustered into three specific risk aspects. Initially, around 50 KPIs have been designed and clustered in collaboration with the infrastructure manager. The first step to get intermediate risk scores related to each specific aspect highlighted on Figure 1 consists in applying PROMETHEE to each sub-set of KPIs.
In order to be fully understandable by the end-users, the PROMETHEE II complete ranking is chosen and modelled as follows. Indeed the partial ranking PROMETHEE I could lead to misunderstanding from end-users due to possible incomparabilities between rail crossings.

Let us define the KPI \( j \) as a function \( g_j \) and the evaluation of the impact of rail crossing \( a \) on KPI \( j \), that is \( g_j(a) \).

If \( A \) is the global set of rail crossings, we consider:

\[
\forall a, b \in A, d_j(a, b) = g_j(a) - g_j(b) \tag{1}
\]

It has to be noted that, for example, the “Max. speed” has to be maximised in order to identify the most risky crossing from that perspective while in the other hand, the “Safety gates” KPI has to be minimized since a linguistic scale “Yes-No” can be associated to quantitative levels “1-0”. It is not the purpose of this paper to discuss what KPIs have to be minimized or maximized, nor to discuss the design of linguistic scales and associated quantitative levels which have to be chosen for non quantifiable KPIs since all KPIs can not be made public. However, it is important to highlight that, from a mathematical modeling perspective, this will impact the next step dedicated to the definition of a preference function allowing to remove barriers linked with specific measure units associated to KPIs and then move to an actual multicriteria agregation process.

For a KPI to be maximized, let us define the usual preference function as follows:

\[
F_j[d_j(a, b)] = \begin{cases} 
O \quad & d_j(a, b) \leq 0 \\
1 \quad & d_j(a, b) > 0 
\end{cases}; \forall a, b \in A \tag{2}
\]

It is trivial that for a criterion to be minimized, the preference function is modelled as follows:

\[
F_j[-d_j(a, b)]; \forall a, b \in A \tag{3}
\]

These functions are used within the frame of the global risk index. However, it can be noticed that a wide range of preference functions could be used according to use cases. As an example, the level preference function can be modelled as follows and requests the definition of both a preference and indifference thresholds:

\[
F_j[d_j(a, b)] = \begin{cases} 
O \quad & d_j(a, b) \leq q \\
\frac{d_j(a, b) - q}{p - q} \quad & q < d_j(a, b) \leq p; \forall a, b \in A \tag{4}
\end{cases}
\]

In order to be able to balance the importance of each KPI within each intermediate risk score according to the expertise of rail infrastructure managers, let’s define \( w_j \) the weight of KPI\( j \). Moreover, let’s define \( m \) the number of KPIs in a risk cluster. By considering the weighted sum of applied preference functions, we obtain:
Then, by aggregating on all rail crossings, we get the “power” and “weakness” of each rail crossing compared with all the others on the basis of all the KPIs and their respective parameters (weight and preference function).

\[
\begin{align*}
\pi(a, b) &= \sum_{j=1}^{k} F_j[d_j(a, b)] \times \omega_j, \forall a, b \in A \quad (5) \\
\pi(b, a) &= \sum_{j=1}^{k} F_j[d_j(b, a)] \times \omega_j
\end{align*}
\]

The above mentioned figures are respectively called positive and negative outranking flows.

The final step simply consists in evaluating the net flow characterizing the risk score of each rail crossing. This can be modelled as follow:

\[
\begin{align*}
\phi^+(a) &= \frac{1}{n-1} \sum_{x \neq a} \pi(a, x), \forall a \in A \quad (6) \\
\phi^-(a) &= \frac{1}{n-1} \sum_{x \neq a} \pi(x, a)
\end{align*}
\]

The above described aggregation method is applied to evaluate the three intermediary risk score: namely the road related risk score, the rail related risk score, and the risk score related to external town planning aspects. Moreover, the same approach is applied to these three macro-risks in order to quantify the global risk index. During the first aggregation step, the following parameters have to be fixed for all KPIs, as previously mentioned in the mathematical modeling:

- Weight
- Minization VS Maximization
- Preference Function

Regarding the second aggregation step based upon the same methodology, only the following parameters have to be fixed:

- Minization VS Maximization
- Preference Function

Indeed, since the intermediate risk scores are the net flows allowing to classify rail crossings from the most to the less risky on a quantitative scale going from 1 to -1. It is trivial that the three intermediate risk scores have to be maximised.
As briefly mentioned in the introduction, an Excel tool is developed in order to make this new decision making framework easily and quickly understandable by the end-users. On top of that, since such an aggregation process involving more than 1800 rail crossings and 50 KPIs, leads to around 300 millions mathematical operations, it is necessary to make this process automatic.

