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MCDA and Risk Analysis in Transport Infrastructure Appraisals: the Rail Baltica Case

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Abstract

This paper sets out a decision support system (DSS), COSIMA, involving the combination of cost-benefit analysis and multi-criteria decision analysis (MCDA) for transport infrastructure appraisals embracing both economic and strategic impacts. However, some shortcomings appear in the methodology regarding the uncertainties embedded within the criteria weights in the MCDA-part of COSIMA. Therefore, this paper presents the perspective of introducing risk analysis and Monte Carlo simulation to the weighting profile in the MCDA-part. The DSS is presented through a case study concerning alternatives for the construction of the *Rail Baltica* railway line through the Baltic countries and Poland.
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Keywords: Decision Support Systems; Cost-Benefit Analysis; Multi-Criteria Decision Analysis; Composite Modelling Assessment; Risk Analysis.

1. Introduction

Decision support within transport infrastructure planning is typically a complex task of choosing between several competing project alternatives taking into account a wide range of impacts. Conventional cost-benefit analysis (CBA) is a generally acknowledged methodological approach providing the decision-makers with an economic assessment of the project alternatives, expressed on a monetary scale. However, an assessment only based on monetary impacts can be too narrow as other impacts besides the monetary can have influence on the final decision making (Barfod et al., 2011; Salling et al., 2007). Hence, the final decision will in many cases involve multiple criteria related to both economic and strategic aspects. Multi-criteria decision analysis (MCDA) can in this context be seen as an applicable tool to assess such multi-criteria problems within the transport infrastructure planning applying different techniques for value measurement, such as suggested by Janic (2003) and Barfod et al. (2011).

Furthermore, a combination of MCDA and CBA can provide the decision-makers with more informed decision support. Leleur et al. (2007) introduce a methodology for composite modelling assessment (COSIMA) based on an idea of extending conventional CBA into a more comprehensive type of appraisal. By combining CBA and MCDA,

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the non-monetary criteria are added to the monetary CBA impacts using a weighting procedure describing the importance of each criterion (Barfod et al., 2011).

The MCDA approach, however, has some shortcomings related to the subjective nature of the preferences given by decision-makers. Particularly, the criteria weights profile can be seen as the uncertain part as it relies heavily on subjective measures and has a large influence on the final outcome. Accordingly, a new approach to transport decision making is introduced in order to account for the embedded uncertainties. Salling (2008) proposes to supplement a traditional transport appraisal by risk analysis and Monte Carlo simulation accounting for uncertainties underlying the single point estimates, to which all the considerations and calculations are reduced into. In this context, the point estimates are transformed into interval results depicting the totality of possible future outcomes, thereby, enabling decision-makers to make informed and robust decisions. For this reason, using risk analysis to account for uncertainties underlying the criteria weighting profile can be seen as perspective for enhancing the level of information also within the MCDA. The modelling system is ultimately applied on a case study dealing with a set of investment package proposals concerning the construction of the *Rail Baltica* railway line through the Baltic countries (Estonia, Latvia and Lithuania) and Poland.

The paper is organized as follows: after this short introduction section 2 presents a case overview, where the different investment packages of the *Rail Baltica* railway line are depicted. Subsequently, section 3 describes the principles of the methodological approach used for the assessment of the case study, whereas sections 3.1, 3.2, and 3.3 present the results of the appraisal. Moreover, special emphasis is made on the shortcomings of the methodological approach in section 3.4 including the proposal for enhancing the decision support in terms of risk analysis. Finally, section 4 presents a conclusion and perspectives for future research tasks.

