EJTIR

Issue 15(4), 2015
pp. 613-634
ISSN: 1567-7141
tlo.tbm.tudelft.nl/ejtir

# Applying multicriteria decision analysis to design safe road projects

**Renaud Sarrazin**[1]
Belgian Road Research Center, Brussels, Belgium.

**Yves De Smet**[2]
Université libre de Bruxelles, Engineering Faculty, Brussels, Belgium.

Over the past decade, the improvement of road safety had been a major issue in transport strategies in Europe. Simultaneously the concept of sustainable development has become a key element in many strategic and operational policies – including the road sector ones. However, considering the design stage of road infrastructure, there are almost no methodologies that both quantify the road safety performance of the project and consider its economic and environmental nature. This study seeks to develop a preventive evaluation model based on a multicriteria decision analysis. It would allow designers to assess the safety performance and to evaluate some of the economic and environmental impacts of their road projects at the design stage. For this purpose, we have defined a set of 13 criteria which describe the problem. The aim of this paper is to highlight the added value and limits of such an approach. A case study is analysed in order to quantify these arguments. In particular, we apply the PROMETHEE-GAIA method to our problem and we conduct a sensitivity analysis to prove the interest of using a multicriteria decision technique in the context of road designing. A brief presentation of the current and future developments introduces the notion of Pareto frontier and its characterization with a genetic algorithm. Finally, the conclusion and discussion point out the possibilities and impossibilities of this research.

***Keywords***: *multicriteria analysis, PROMETHEE, road design, road safety.*

## 1. Introduction

For many years, considering sustainable development and improving road safety have been two majors concerns in mobility and transport policies in Europe. Since 2001, the European Commission (EC) had published several reports and directives about the improvement of the safety level on the European road network. In particular, the European White Paper on Transport Policy (EC, 2001) had fixed an objective of halving the overall number of road deaths in the European Union by 2010. In 2010, this challenging objective has been updated in the Road Safety Programme 2011-2020 and it has been completed with several strategic objectives and principles. Among them, the development of an integrated approach to road safety has been highlighted (EC, 2010). In 2003, the European Road Safety Charter was published and submitted to several actors of the road sector, as a commitment to take concrete actions in order to reduce road accident fatalities. Additionally, in 2010, the EC had published the Greening Transport Package about strategies to apply in order to strive for a transport system more respectful of the environment.

[1] A: Boulevard de la Woluwe 42, 1200 Brussels, Belgium T: +32 1023 65 40 E: r.sarrazin@brrc.be
[2] A: Avenue F.D. Roosevelt 50, 1050 Brussels, Belgium T: +32 2650 59 57 E: yves.de.smet@ulb.ac.be

In Belgium, the Federal Commission for the Road Safety was formed in 2002 with intent to fulfil the objectives of the EC. In 2011, the initiative "Go For Zero" has been launched by the State Secretary for Mobility and the Belgian Institute for Road Safety. Several actions and campaigns have then been conducted to make the road users sensitive to road safety issues (e.g. speed enforcement, seatbelt, alcohol and driving, etc.). In Wallonia, the government reaffirmed its willingness to promote sustainable mobility for every road users in its declaration of regional policy for the period 2009-2014.

However, despite an increasing and sustained political support at the national and international levels, the assessment of the road safety performance of an infrastructure is still essentially based on reactive approaches such as the evaluation of databases containing accident statistics (IRTAD, 2014; IBSR 2014). In Belgium, an extensive black spot treatment programme had led to promising results regarding road safety improvement since 2000 (De Pauw et. al, 2014). All these methods consist of curative analysis and handling of the high accident concentration areas. In order to meet the objectives of the EC (i.e. simultaneously improving road safety and considering sustainable character of the road transport infrastructure), it has become essential to develop new preventive and innovative tools.

In the field of operational research, only a few studies were conducted to address the problem of road safety assessment from a multicriteria perspective. Among them, we could cite studies that were related to the development of safety performance indicators (COST, 2008) or aggregated indices (Bao, 2010) based on ex-post evaluation of road projects or features. Recently, multicriteria decision making techniques were applied to specific safety assessment problems such as prioritizing the accident hot spots based on geometric and traffic conditions of the road network (Pirdavani et al., 2010) or evaluating the safety performances of pedestrian crosswalks (Zhao et al., 2012). In 2002, the research project ROSEBUD was conducted on the assessment of the performance of several safety measures from benefit-cost and cost-effectiveness analysis (ROSEBUD, 2006). However, this project focused more on the evaluation of standardized safety techniques than on the preventive assessment of road designs in their direct environment.

Moreover, a recent review paper pointed out that approximately 300 published papers were concerned by the application of multicriteria decision techniques in the field of infrastructure management during 1980-2012 (Kabir et al., 2013). This result suggests a growing interest of the road sector in the use of multicriteria decision techniques. Nevertheless, it is still restricted to infrastructure management applications. In the field of transportation planning and road designing, we could cite the work of Dumont and Tille about the interest of using a multicriteria decision making approach to design more sustainable road infrastructures (Dumont and Tille, 2003). In 2014, de Luca published a paper about the application of the Analytic Hierarchy Process to support the public engagement during the whole transportation planning process (de Luca, 2014). The evaluation of the alternatives was based on several criteria such as the accessibility of the road, the travel safety and comfort, the impact on the environment and the preservation of the landscape. However, the assessment of the safety performances was highly qualitative. In 2008, Brauers developed a multiobjective optimization approach to support decision makers in the selection of a road design alternatives but the evaluation process was restricted to the longevity of the infrastructure, the construction price and duration, the environment protection and the economic validity (Brauers et. al, 2008). Road safety performances were not considered.

Based on these observations, this research project was initiated with the aim of developing a multicriteria analysis method to preventively assess the safety performances of road projects at the design stage. Moreover, in order to consider the sustainable character of road infrastructures, we enrich the multicriteria evaluation with some sustainable concerns frequently encountered in road project assessment.

In this paper, we start with a description of the theoretical concept of sustainable road safety and we address the multicriteria problem by detailing the set of considered criteria. Next, we illustrate the multicriteria approach on a case study. Then, the current and future developments on the multiobjective mathematical model are briefly presented. Finally, a discussion and some conclusions are provided.

## 2. Research motivation

### *2.1 Towards a preventive evaluation of road safety*

At first, to define theoretically what road safety is, we can use the elementary triangle of road safety which is composed of the dimensions vehicle, driver and road equipment (cf. Figure 1). On the basis of this triangle, we may classify all the causes of an accident in one or more of the three main dimensions (i.e. apexes of the triangle) or their interactions (i.e. sides of the triangle).

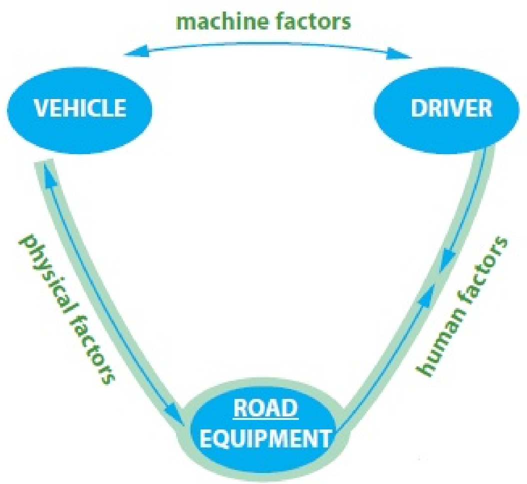


*Figure 1. Elementary triangle of road safety*

If we want to improve the global level of road safety of an infrastructure, we have to take an interest in the components of this triangle. According to a study of OECD, from 18% to 28% of the accidents are due to an unsafe road environment or infrastructure (OECD, 1999). Consequently, the improvement of the infrastructure and its compatibility with its direct environment appear to be a consistent strategy in respect to the objectives of the EC. Within the framework of this research, we are then focusing on the road equipment dimension and the human and physical factors. In addition, considering the major differences between the rural and the urban environment with respect to road performance assessment, we are focusing in this study on the evaluation of secondary rural roads of the Belgian network. New road and existing road projects are both considered.