The following use case is dedicated to a sub-set of rail crossings, namely crossings related to freight transport. Indeed, above the quantification of the risk index, the end-users can select thanks to various filters, some sub-sets of crossings in order to finetune the analysis and focus on e.g. a specific geographical area, crossings in ports, or some specific lines. The following business case is based upon the consideration of crossings concerned by freight transport.

The following screenshots highlight the rankings of crossings regarding the three intermediate risk scores. The four first columns present specific internal attributes while the two last ones emphasize the intermediate score itself, in other words the netflow, and the ranking. It has to be noticed that these figures only show the first 10 crossings of the ranking for a better readability.

![Figure 2 Intermediate road related risk score](image1)

![Figure 3 Intermediate rail related risk score](image2)

![Figure 4 Intermediate town planning related risk score](image3)
It is quite obvious that these three rankings differ since the basic KPIs used are different. Then, the second aggregation step can be applied to these intermediate risk scores in order to provide the final ranking from the most to the less risky crossing as emphasized on the next figure.

<table>
<thead>
<tr>
<th>nom PN</th>
<th>Final</th>
<th>Route</th>
<th>Ferroviaire</th>
<th>Environnement du PN</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-106-3</td>
<td>106</td>
<td>FREIGHT</td>
<td>0,875</td>
<td>0,128</td>
</tr>
<tr>
<td>L-214-2</td>
<td>214</td>
<td>FREIGHT</td>
<td>0,667</td>
<td>0,123</td>
</tr>
<tr>
<td>L-55-22</td>
<td>55</td>
<td>FREIGHT</td>
<td>0,630</td>
<td>0,226</td>
</tr>
<tr>
<td>L-10-3</td>
<td>10</td>
<td>FREIGHT</td>
<td>0,954</td>
<td>0,097</td>
</tr>
<tr>
<td>L-55-13</td>
<td>55</td>
<td>FREIGHT</td>
<td>0,587</td>
<td>0,010</td>
</tr>
<tr>
<td>L-87-8</td>
<td>87</td>
<td>FREIGHT</td>
<td>0,588</td>
<td>0,040</td>
</tr>
<tr>
<td>L-87-7</td>
<td>87</td>
<td>FREIGHT</td>
<td>0,514</td>
<td>0,123</td>
</tr>
<tr>
<td>L-17-43</td>
<td>17</td>
<td>FREIGHT</td>
<td>0,497</td>
<td>0,011</td>
</tr>
<tr>
<td>L-10-11</td>
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<td>FREIGHT</td>
<td>0,490</td>
<td>0,388</td>
</tr>
<tr>
<td>L-207-14</td>
<td>207</td>
<td>FREIGHT</td>
<td>0,459</td>
<td>0,119</td>
</tr>
</tbody>
</table>

Figure 5 Final risk index

The first fourth columns present the internal attributes of the crossings while the last four columns present the global risk index and remind the three intermediate scores. The colour code used pinpoints the risk level of crossings regarding the global risk level and the sub-levels. In order to fix these colour codes, we consider the range between the maximum and minimum score within each type of risk and divide it by 5 in order to obtain a 5-levels colour code scale going from red (most risky) to green (less risk, which does not appear in Figure 5 since we only focus on the 10 most risky crossings).

Conclusion

The framework and associated tool developed within the frame of this paper consists in an actual investment handbook for priorizing safety measures to be taken at most risky railway crossings. Indeed, on the basis of the global risk index, the end-user can analyse the main trends regarding the most risky locations. Then, when moving back into the pyramidal aggregation structure, the end-user can precisely identify what KPIs are responsible for the high risk level and then select the most appropriate measure in order to counterbalance that weak performance.

Finally, it has to be noted that such a framework and tool can be configured in order to meet the objectives of other local contexts. By adding, deleting, modifying key performance indicators, the transferability of this global risk index could be successful.

References