2. The case study

The case study, identified as priority project No. 27 in the TEN-T programme, concerns a strategic north-south rail network project, entitled *Rail Baltica*, linking the four Eastern European cities within the European Union along the Baltic Sea, i.e. Tallinn (Estonia), Riga (Latvia), Kaunas (Lithuania) and Warsaw (Poland), with the rest of Europe (Telicka, 2006). The current state of the railways in these countries and the main problems related to the railway transportation issues in the region show a high necessity of making improvements in the railway transport system. The existing north-south railway network is of a very poor quality causing low speed and low level of service. For this reason, the international and domestic passenger and freight transport by rail holds a rather low market share in comparison with the corresponding dominating road transport or rapidly growing air transport. Furthermore, to make matters worse the widths of the railway tracks are differing between the gauge standards provided in respectively the Central and Western Europe and the Baltic countries, thus, presenting an obstacle for free movement of goods and citizens between the Member States of the European Union. The *Rail Baltica* project, therefore, aims to provide a high quality of service for passenger and freight transportation, thus, improving the three Baltic countries' links through Poland into the enlarged Union (Bentzen and Cerneckyte, 2007). COWI (2007) has investigated three possible investment packages for the *Rail Baltica* railway line given as follows (Figure 1):

1. Investment package 1 (P1) – the solution for *Rail Baltica*, which considers an upgrade of the current infrastructure in order to maintain a minimum design speed of 120 km/h from Tallinn to Warsaw. The existing Russian standard gauge would be maintained in Estonia, Latvia and Lithuania, except the section between Kaunas and the Lithuanian/Polish (LT/PL) border, where a new European standard gauge railway line would be constructed. The construction costs for P1 are estimated to be 979 million EUR (2006 price level).
2. Investment package 2 (P2) – the solution for *Rail Baltica*, which considers an upgrade of existing infrastructure as well as construction of some new railway sections enabling to maintain a minimum design speed of 160 km/h. The proposed gauge system is the same as in P1, i.e. the new European standard gauge railway line only in the section Kaunas – the LT/PL border. The construction costs for P2 are estimated to be 1,546 million EUR (2006 price level).

3. Investment package 3 (P3) – the solution for *Rail Baltica*, which secures a minimum design speed of 200 km/h on some sections of the railway corridor. The package includes the European standard gauge on all north-south sections as well as the electrification from the LT/PL border to Bialystok in Poland. The construction costs for P3 are estimated to be 2,369 million EUR (2006 price level).

Figure 1. The investment packages for *Rail Baltica*

The assessment of the alternatives by COWI (2007) is solely based on monetary impacts as it is considered decisive whether the investment packages are economically feasible or not. However, besides the monetary impacts, the new infrastructure will have other impacts, which are left behind in a socio-economic assessment. Therefore, a broader type of appraisal embracing both monetary impacts and criteria of a more strategic character is conducted by combining CBA and MCDA in a composite analysis, the COSIMA decision support model, in order to assist the decision-makers in making a more informed decision (Ambrasaite, 2010).

3. The methodological approach (COSIMA)

CBA is traditionally applied to evaluate the feasibility of transport investments and to rank the alternative investments. The approach incorporates impacts, such as travel time savings, ticket revenue, maintenance and operating costs, accident savings, air-pollution, etc. By modelling the net changes of these impacts, it becomes possible to evaluate the benefits and costs for society, hence, allowing for a socio-economic analysis. Hereafter, the calculated benefits can be compared to the costs of the project resulting in a set of evaluation criteria. However, 'missing' decision criteria, such as landscape effects, environmental effects and wider economic effects, are getting more and more emphasis within transport decision making (Salling et al., 2007; Barfod et al., 2011).

The COSIMA decision support model consists of the combination of a CBA-part and a MCDA-part, where the sum of non-monetary criteria is multiplied by a calibration factor, describing the trade-off between CBA and MCDA, and added to the sum of the monetary benefits of a project alternative. Hereafter, this total value is divided by the total costs resulting in a total rate of return (TRR) indicating a total rate with regard to the attractiveness of a project alternative A_k in relation to the total costs (Barfod et al., 2011):

$$TRR(A_k) = \frac{1}{C_k} \cdot \left(\sum_{i=1}^{I} V_{CBA}(X_{ik}) + \alpha \cdot \left[\sum_{j=1}^{J} w(j) \cdot V_{MCDA}(X_{jk}) \right] \right) \quad (1)$$

where
- A_k is a project alternative k;
- C_k is the total costs of alternative k;
- $V_{CBA}(X_{ik})$ is the value in monetary units of CBA effect i for alternative k;
- $V_{MCDA}(X_{jk})$ is the value function score of alternative k for MCDA-criterion j;
- $w(j)$ is the weight that expresses the importance of criterion j;
- α is the calibration factor that expresses the balance between the CBA and MCDA parts in the model.