### *2.2 An integrated and sustainable approach of road safety*

Due to its collective nature, the road sector has a significant impact on the environment, the social development and the economic efficiency of the areas that the roads cross. It has then become essential to integrate the road sector policies into a more sustainable approach.

From a social perspective, the accidents from the road transport caused 26,025 deaths in the European Union in 2013. It corresponds to a year-to-year decrease of 6.2% between 2012, while a reduction of 6.7% is needed over the 2010-2020 period to reach the objectives of the EC (ETSC, 2014).

Regarding the environment, the road sector has close links with sustainable topics such as energy consumption (EEA, 2011), noise disturbance (OFEFP, 1995; den Boer et. al, 2007), land use or preservation of the soil quality and the water balance (Muench et. al, 2011). In practice, it both implies to reconsider current policies by taking into account sustainable development concerns and to develop some new evaluation processes and decision aiding tools to offer road sector a common definition about sustainability. As mentioned below, several reports were published during the past years by national and European organizations in order to promote sustainable roads. In this research project, we have decided to enrich the technical evaluation of road projects – considering road safety, with some concerns related to their environmental, social and economic performances. By doing so, we define a more complete and integrated assessment model which would meet the needs of the transport and mobility policies in Europe. For methodological reasons, we have decided to limit our evaluation to local and project-related concerns (e.g. financial design aspects, air pollution, noise disturbance, and accessibility of the infrastructure).

### 2.3 *A support to innovative projects*

During the design stage of a road infrastructure, several alternatives are modelled by the engineers in charge of the project. Different design choices are made by varying several parameters that represent the main characteristics of the project (e.g. number of lanes, lane width, nature of an eventual cycle lane, nature of the road signs or vehicle restraint systems, type of intersections, etc.). At the end of this modelling stage, an alternative is selected among all of those that were modelled (cf. Figure 2). Even if this selection is not exclusively motivated by the economic criterion, there is to date no integrated tool that could help the design engineers to analyse each alternative and to select the most appropriate to the characteristics, the uniqueness, the challenges and the stakes of the project.

This research aims to fill that void and to offer design engineers assistance in the evaluation of their project alternatives and the identification of the best candidates. As mentioned in the previous section, this evaluation quantifies the performances of the project alternatives from a set of criteria which is composed of road safety, economic, social and environmental criteria. We propose to use this set of criteria as a representation of the concept of sustainable road safety – even if in a first phase, the sustainability is limited to a few number of local concerns that are linked to design aspects.

With the assistance of the multicriteria model, a design engineer would then be able to evaluate and to compare several alternatives of a road project and to classify them with respect to their performances. By doing so, the engineers would be able to identify a priori the profile of the best solutions for a specific road design project. Considering the multidisciplinary nature of the criteria, some of them are antagonistic (e.g. small construction costs vs high performance equipment) and the identification of an optimized solution is then impossible. The use of multicriteria decision making techniques would allow the decision maker to deal with the conflicting nature of the criteria and to find compromise solutions.

In the end, the use of a sensitivity analysis would support the decision makers in evaluating the robustness of the final solutions. Therefore, it would be possible to select the best solution according to the nature of the project, the characteristics of the road environment or the demands of the specification (e.g. more weight should be allocated to certain criteria).

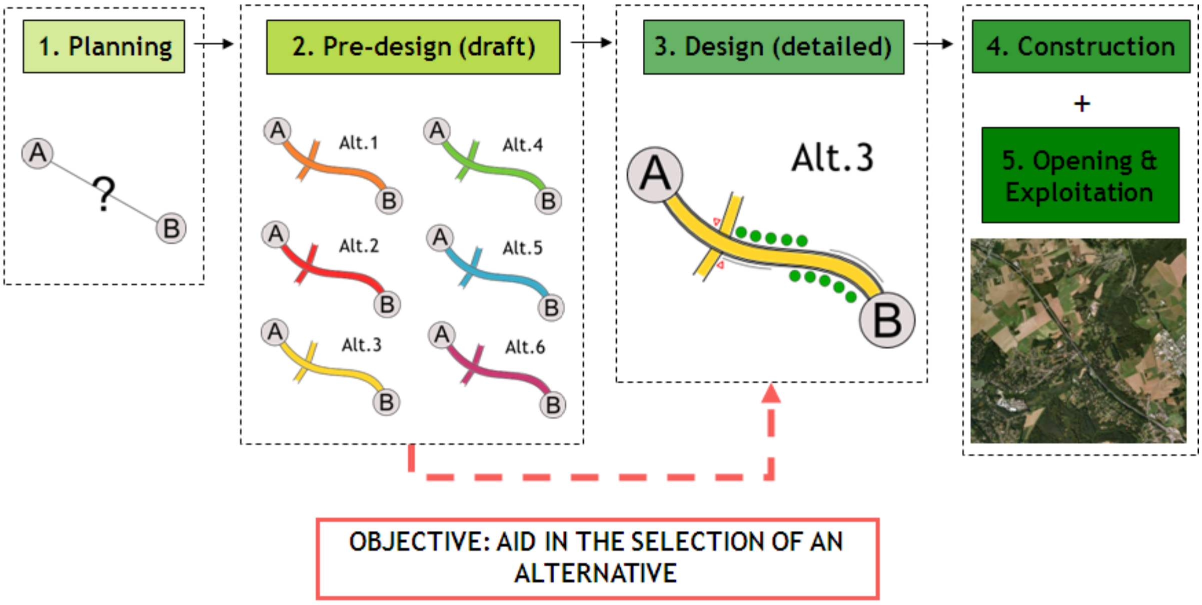


*Figure 2. Design stage of an infrastructure and objective of the project*

Moreover, the design stage of a road infrastructure remains an interactive process between several actors of the project. So, the use of a multicriteria decision aiding approach would preserve this collaborative nature while assuring the consistency and robustness of the analysis. In the long run, it should then promote the development of innovative and sustainable solutions.

## 3. Multicriteria decision analysis applied to sustainable road safety

Based on the observations presented in the previous section, this research project was initiated to fulfil two main objectives. At first, the integration of road project evaluations into a more sustainable approach by introducing the concept of sustainable road safety. Secondly, the development of a multicriteria analysis methodology which would allow us to carry out an integrated and preventive assessment of infrastructure projects at the design stage.

### *3.1 Definition of the concept of sustainable road safety*

One of the main developments of this on-going research project is the definition of the concept of sustainable road safety and its representation into quantitative criteria. From the analysis of several studies that were conducted on the topic of road safety issues (COST, 2008; Gitelman and Hakker, 2006; OECD, 1999; Zegeer et. al, 1994), we define the eight following topics, spread in the dimensions Infrastructure (INF) and Services (SRV).

**Table 1. Topics related to the road safety criteria**

| Dimension | Code | Name |
|---|---|---|
| Infrastructure | INF1 | Legibility and consistency of the infrastructure |
| Infrastructure | INF2 | Visibility of the infrastructure |
| Infrastructure | INF3 | Protection of the vulnerable roads users |
| Infrastructure | INF4 | Quality of the road pavement materials |
| Infrastructure | INF5 | Road design and safety equipment |
| Infrastructure | INF6 | Intersections |
| Infrastructure | INF7 | Safety on road works |
| Services | SRV1 | Information and intervention services |

These topics constitute the first part of the set of criteria that is used in the proposed multicriteria methodology. They will allow us to quantify the social and technical performances of the road infrastructure projects in relation to safety.