The general principle of COSIMA, as presented by (1), reflects, that the MCDA-part is additive to the CBA. Hence, the CBA impacts are supplemented with MCDA-criteria, which are expressed by a net value, similarly to the impacts in the CBA. This is achieved by assigning fictitious monetary values to each of the non-monetary criteria using the calibration factor α and the weight $w(j)$, depicting the relative importance of criterion j, as well as the alternative's value function score $V_{MCDA}(X_{jk})$ within criterion j. The value function scores are computed via direct ratings using pair wise comparisons (Belton & Stewart, 2002). These scores are then multiplied by the determined criteria weights $w(j)$. Subsequently, the MCDA-part is multiplied with a calibration factor α indicating a balance between the CBA and MCDA, i.e. the MCDA-part's influence on the total rate of return (Barfod et al., 2011). Hereby, the TRR can be calculated comprising the information related to both the economic argument and the MCDA-criteria expressed in one single value.

The following three sections elaborate on the three methodologies of CBA, MCDA and COSIMA – all related to the case study of the *Rail Baltica* project.

3.1. Cost-benefit analysis (CBA)

The first step in the COSIMA approach is to conduct a traditional CBA, which ultimately results in a set of economic decision criteria, such as the net present value (NPV), the internal rate of return (IRR) and the benefit-cost ratio (BCR). The CBA is conducted using the CBA-DK model (Salling, 2008) entering all relevant impacts and parameters necessary for the calculation. The key data and assumptions are based on the final report of the feasibility study on the *Rail Baltica* case conducted by COWI (2007) since other sources of information in relation to the project unfortunately were unavailable. The provided data are not complete and some information had to be interpreted by the authors. For this reason, the obtained results slightly differ from the ones given by COWI (2007). All the parameters required for the CBA are based on the European standards and guidelines presented in IER (2006) and the Directorate General Regional Policy report (2008).

The resulting evaluation criteria for all three investment packages are listed in Table 1, where the point estimates indicate a high feasibility of all the investment packages.

Table 1. Overview of results for the three investment packages (Ambrasaite, 2010)

	P1	P2	P3
NPV, mill. EUR	2,372.7	3,371.7	4,302.6
IRR, %	9.86	9.12	8.24
BCR	2.92	2.65	2.27

Considering the NPVs, the choice of P3 will result in the highest gain for the society. P2 is the second highest-ranking package according to the NPV and the least desired is P1. Considering the two other evaluation criteria: BCRs and IRRs, P1 achieves the highest socio-economic feasibility. In the context of mutual exclusive projects, the selection of the project alternative with the highest NPV would be the optimal solution for the society (Leleur, 2000). Hence, P3 with the highest NPV should be chosen. However, dealing with limited funds, one might argue, that the BCR would be the most appropriate criterion to use in order to maximise the outcome per invested monetary unit.

3.2. Multi-criteria decision analysis

The second step in the COSIMA model is to determine the impact of the non-monetary criteria within the MCDA. It is obvious, that the transport infrastructure project could affect the society in many different ways. The CBA is able to capture an important part of the overall economic impacts. However, there could be other significant impacts often referred to as strategic criteria, which cannot be included in CBA due to difficulties to quantify and evaluate them on a monetary scale. Evidently, the following proposes to apply a MCDA approach based upon the Analytical Hierarchy Process (AHP) in order to assess the various non-monetary criteria.

In the *Rail Baltica* case, three different strategic criteria have been stated by COWI (2007): business development; location of companies and logistics centres and effect on tourism (see Table 2). These criteria are regarded as potential impacts, which are more of a strategic character than an economic. However, due to the mentioned technical difficulties regarding quantification of these they have not been treated further in COWI (2007). Therefore, it has been decided to evaluate the overall impact of each investment package under these criteria. In addition, a criterion describing the effect on landscape is added by the authors as this is regarded to be important due to some sensitive areas along the railway corridor (Figure 1).

Table 2. The non-monetary criteria to be assessed in the MCDA

Criteria	Definition
C1. Business development	The criterion favours alternatives that contribute to attract new markets and companies and to strengthen existing markets.
C2. Location of companies and logistics centres	The criterion favours alternatives that have the least effect on the current location of companies and logistics centres in the region.
C3. Effect on tourism	The criterion favours alternatives that contribute to attract tourists to the project countries and promote tourism.
C4. Effect on landscape	The criterion covers the alternatives impact on the landscape and favours those alternatives that have the least negative impact on surroundings.

Note: the criteria are not necessarily supported by the quantitative/qualitative indicators leaving their evaluation solely based on the preferences and judgments of decision-makers.

The AHP-technique by Saaty (1977, 2001) for MCDA has been selected to determine the impact of the alternatives within the defined criteria as the method has shown its usefulness and applicability in a wide range of decision situations (Vaiyda & Kumar, 2006). Using AHP, the decision-makers have to set their preferences considering pair wise comparisons of the alternatives within each of the criteria using an intensity scale of importance from 1 to 9 (see Table 3).

Table 3. The intensity scale of importance for the pair wise comparisons (Saaty, 1997)

Scale value	Definition	Explanation
1	Indifference	Two elements contribute equally to the objective
3	Weak	An element is slightly favoured over another
5	Definite	An element definitely favoured over another
7	Strong	An element is favoured strongly over another
9	Very strong	An element is favoured very strongly over another
2, 4, 6, 8	Compromise between the above values	A numerically interpolated compromise judgment

The scale values obtained by the pair wise comparisons are implemented in a comparison matrix for each of the criteria, where after AHP scores are derived using the geometric mean method (Brazilai et al., 1987). The example of such a comparison matrix is shown in Table 4, where the investment packages are compared under the criterion C1: business development.

Table 4. Example of pair wise comparisons of alternatives with regard to criterion C1: business development

Pair wise comparison of investment packages under criterion C1: Business development				
Scale value	P1	P2	P3	AHP score
P1	1	1/5	1/7	0.075
P2	5	1	1/2	0.334
P3	7	2	1	0.591

The criteria are compared against each other using the same intensity scale of importance as each criterion contributes differently to the overall assessment. Hereafter, normalized weights for all four criteria are obtained using the geometric mean method ($w(C_1) = 0.624$; $w(C_2) = 0.193$; $w(C_3) = 0.113$; $w(C_4) = 0.070$)). Considering the latter, the weighted score for each investment package is calculated using an additive model as given in Table 5. For example, the weighted score for P1 is calculated as follows:

$$Total\ AHP\ score(P1) = 0.075 \cdot 0.624 + 0.350 \cdot 0.193 + 0.100 \cdot 0.113 + 0.525 \cdot 0.070 = 0.163$$

It is important to note, that the assessment of alternatives should be based on the involvement of different decision-makers and key stakeholders in order to take into account different opinions and points of view. In this case, the pair wise comparisons are solely made by the authors of this paper and represent the authors view on the issues.

Table 5. The AHP scores for the performance of the investment packages within the criteria (Ambrasaite, 2010)

		AHP scores		
	Criteria weight	P1	P2	P3
C1	(0.624)	0.075	0.334	0.591
C2	(0.193)	0.350	0.350	0.300
C3	(0.113)	0.100	0.300	0.600
C4	(0.070)	0.525	0.344	0.142
	Total AHP score	0.163	0.333	0.504

If the analysis only relied on the MCDA approach, P3 would be selected for implementation due to a generally more ambitious plan for the future railway connection (especially due to its high scores on C1 and C3). However, even if P3 stands out from the MCDA, it is important to note, that no economic indicators are present in the above mentioned analysis. Thus, it is necessary to combine the two types of analysis as presented in the terms of COSIMA.