In order to enrich the evaluation of road projects with sustainable concerns, we need to define the additional topics that would represent the concept of sustainable road safety. As mentioned in the previous section, the integration of sustainable topics in the analysis was limited in a first stage to a few concerns that are related to design aspects and choices. Even if this sustainability analysis is not exhaustive and should be completed with additional topics in the long run, it would most probably raise awareness among road designers about the interest of a multidisciplinary evaluation of their projects.

Over the past few years, several studies were conducted on the topics of sustainable roads such as the projects GreenRoads (Muench et. al, 2011), NISTRA (OFROU, 2003), or the French approaches Routes durables (Nossent, 2011) and Grille RST02 (Boutefeu, 2008)). Additionally, the concept of sustainable safety was introduced in the projects Vision Zero (Tingvall and Harworth, 1999) and Sustainable Safety (Aarts and Wegman, 2006). But regarding the sustainable safety concept, these studies are exclusively focused on the social dimension of the sustainable development. As a part of this project, we have broadened the sustainability notion to the three pillars of sustainable development – economic (ECO), social (SOC) and environmental (ENVI). To illustrate the sustainability issues in our analysis, we have then selected the five following topics. Given that the aim of the multicriteria model is to evaluate and distinguish different alternatives of a road project based on their performances, we limit our selection in a first stage to criteria that would be significantly affected by local design strategies and characteristics.

**Table 2. Topics related to road sustainability criteria**

| Dimension | Code | Name |
|---|---|---|
| Environmental | ENVI1 | Reduction of road emissions |
| Environmental | ENVI2 | Limitation of noise pollution |
| Social | SOC1 | Ensure a good level of service |
| Economic | ECO1 | Limitation of the construction costs |
| Economic | ECO2 | Limitation of the maintenance costs |

Finally, the association of all these thirteen topics (Tables 1 and 2) illustrates the concept of sustainable road safety. We are manifestly dealing with a typical multicriteria decision aiding problem wherein the alternatives of the problem are the draft alternatives of the project at the design stage, and the criteria are the sustainable safety performances.

### 3.2 *Structuring the multicriteria problem*

In order to solve this multicriteria problem and to ensure the consistency of the model, it is important to develop a consistent set of criteria by identifying the key factors and parameters of each topic. As far as possible, even if we cannot completely avoid the subjectivity of the decision maker within the decision process, we must try to develop quantitative criteria to maximize the impartiality of the multicriteria analysis. In this study, we have developed a set of criteria by conducting an important literature review. Meetings were organized with experts from the road sector to criticize and validate the final set of criteria. In addition, an important stage of modelling and creation of data was necessary to transform the initial topics – sometimes exclusively qualitative or descriptive – into quantitative criteria. This transformation would allow us to ensure a consistent and meaningful analysis. Because of the complexity of several theoretical concepts, the developments of some criteria were deliberately limited to a qualitative assessment.

In the following, we briefly describe the set of criteria (by referring to the five dimensions introduced in the previous section) to illustrate the multidisciplinary nature of the multicriteria problem and its complexity.

*INF1. Legibility and consistency of the infrastructure*
When a driver is traveling on a road, he generates a mental representation of the road which will condition his behaviour on it. The driver's mental representation of the road will depend on some roadway geometric design elements such as vertical and horizontal alignments, the type of cross-section or the roadside development (OECD, 1999). In order to control the adequacy of the operating speed with regard to geometry of the road, we can measure the sight distance on each section of the road. The sight distance refers to the distance which is "required for a driver to avoid an obstacle on the road". According to the World Road Association (PIARC, 2003), there are three main types of sight distance: the stopping sight distance (or minimum sight distance), the overtaking sight distance and the manoeuvre sight distance. The stopping sight distance, denoted $DVA$, corresponds to the distance required for a driver to stop at an intersection or in front of an obstacle on the road. This distance is calculated with the 85th percentile of the speed $V_i$ (km/h), the reaction time $t$ (s), the coefficient of longitudinal friction $f_l$ and the eventual percentage of the gradient $G$ (%).

$$DVA_{op} = \frac{V_i \times t}{3.6} + \frac{V_i^2}{254\left(f_l \pm \frac{G}{100}\right)} \tag{1}$$

The measure of sight distance as a criterion to evaluate the legibility of a road has been introduced in many studies (OECD, 1999; FHWA, 1992). Consequently, this criterion evaluates the level of legibility and consistency of the road from the measure of the stopping sight distance on the $n$ sections of the road (2).

$$C_{LC} = \frac{1}{n}\sum_{i=1}^{n} Min(1; \frac{DVA_{i,op}}{DVA_{i,th}}) \tag{2}$$

In this equation, $DVA_{i,op}$ is the operating sight distance (1) and $DVA_{i,th}$ is the theoretical sight distance (i.e. minimum sight distance to ensure safety on the section i) and it is available in the literature (Harwood et al., 1995). This criterion has to be minimized.

*INF2. Visibility of the infrastructure*
The visibility of the road refers to the roadway elements and equipment which convey visual information to the road drivers, such as road signs, geometric design elements and road lighting. These elements could affect (positively or negatively) the global understanding of the infrastructure by the road user. Then, the aim of this criterion is to evaluate the influence of roadway equipment on the visual recognition of the road by the road users. The level of visibility of the road $C_V$ is measured by summing the coefficients of visibility $a_k$ of the m roadway elements and equipment (3). The coefficient $a_k$ is an integer between 0 (very bad) and 10 (very good) which is attributed by the expert to each $k$ roadway element. Due to the lack of information about this topic in the literature, we have determined the values of this coefficient by ourselves and we submitted them to the expertise of the members of the Technical Committee for Road Safety of the Belgian Road Research Centre. By definition, this criterion has to be maximized.

$$C_V = \frac{1}{m}\sum_{k=1}^{m} \alpha_k \tag{3}$$

*INF3. Protection of the Vulnerable Road Users*
One of the main characteristics of a secondary rural road is its multimodal nature. Many types of users are traveling on the same road with very different speeds and mass. Thus, as a consequence of these differences among users, the risk of accidents is high on rural roads for pedestrians, bicycles and motorcycles – who are usually classified as the vulnerable road users (VRU). In 2008, on Belgian rural roads, 30% of the road killed and 34% of the severe injuries concerned vulnerable road users.

Thus, concerning the bicyclists, suitable equipment must be selected considering some factors such as the operating speed of the motorized traffic, some geometric design parameters (e.g. lane width, separation distance between the roadway and the cycle path) or the volume of traffic. On the basis of the Compatibility of Roads for Cyclists Index *CRCI* in rural areas (Noël et al, 2003) and the Pedestrian and Bicyclist Safety Indices at Intersections *P/BSII* (FHWA, 2006), we have defined a global index $C_{BSI}$ which expresses the global level of safety of a bicycle equipment on a road (4).

$$C_{BSI} = 0.5 \cdot C_{BSI,segment} + 0.5 \cdot C_{BSI,inters} = 0.5 \cdot CRCI + 0.5 \cdot BSII \qquad (4)$$

wherein $C_{BSI,segment}$ is the CRC Index on straight segments of the road and $C_{BSI,inters}$ is the Bicycle Safety Index at intersections. Given that the ratio of cyclist fatalities in Belgium is slightly the same in section or at the intersections (Martensen et. al, 2009), an equal weight is allocated to the *CRCI* and *BSII* indices. These indexes are calculated by taking into account some parameters such as the average daily traffic, the speed limit, the separation distance between the roadway and the cycle lane or even some signalization factors. The value of $C_{BSI}$ is expressed on a scale which defines the level of safety of the cycle facilities.