3.3. The composite model for assessment (COSIMA)

For incorporating the results from the CBA and the MCDA in a composite assessment, it is necessary to transform the monetary CBA impacts and the non-monetary MCDA-criteria into the same 'language'. Each alternative in terms of non-monetary criteria should be associated with a net value, similarly to the assessment in the CBA. This is done by applying value function scores depicting the attractiveness of the alternatives with regard to the criteria (Belton & Stewart 2002). The value function scores are determined using a local scale going from 0 to 100, where 0 describes the worst performing alternative and 100 the best performing alternative (see Table 6). The intermediate scores are defined based on a linear assumption between the end points (Belton & Stewart, 2002).

Table 6. Value function scores for the investment packages within the criteria (Ambrasaite, 2010)

Alternatives	C1	C2	C3	C4
P1	0	100	0	100
P2	50	100	40	50
P3	100	0	100	0

When the value function scores with regard to each criterion are defined, these scores are multiplied by the criteria weights previously determined in the MCDA. Hereafter, the composite assessment is conducted by multiplying the MCDA-part with the factor α that is calibrated based on the decision-maker determined trade-off level between the CBA and MCDA, i.e. how much the CBA-part (monetary impacts) should count against the MCDA-part (non-monetary criteria). The calibration is repeated for different trade-off levels between CBA and MCDA if a sensitivity measure is desired. It should be noted, that the CBA results in form of the BCRs remain unchanged at each calibration of the composite assessment, but the values of the MCDA-criteria will change based on the weight assigned to the MCDA-part (Salling et al., 2007; Barfod et al., 2011). Test results of different weights assigned to the MCDA-part are presented in Figure 2, making it possible to review the results sensitivity with regard to the CBA/MCDA trade-off. On the figure the MCDA% refers to the relative weight of the MCDA-criteria in the composite assessment (0% MCDA express, that only the CBA counts, while 50% MCDA express an equal weight to both the MCDA and CBA).

Figure 2 depicts, that the TRR increases for all the investment packages as a higher weight is applied to the MCDA-part. A specific MCDA% or a short interval must be chosen before deciding about the alternatives. In most cases, the MCDA% values are presumed to be in the range between 20 to 30% (Barfod et al., 2011) expressing a higher importance to the CBA-part than the MCDA-part. In this case, the TRRs point out different alternatives as the most attractive depending on what weight is assigned to the MCDA-part within the latter interval. P1 presents the highest TRR, when the weight for the MCDA-part is 25% or below, i.e. when the economic analysis has a higher importance. Thus, P1 is the most attractive alternative as it has the highest BCR. However, the P1 is inferior to P2, when the weight for the MCDA-criteria is above 25%. This is due to P2's good overall performance within the MCDA.
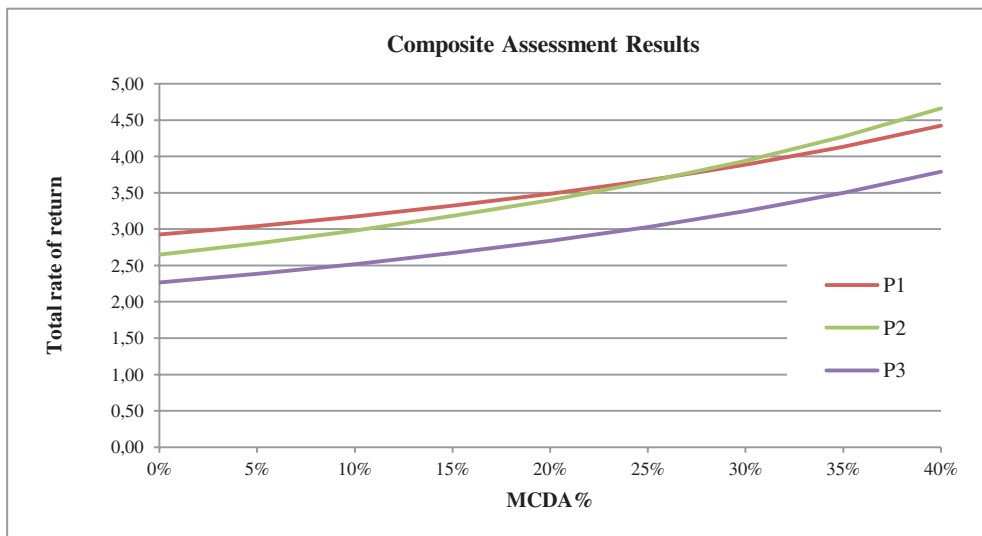

Figure 2. The total rate of returns (TRRs) for the three investment packages (Ambrasaite, 2010)

The outcome of the composite assessment, as presented in equation (1), refers to the present value per invested monetary unit (TRR), therefore, P1 with the highest BCR has the greatest possibility to be selected. However, the situation would change if only the present values of the alternatives were considered. As the P3 has the highest NPV as well as good overall value function scores, it would probably be the leading alternative no matter what the MCDA% is assigned if the COSIMA approach were based on the NPV instead of the BCR. Nevertheless, due to the limited funds within the resent economic situation it is reasonable to consider BCR in order to maximise the alternatives outcome per invested monetary unit.

The variation of the TRRs evidently poses some key research questions regarding the importance of the criteria weights to be determined (i.e. from Table 5). The following section investigates the variation of criteria weights in

terms of allowing for interval results (probability distribution functions) instead of 'point estimates' as derived from Figure 2 by introducing Monte Carlo simulation to the COSIMA approach.

3.4. Uncertainty within the methodological approach

The principles of the MCDA-part of COSIMA are based on decision-maker involvement, while the CBA-part is based on a generally applicable basis. Unlike the latter that requires objective measurement data, the MCDA is based on value measurement, which involves a certain element of subjectivity – particularly, within the criteria weighting profile as the criteria weights are often the greatest source of controversy and uncertainty among the decision-makers (Alfares & Duffuaa, 2008). This can be referred to the fact, that decision-makers and/or stakeholders may not be absolutely aware of their preferences regarding the criteria, or the nature and scale of the criteria may not be known to them (Leleur, 2008). In some cases, the setting of criteria weights could make a huge difference in the resulting assessment of alternatives; therefore, it is important to assess the robustness of the final decision (Hobbs & Meier, 2000).

The resulting single point estimates as provided by both CBA and MCDA within COSIMA are the estimates, where all the variables as well as decision-makers' and/or stakeholders' preferences are aggregated into. Thus, these estimates are embedded with a certain degree of uncertainty. Salling and Banister (2009) link uncertainties within transport appraisals to quantitative risk analysis and Monte Carlo simulation, where relevant probability distributions are applied to conventional transportation impacts, such as construction cost and travel time savings. In this manner, the decision-makers are provided with the totality of the possible future outcomes related to the monetary results. This approach is adopted with regard to the variation of the criteria weights, i.e. allowing for distributional information. Accordingly, it has been assumed to simulate around the most important criteria, C1: business development, leaving the remaining three criteria weights randomly chosen, i.e. based on the simulated weight of C1 criterion the other three MCDA criteria are assigned with random weights such, that all weights sum up to 1.00.

The distribution function selected for this preliminary test run is the triangular distribution, which has been considered to be appropriate since it favours uncertainty issues that often can be described through expert opinion (Law & Kelton, 2000; Vose, 2002). The input information, thus, allows for a minimum value of 0 and a maximum value of 1 with the most likely value of 0.624 as depicted in Table 5. The resulting outcome from the Monte Carlo simulation depicts the probability of achieving a specific TRR or above for the investment packages, when the MCDA% is set to 25%, see Figure 3.

Figure 3 presents the probability curves for the TRRs of the three investment packages. With the TRR on the x-axis and the probability of achieving a TRR on the y-axis, Figure 3 depicts a 70% probability for P1 to be "best" compared with a 30% probability for P2. From Figure 3 it is clear, that P3 should not be selected for implementation as it never obtains TRRs higher than P1 and P2.

Analyzing the simulation data and the computed criteria weights further, it is found, that P2 achieves the highest TRR, when either C1: business development or C3: effect on tourism is assigned with the highest weight. Accordingly, P1 gains the highest TRR, when the weights are respectively lowered and a higher importance is assigned to the criteria related either to C2: location of the companies and logistics centres or C4: effect on the landscape. However, looking at the probability of achieving the highest TRR, P2 has the greatest chances to be selected; this is influenced by the package's high value function scores within the two mentioned criteria.