Concerning the pedestrians, we have defined a similar index $C_{PSI}$ which evaluates the global level of safety of a pedestrians' equipment (straight sections and crossings). As regards motorcyclists and moped drivers, it is important to pay attention to the slippery surfaces or road markings and to the roadside safety barriers (OECD, 1999). However, due to the lack of information about this topic in the literature, we have not included this category of users in the criterion for the moment.

Then, we define the criterion $C_{VRU}$ which expresses the global level of safety for vulnerable road users on the road based on the indexes $C_{BSI}$ and $C_{PSI}$ defined above (5). The actual weights were defined on the basis of the probabilities of accidents of pedestrians and bicyclists on rural roads in Belgium in 2012 (DGSIE, 2013).

$$C_{VRU} = 0.52 \cdot C_{BSI} + 0.48 \cdot C_{PSI} \qquad (5)$$

*INF4. Quality of the road pavement materials*
A poor road surface quality can result in a loss of control of the vehicle (e.g. skidding). Combined with the high speeds on rural roads, these structural defects can lead to highly severe accidents. Consequently, it is crucial to preserve the quality of the road surface. On the basis on researches about the development of performance indicators for the selection of road pavements (COST, 2008; De Jonghe, 2006), we can define a safety index for the road surface $C_{RS}$. This index is calculated with some performance indicators about the transverse evenness $PI_R$, the skid resistance $PI_F$, the drainability $PI_D$ and the sensitivity to winter conditions $PI_{WC}$.

$$C_{RS} = 0.45 \cdot (0.7 \cdot PI_R + 0.3 \cdot PI_D) + 0.4 \cdot PI_F + 0.15 \cdot PI_{WC} \qquad (6)$$

The actual weighting has been defined in the mentioned literature. However, a sensitivity analysis will be conducted on these weights at the end of the calculation process in order to ensure their robustness. The performance indicators are common values stored in our model for several road pavement materials. This criterion must be minimized.

*INF5. Road design and safety equipment*
According to the Belgian Institute for Road Safety, run-off accidents represent around 32% of all fatal rural accidents on Belgian rural roads. Then, if we cannot totally avoid this type of accidents, we can reduce their severity by installing some safety equipment along the infrastructure. Thus, the criterion "Road design and safety equipment" evaluates the performance of the infrastructure regarding to its geometry, the environment and the safety equipment (e.g. vehicle restraint systems). The evaluation is based on a prediction model from the Highway Safety Research Center which measures a predictive accident rate from several parameters such as the lane width, the shoulder width or the roadside safety (Zegeer et al., 1994).

$$C_{SE} = c_0 \cdot AADT^{c1} \cdot c_2^{LW} \cdot c_3^{PS} \cdot c_4^{UP} \cdot c_5^{RS} \cdot c_6^{TER1} \cdot c_7^{TER2} \quad (7)$$

In (7), $c_i$ are model parameters adapted to the Belgian road network context, $AADT$ is the annual average daily traffic, $LW$ is the lane width, $PS$ is the width of paved shoulders, $UP$ is the width of unpaved shoulders, $RS$ is the roadside safety coefficient and $TER$ are variables related to the roadway environment. Given that this criterion measures a predictive accident rate, it must be minimized.

*INF6. Intersections*
This criterion quantifies the consistency of the intersections of the project with the function of the road, the volume and the composition of the traffic, the operating speed and some others characteristics of the project. Depending on the type of intersection, we compare the time which is necessary to realize different manoeuvres in the crossroads with the minimum time that is required to ensure safety conditions to the users. In practice, we evaluate this global required time to manoeuvre by calculating the operating traffic capacity at the intersection.

*INF7. Safety on road works*
This last criterion of the dimension infrastructure refers to the protection of workers and road users during reconstruction or maintenance activities. Indeed, during these road works, the normal traffic situation is disrupted and this could affect the safety around the work zones. Then, based on methodology that have been developed for the European project STARs about the safety on road works (Weekley et al., 2014), we measure a road worker safety risk score. To date, the calculation procedure of this criterion is confidential because the STARs project is still an on-going research.

*SRV1 – Information and intervention services*
This criterion has been developed to take into account the quality of the information and the intervention services in the evaluation of the road safety performances of a project alternative. However, because of the lack of knowledge and information in this research area, no pertinent criterion has been defined yet. To date, this criterion is a descriptive scale that ranks the quality of services regarding to the type of service equipment available (e.g. emergency call terminal, clear zone or emergency lane along the road, safety camera, etc.).

*ENVI1 – Reducing road emissions*
The restriction of road emissions is one of the most frequently used criteria to represent environmental concerns (Gasparatos et. al, 2008). The criterion $C_{EM}$ measures the annual average concentration of $PM_{10}$ ($c_{PM}$) and $NO_2$ ($c_{NO}$) generated by a road project. Based on the development of a recent study from IBGE, the values of concentration depend on the traffic volume and composition, some emission factors, the direct environment of the road, the operating speed and the roadway surface (IBGE, 2012).

While we have calculated the values of annual average concentration of $PM_{10}$ and $NO_2$, we normalize these values on a scale from 0 to 5. This normalization is based on the minimum, maximum and thresholds values of concentration in Belgium measured every year by the Belgian Interregional Environment Agency. From there, we calculate a weighted sum (8) wherein the weights of the normalized evaluation of concentration $|c_{PM}|$ and $|c_{NO}|$ are respectively the evaluation of $|c_{NO}|$ and $|c_{PM}|$. This criterion must be minimized.

$$C_{EM} = \frac{|c_{PM}|^2 + |c_{NO}|^2}{|c_{PM}| + |c_{NO}|} \tag{8}$$

*ENVI2 – Limitation of noise pollution*

The noise pollution refers to the noise generated by the vehicular traffic on the roadway. The intensity of the noise depends on the characteristics of the vehicles (e.g. motor and tire types), the roadway surface type, the operating speed and some geometric design parameters. Then, if the evaluation of the "operating" noise pollution is complex and requires the development of computer models, many studies were interested in the definition of simplest evaluation of noise pollution. In Switzerland, a project of the Federal Office for the Environment had led to the development of a model which calculates the noise pollution generated by a road infrastructure (OFEFP, 1995). This evaluation is based on the characteristics of the infrastructure such as the traffic density and composition, the speed limit, the nature of road surface material or even the nature of the roadside environment (9). Then, this value is compared to the limit values for noise pollution (or acceptable values with regards to comfort and health) which were defined by the noise pollution standards.

$$L = A + 10 \cdot \log\left[\left(1 + \left(\frac{v}{50}\right)^3\right) + \left(1 + B \cdot Eta \cdot \left(1 - \frac{v}{150}\right)\right)\right] + 10 \cdot \log(M) + \Delta R \tag{9}$$

In (9), $A$ is a coefficient depending on the road pavement material, $B$ is an empirical constant, $v$ is the operating speed, $M$ is the traffic low (vehicles by hour), $Eta$ is the proportion of heavy trucks and $\Delta R$ is a corrective coefficient for noise reflections (depending on geometric data such as the width of the roadway, the height of the potential buildings, etc.). The level of noise $L$ is measured in dB(A). It can be applied for daytime (Ld), evening time (Le) or night time noise (Ln). Thus, the criterion "*Noise pollution*" calculates the level of noise generated by the infrastructure during night time, day time and evening time by referring to the Ln and Lden indices (10). The level Lden is calculated as follows.

$$Lden = 10 \cdot \log 10\left[\frac{\left(12 \cdot 10^{\frac{Ld}{10}} + 3 \cdot 10^{\frac{Le+5}{10}} + 9 \cdot 10^{\frac{Ln+10}{10}}\right)}{24}\right] \tag{10}$$

The values Ln (11) and Lden (12) in dB(A) are normalized on a scale from 0 to 5.

$$|Ln| = \begin{cases} 0 \text{ if } Ln \prec 30 \\ 2.5 \cdot \frac{Ln}{30} - 2.5 \text{ if } 30 \le Ln \prec 60 \\ 2.5 \cdot \frac{Ln}{50} - 0.5 \text{ if } 60 \le Ln \prec 110 \\ 5 \text{ if } Ln \succ 110 \end{cases} \tag{11}$$

$$\left|Lden\right| = \begin{cases} 0 \text{ if } Lden \prec 30 \\ 5 \cdot \dfrac{Lden}{80} - 1.875 \text{ if } 30 \leq Ln \prec 110 \\ 5 \text{ if } Ln \succ 110 \end{cases} \tag{12}$$

Finally, we obtain the criterion $C_{NP}$ which must be minimized (13).

$$C_{NP} = \frac{\left|Ln\right|^2 + \left|Lden\right|^2}{\left|Ln\right| + \left|Lden\right|} \tag{13}$$

*SOC1. Ensure a good level of service*

By nature, the assessment of the road safety performance of an infrastructure project has strong links with social aspects such as the reduction of road accidents for all the users and the protection of the road workers. However, another social dimension of road projects could be considered in the multicriteria evaluation by considering the level of service of the infrastructure. Indeed, guarantying a good mobility and accessibility on the road infrastructure is an important element with regard to the social performance of a road project. Then, based on the developments from the Highway Capacity Manual (TRB, 2010), we assess the quality of service provided by the road infrastructure by measuring its level of service (LOS).

According to the Transportation Research Board, level of service is a "quantitative stratification of a performance measure or measures that represent quality of service [the operational performance of the infrastructure from the traveller's perspective]" (TRB, 2010). Considering the theoretical traffic capacity of the infrastructure (which depends on parameters such as the number of lanes, the type of intersection, the speed limit, etc.) and the predictive traffic flows, the criterion "*Ensure a good level of service*" measures the level of service of the infrastructure on an ordinal scale from A to F.

*ECO1. Limitation of construction costs*

This criterion enables the decision maker to evaluate the economic performance of a road project simply by calculating the construction costs. However, considering that it is complex to obtain detailed and updated economic data about road projects in Belgium (mainly due to some confidential issues), the evaluation of this criterion remains quite vague for the moment. This criterion is expressed in euros and must be minimized.

*ECO2. Limitation of maintenance costs*

This criterion is similar to ECO1, except that it evaluates the maintenance costs. This criterion is expressed in euros and must be minimized.

### *3.3 Definition of the alternatives of the problem*

Once a complete set of criteria has been developed, the next step is to identify all the efficient solutions that constitute the alternatives of the multicriteria problem (Vincke, 1989). The efficient solutions could be defined as the best candidates to solve the problem. From a theoretical point of view, a solution $S_i$ is called efficient if there is no solution $S_j$ in the set such that $S_j$ is at least as good as $S_i$ on all the criteria and strictly better for at least one of them. Obviously, all non-efficient solutions of the problem can be removed. Only efficient solutions have to be considered.

During the design stage of a road infrastructure, several alternatives are modelled by the design engineers in charge of the project. In practice, only a small number of alternatives are defined and they represent a limited set of design choices. However, it would be an interesting added value to solve the complete problem by generating all the alternatives that would be technically feasible for a given infrastructure project. Then, it would allow the decision maker to identify the most relevant alternatives considering the road environment, the nature and stakes of the project or the preferences of the decision maker.

In this study, the set of alternatives of the multicriteria problem is constituted of all the feasible solutions that could be generated for a specific project. To do so, we identify all the parameters that represent the main characteristics of the project and we generate the complete set of alternatives by combining these parameters (e.g. number of lanes, lane width, nature of an eventual cycle lane, road signs, vehicle restraint systems, type of intersections, etc.). In order to guarantee the feasibility of the solutions, we must define the constraints of the project (e.g. maximum width available).

As an example, Table 3 shows that even for a simplified case study with only 12 input parameters (ranging from 2 to 5 values each, except *cp_nat*), we could generate more than $10^6$ feasible alternatives. Obviously, only a small proportion of these alternatives would be non-dominated and selected as interesting candidates. In Section 5, we will see how the use of a genetic algorithm would support us in the identification of the non-dominated solutions.

**Table 3. Amount of alternatives for a simplified problem**

| Variable | Value | Description |
|---|---|---|
| w_max | 14 | maximum available width (fixed parameter) |
| w_l | {2.5;3;3.5} | roadway lane width |
| n_l | {2;3;4} | number of lanes |
| w_sh | {0;1;2;3} | shoulder width |
| b_sh | {Y;N} | physical separation with shoulders (e.g. barriers) |
| cp_nat | [1:17] | type of bicyclist equipment |
| w_med | {Y;N} | physical separation between flow and contraflow |
| mat_nat | {1;2;3;4;5} | type of road surface material |
| rsign | {1;2} | nature of the signalization equipment |
| marking | {1;2} | nature of the marking equipment |
| lighting | {0;1;2;3} | nature of the lighting equipment |
| intertype | {1;2;3;4} | type of intersection |
| v | {50;70;90} | speed limit |
| alt | 1,000,320 | amount of feasible alternatives |

## 4. Case study

As introduced previously, the aim of this study is to help engineers in the evaluation and the selection of design road project alternatives. In the following section, we propose to use the set of criteria developed previously on an illustrative case study in order to prove the interest of this multicriteria approach and to underline the kind of results we may obtain.

**Table 4. Description of the case study**

| Parameter | Value |
|---|---|
| Area | Rural |
| Function of the road | Secondary road |
| Length | 2.0 km |
| Maximum width | 12 m |
| Number of intersections | 2 |
| Traffic volume (AADT) | 2500 veh/day |
| Fraction of heavy vehicles | 10% |
| Presence of cyclists | Yes |
| Presence of pedestrians | No |
| Presence of obstacles | Yes (trees along the roadway) |

This case study concerns the redevelopment of a secondary road in a rural area with a multimodal traffic (Table 4). In the following example, we will only consider a limited set of 10 alternatives to ensure the readability and the global understanding of the multicriteria approach. However, for a real case study, we define all the feasible alternatives of the problem by a combination of parameters to ensure an exhaustive analysis of the design space. In addition, we will consider a limited set of 6 criteria due to the nature of the case study. A simplified version of the criterion "Intersection" has been used.

Based on the characteristics of the road project and its direct environment, we have designed 10 different draft alternatives (Table 5) by modifying some design parameters such as the number of lanes, the width of the lanes and shoulders, the nature and width of the cycle path, the speed limit, the nature of the safety equipment and the type of intersections. Additional information on the parameters is available in the Appendices. To limit the size of the problem, we have considered the same road surface material and the same road signing, marking and lighting equipment for every alternative. We have then calculated their evaluation on each criterion of the set (Table 6).