The further assessment should include simulations on the criteria weights, when different CBA/MCDA trade-off levels are selected. This would allow the decision-makers to see the full spectre of possible outcomes of the composite assessment, when different weights are assigned to the MCDA-part. Based on this the decision-makers should be capable of selecting the most robust alternative.
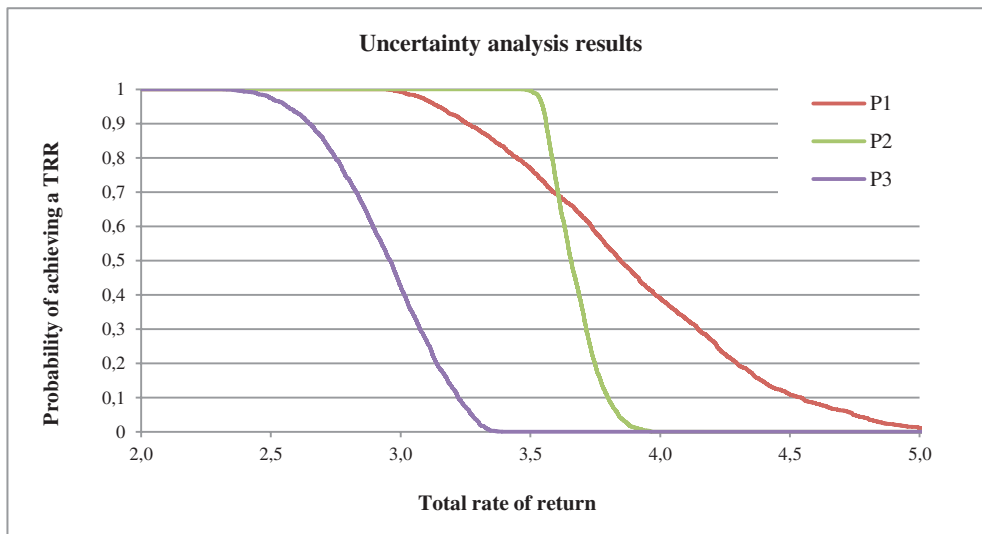
Figure 3. The probability curves for the TRR-values of investment packages

4. Conclusion and perspectives

This paper has presented the composite decision support system, denominated as the COSIMA decision support system (DSS), where conventional cost-benefit analysis is combined with multi-criteria decision analysis for transport planning problems. The principles of the DSS have been presented through a case study concerning three investment packages for the *Rail Baltica* railway line.

The combination of economic impacts as well as strategic criteria in a composite assessment has been found to be a powerful tool for enhancing the decision support. In this way, such methodology simply adds the 'missing criteria' without hiding or changing the CBA information in order to explore whether these criteria complementing the CBA can make the attractiveness of projects to change.

However, the composite assessment is embedded with a certain degree of uncertainty related to the criteria weighting profile in the MCDA as the decision-makers' judgments involve subjectivity. To overcome this issue the perspective of introducing uncertainty analysis within the appraisal scheme is presented through the case study. Transferring the point estimates into probability curves for the TRRs of the alternatives has proven to be useful decision support for enabling a robust decision. This will ultimately lead to feasibility risk assessment providing a totality of possible future outcomes related to the TRRs and the selection of project alternative.

Further concern must be addressed to the uncertainties underlying the CBA scheme in terms of the modelled first year impacts and pricing principles. In most cases, the largest sources of uncertainties are found to be the construction costs and the traffic demand forecasts, which lays the foundation for the travel time related benefits (denoted in literature as Optimism Bias). Due to the cost overruns and overestimated traffic demands, the viability of the projects is threatened ultimately creating grounds for projects with socio-economic infeasibility (Flyvbjerg et al., 2003; Salling, 2008). For that reason, accounting for the risks and uncertainties within the CBA scheme becomes of great relevance in order to make robust decisions. Therefore, the implementation of risk analysis for both the CBA and MCDA within COSIMA can be seen as a future perspective for providing the decision-makers with a more explicit and reliable assessment of transport related problems.

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