**Table 5. Definition of the alternatives of the case study**

| Variable | A1 | A2 | A3 | A4 | A5 | A6 | A7 | A8 | A9 | A10 |
|---|---|---|---|---|---|---|---|---|---|---|
| w_l | 2.5 | 3.5 | 2.5 | 3 | 2.5 | 3 | 3 | 3 | 2.5 | 2.5 |
| n_l | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 4 | 4 |
| w_sh | 2 | 1 | 2 | 2 | 2 | 1 | 3 | 1 | 1 | 1 |
| b_sh | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| cp_nat | 6 | 7 | 8 | 2 | 3 | 8 | 2 | 6 | 3 | 3 |
| intertype | 2 | 1 | 1 | 3 | 2 | 4 | 4 | 2 | 4 | 3 |
| v | 50 | 50 | 70 | 50 | 50 | 70 | 50 | 90 | 70 | 50 |

**Table 6. Evaluation table of the multicriteria problem**

| Alt. | INF3 VRU | INF5 Design | INF6 Intersections | ENVI1 Emissions | ENVI2 Noise | ECO1 Costs |
|---|---|---|---|---|---|---|
| A1 | 37 | 0.32377 | 3 | 4.2842 | 2.8649 | 132,450.0 |
| A2 | 7 | 0.32844 | 3 | 4.2867 | 2.6951 | 432,780.0 |
| A3 | 12 | 0.32377 | 3 | 4.2842 | 2.7674 | 932,770.0 |
| A4 | 22 | 0.53063 | 1 | 4.2884 | 2.6951 | 961,980.0 |
| A5 | 42 | 0.49842 | 3 | 4.2856 | 2.6951 | 102,030.0 |
| A6 | 12 | 0.36597 | 2 | 4.2856 | 2.7674 | 931,780.0 |
| A7 | 22 | 0.49978 | 2 | 4.2897 | 2.6951 | 162,200.0 |
| A8 | 37 | 0.36597 | 3 | 4.2856 | 2.8649 | 122,310.0 |
| A9 | 50 | 0.81102 | 2 | 4.2884 | 2.7674 | 169,200.0 |
| A10 | 45 | 0.81102 | 1 | 4.2884 | 2.6951 | 179,270.0 |

Then, let consider an equal distribution of the weights among the criteria (i.e. 16.7% each), we can generate a multicriteria ranking of the alternatives by using the net flow scores of the outranking method PROMETHEE II (Vincke, 1989). This method is based on pairwise comparisons of the evaluations of the alternatives and the representation of the preference and indifference with the assistance of preference functions. These functions remove the scale factors between criteria of different units and they allow the decision maker to treat criteria with quantitative or qualitative evaluations. Moreover, one of the main theoretical concepts of the PROMETHEE methods is the enrichment of the dominance relation. It means that the comparison of two alternatives could lead either to preference, indifference or incomparability. In real-world applications, it could be very interesting given that the alternatives may have profiles that are different or even incomparable.

The exhaustive description of the methodology of PROMETHEE goes beyond the scope of this paper but a short overview is presented in Appendix 2. In this example, we have chosen usual preference functions for the criteria INF6, ENVI1 and ENVI2. We have defined U-shape preference functions for the criteria INF3 (*q*=5) and INF5 (*q*=0.05). And we have defined a linear preference function for the criterion ECO1 (*q*=5,000; *p*=100,000). We have used the D-SIGHT software to generate the ranking on Figure 3 (Hayez et al., 2012).

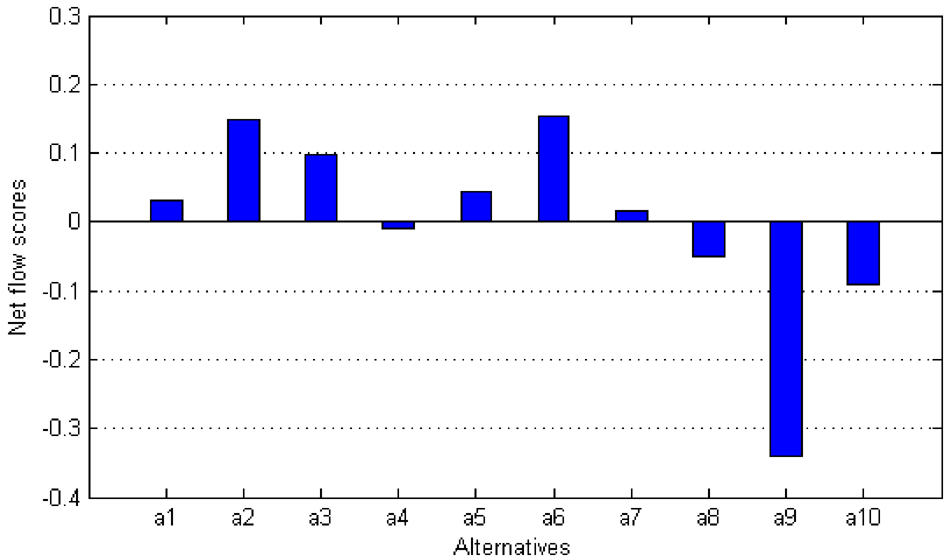


*Figure 3. Ranking of the alternatives based on PROMETHEE II net flow scores*

Table 7 and Figure 3 represent the ranking of the solutions based on the PROMETHEE II net flow scores. The global net flow score is calculated by subtracting the positive to the negative net flow score. The alternatives a2, a3 and a6 are the preferred solutions of the problem according to the preferences of the decision maker.

**Table 7. PROMETHEE II net flow scores**

| Alternatives | Rank | Net flow | Flow+ | Flow- |
|---|---|---|---|---|
| a1 | 5 | 0.031727 | 0.37102 | 0.33929 |
| a2 | 2 | 0.14815 | 0.44444 | 0.2963 |
| a3 | 3 | 0.097312 | 0.41213 | 0.31481 |
| a4 | 7 | -0.0096316 | 0.38889 | 0.39852 |
| a5 | 4 | 0.044889 | 0.3597 | 0.31481 |
| a6 | 1 | 0.15306 | 0.44936 | 0.2963 |
| a7 | 6 | 0.0174 | 0.39163 | 0.37423 |
| a8 | 8 | -0.050955 | 0.32239 | 0.37335 |
| a9 | 10 | -0.34069 | 0.22321 | 0.5639 |
| a10 | 9 | -0.091259 | 0.33333 | 0.42459 |

Table 8 represents the stability of the alternative a6 as the first ranked solution of the problem.

**Table 8. Stability intervals for the first ranked alternative**

| Criteria | Min Weight | Value | Max Weight |
|---|---|---|---|
| INF3 | 8.6% | 16.7% | 100.0% |
| INF5 | 5.1% | 16.7% | 100.0% |
| INF6 | 16.2% | 16.7% | 35.5% |
| ENVI1 | 15.7% | 16.7% | 24.3% |
| ENVI2 | 0.0% | 16.7% | 17.1% |
| ECO1 | 0.0% | 16.7% | 17.6% |

Based on the stability intervals of each criterion (Brans and Mareschal, 2002), we can observe that the alternative a6 is robust on a certain range of weights. Indeed, if we could modify the weights of criteria INF3 and INF5 on large intervals without changing the top position of the alternative a6 in the ranking, we have to pay attention when modifying the weights of the others criteria. In particular, we could invert the position of a6 and a2 in the ranking by decreasing to 16.0% the weight associated to INF6.

In practice, the definition of the weights could be done on the basis of the project requirements or by computing an interactive process with the decision maker. A well-known approach is the preference elicitation method in the Analytic Hierarchy Process. This method generates the weights from a pairwise comparison between all the criteria and the expression of the preference on an ordered scale from 1 to 9 (Saaty, 1980).

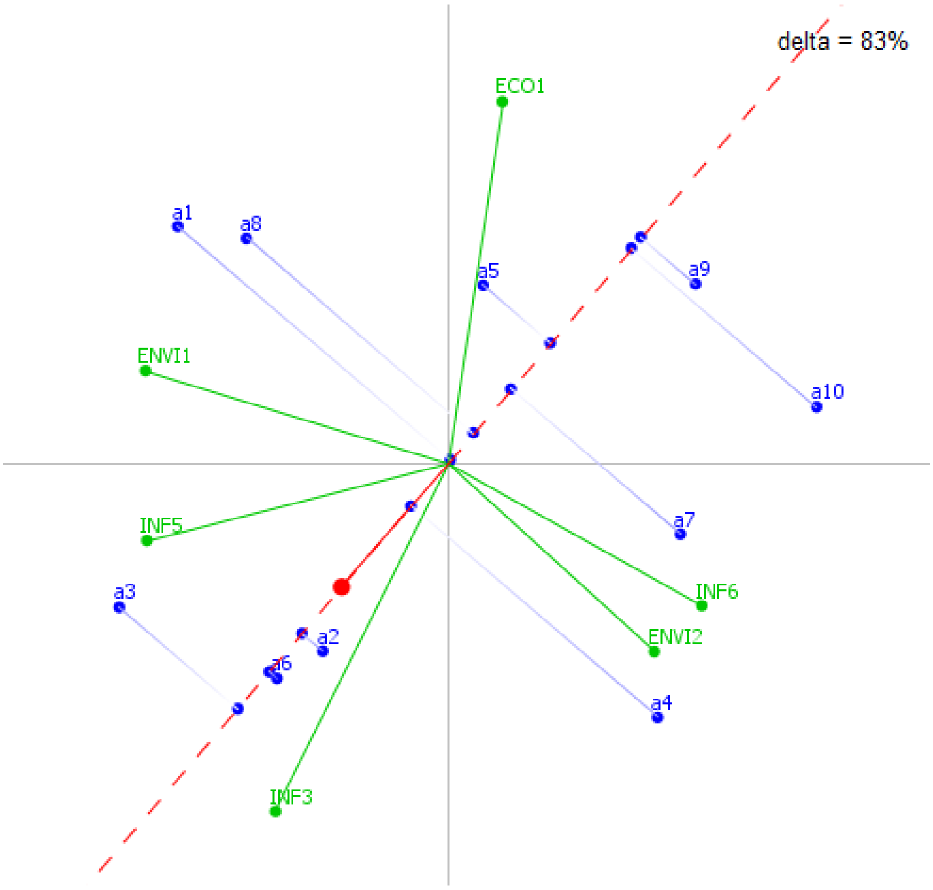


*Figure 4. Visual representation of the problem on the GAIA plane*

In addition, we may use a global visualization tool given by the GAIA plane to analyse more precisely the characteristics of the problem and the nature of the solutions. Figure 4 represents the plane obtained after applying a principal components analysis to the alternatives of the problem. Due to the projection, there is a small loss of information (about 17% here) but the study of the GAIA plane still leads to interesting observations. At first, we may notice that alternative a6 and a2 perform well in the criteria INF3, INF5 while they obtain neutral evaluation on INF6, ENVI2 and ENVI1 and bad evaluations on criteria ECO1. At the contrary, the alternative a8 performs significantly well on the economic and noise criteria but suffers from bad evaluations on the criteria related to the infrastructure performances (except INF5).

In addition, the ranking on the Figure 3 shows that the alternatives a2 and a3 obtain a similar net flow score – respectively 0.148 and 0.097, while the analysis of the GAIA plane points out that their profiles are slightly different (on INF6, ENVI1 and ENVI2 essentially). This means that the final choice has to be done with caution. Consequently, the use of complementary tools such as the GAIA plane or the sensitivity analysis will support the decision maker in the understanding of the results and the selection of a final solution.

## 5. Current and future developments

Considering that the actions are defined a priori by combinations of parameters (e.g. number of lanes, width of lanes, roadway materials, type of cycle equipment, type of safety equipment, type of lighting equipment, etc.), the size of the problem may rapidly become important. In the section 3.3, we have seen that even a simplified road design project, the set of alternatives could rapidly reach $10^6$ items (Table 3). Then, considering the large number of alternatives and criteria of our problem, the exhaustive enumerations of all the solutions would imply an important calculation time. Moreover, due to the non-linear nature of the criteria, the use of a linear programming method was not possible to solve the problem. Therefore, we have decided to apply a metaheuristic to address this issue.

In this research project, we have used the multi-objective evolutionary algorithm NSGA-II (Deb, 2002). This algorithm is a metaheuristic that is able to deal with large problem and to find solutions with a high convergence speed. From the complete set of alternatives, we randomly select a limited sample of alternatives that constitutes the initial population. We generate the evaluation table of this initial population and then, we identify the non-dominated solutions. We start the genetic process and we improve the quality of the initial solutions by applying crossover and mutation operations on each successive set of solutions. At the end, the set of solutions has converged and the set of non-dominated solutions of our problem has been identified.

**Table 9. Amount of Pareto solutions obtained after NSGA-II (150 generations)**

| Variable | Value | Description |
|---|---|---|
| Alt | 1,000,320 | Total amount of feasible alternatives |
| initial_pop | 150 | Size of the initial population for NSGA-II |
| Gen | 150 | Number of generations in NSGA-II |
| pareto_sol | 61 | amount of pareto solutions |

Table 9 contains the results of the simplified problem introduced in section 3.3 after using NSGA-II. The initial population was composed of 150 alternatives randomly selected and 150 generations were conducted in NSGA-II. At the end of the process, 61 non-dominated (or Pareto) solutions were identified.

Figure 5 shows a projection view on the objectives ECO1 (i.e. construction costs) and INF5 (i.e. safety equipment) of the initial population (blue dots) and the non-dominated solutions (red triangles). These interesting results illustrate the added value of using a multi-objective evolutionary algorithm, given that it proceeds to an efficient and extensive design space exploration.

This heuristic allows us to consider several criteria at the same time and then to give relevant information to the decision maker. For example, if we consider the closest triangles to the axis of the Figure 5, we observe that a small gain on the criterion *SafEq* from 0.5 to 0.35 accidents per $10^6$ veh.km implies an increase of the *Costs* from 9,000€ to 22,000€.

Once the Pareto frontier has been identified, we may analysis the quality of the solutions and the performance of the NSGA-II algorithm by using performance indicators available in the literature. For instance, we may evaluate the density and diversity of the solutions which compose the frontier (e.g. spread, binary hypervolume indicator), and the convergence of the algorithm (e.g. contribution, binary ε-indicator, binary hypervolume indicator) (Talbi, 2009).

Finally, we may use a complementary methodology to solve the multicriteria problem. However, a detailed analysis of this solving process goes beyond the scope of this paper (Sarrazin and De Smet, 2014).

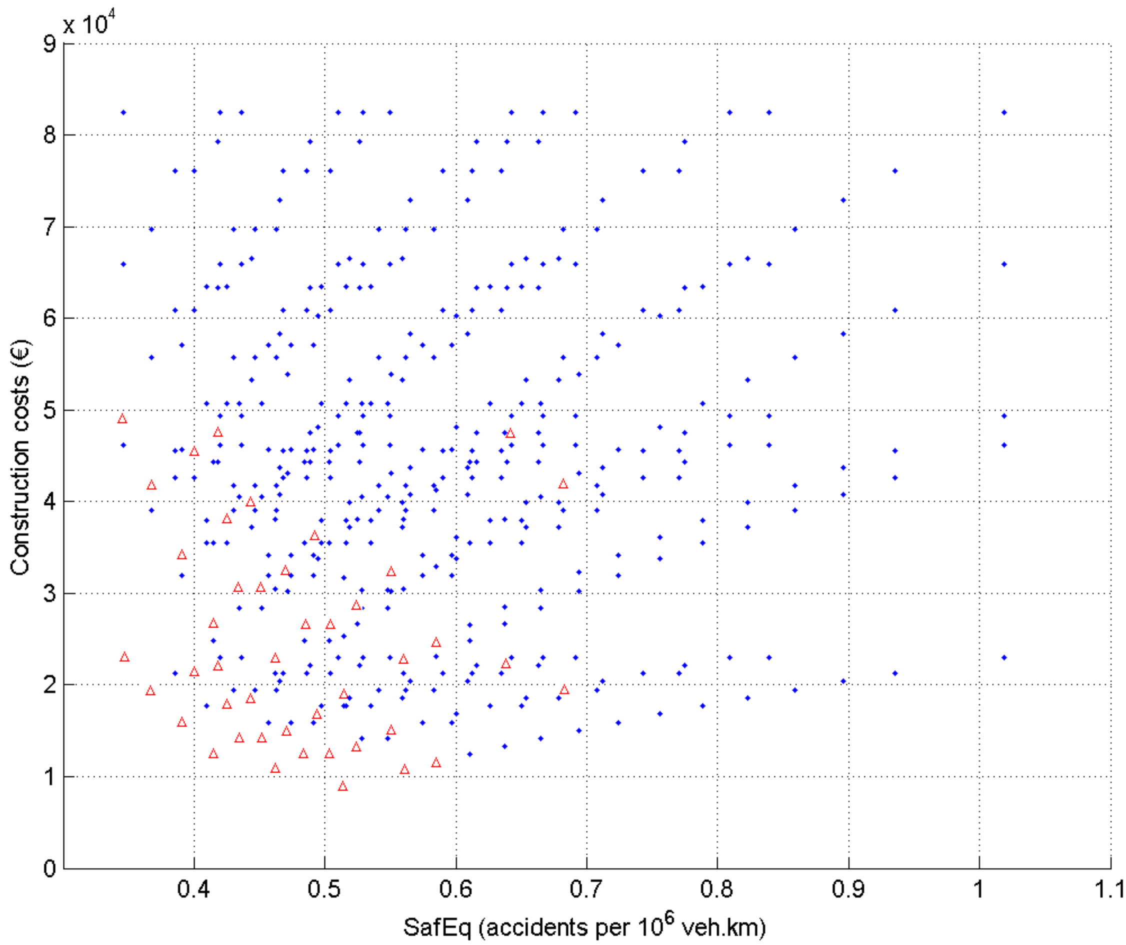


*Figure 5. two-axis projection view of the dominated and non-dominated solutions*

## 6. Conclusion and discussion

In this study, we have developed an innovative model to assess both the road safety and the sustainable performances of a project at the design stage. Considering the objectives of the EC to reduce the number of fatalities on the road network by 2020, we have initiated the development of a preventive approach based on the concept of sustainable road safety. In addition, we have decided to use a multicriteria decision aiding methodology to assist the engineers during the design process of an infrastructure. At the pre-design stage of the process, we first generate all the feasible alternatives of the project by applying parameter combinations. Then, we support the engineers in the evaluation and the selection of the best solutions for a specific road infrastructure problem by using a multicriteria model. This model is based on the NSGA-II algorithm.

To date, the first results of this on-going research are promising and due to its multidisciplinary nature, the use of a multicriteria methodology seems fully relevant. From a multicriteria perspective, the design of a road project is a complex and challenging problem. The application of the proposed model on a case study showed that the multicriteria problem involves conflicting criteria. Moreover, the visual representation of the solutions on the GAIA plane illustrated the diversity of profiles among the good solutions. Then, the use of a multicriteria decision aiding model constitutes a quantitative approach that allows the decision maker to interact with the other actors of the project. Consequently, all these observations demonstrate the added value of using a multicriteria decision analysis model to solve the problem.

However, the proposed model has some limitations that would require further research. The set of criteria should be improved and completed with economic, social and environmental issues which are related to the design of a road project. The predictive accident model that we use should be updated with respect to the Belgian context. In addition, the exhaustive generation of the alternatives causes a lack of precision in the final results. Indeed, due to the automated nature of the process, we restrain the alternatives to a finite number of design parameters that are used by the evaluation formula of the criteria. So, the more we add parameters to define the alternatives, the more the criteria are complex. Consequently, we have to find a compromise between the precision of the alternatives and the complexity of the criteria evaluations.

From a methodological point of view, we will focus in the short term on the study of the set of non-dominated solutions which constitute the Pareto frontier and the final solving of the problem. In the long run, the use of this model may lead to the definition of innovative and integrated solutions. Additionally, the improvement of the set of criteria may help us to have a better understanding of the road safety issues and them quantification.

## Acknowledgements

This research has been made possible with the assistance of the First DoCA program funded by the Department of the Research Programs DGO6 of the Walloon Region.

## References

Aarts, L. and Wegman, F. (2006) *Advancing sustainable safety: National Road Safety Outlook for 2005-2010*. SWOV, Leidschendam, The Nederlands.

Bao, Q. (2010) *Multi-criteria decision making techniques for combining different sets of road safety performance indicators into an overall index*. Master thesis, Interfaculty Institute Transportation Sciences, Hasselt University, The Nederlands.

Boutefeu, E. (2008) *Prendre en compte le développement durable dans un projet : guide d'utilisation de la grille RST02.* Centre d'études sur les réseaux, les transports et l'urbanisme, Paris, France.

Brans, J.P. and Mareschal, B. (2002) *PROMETHEE-GAIA : une méthodologie d'aide à la décision en présence de critères multiples*. Editions de l'Université de Bruxelles, Brussels, Belgium.

Brauers, W., Zavadskas, E., Peldschus, F. and Turskis, Z. (2008). Multi-objective decision-making for road design. *Transport*. 23(3). p.183-193.

COST (2008) The way forward for pavement performance indicators across Europe, in *COST Action 354 Performance Indicators for Road Pavements*, COST Office and Austrian Transportation Research Association.

De Jonghe, T. et. al (2006) *Code de bonne pratique pour le choix du revêtement bitumineux lors de la conception ou de l'entretien des chaussées*. Code de bonne pratique, Belgian Road Research Centre (ed), BRRC R78/06, Brussels, Belgium.

de Luca, S. (2014) Public engagement in strategic transportation planning: An analytic hierarchy process based approach. *Transport Policy*. Volume 33, May 2014. p.110-124. ISSN 0967-070X.

De Pauw E., Daniels S., Brijs T., Hermans E. and Wets G. (2014) Safety effects of an extensive black spot treatment programme in Flanders-Belgium. *Accident Analysis & Prevention*. Volume 66, May 2014. p. 72-79. ISSN 0001-4575.

Deb, K., Pratap, A., Agarwal, S. and Meyarivan, T. A. M. T. (2002) A fast and elitist multiobjective genetic algorithm: NSGA-II. *Evolutionary Computation, IEEE Transactions on*. *6*(2). p.182-197.

Direction générale Statistique et Information économique (2013) *Circulation et transport – Accidents de la circulation dossier 2012*. SPF Economie PME, Classes moyennes et Energie. Communiqué de Presse, Brussels, Belgium.

Dumont, A-G. and Tille, M. (2003). The multicriteria decision making methods: a practical tool for design a sustainability road infrastructure. In: *The XXIInd PIARC World Road Congress*. October 2003, Durban, South Africa.

EEA (2011) *Energy efficiency and energy consumption in the transport sector*. Technical Report ENER 023. European Environment Agency.

ETSC (2014) *Ranking EU Progress on Road Safety: 8th Road Safety Performance Index Report*. European Transport Safety Council, Brussels, Belgium.

European Commission (2001) *European Transport Policy for 2010: Time to Decide - White Paper*. Communication from the Commission, COM (2001) 370 final.

European Commission (2010) *Towards a European road safety area: policy orientations on road safety 2011-2020*. Communication from the Commission, COM (2010) 389 final.

FHWA (1992) Volume III: Cross sections. In Federal Highway Administration (ed). *Safety Effectiveness of Highway Design Features*. Washington DC, USA.

FHWA (2006) *Pedestrian and Bicyclist Intersection Safety Indices*. Federal Highway Administration (ed), FHWA-HRT-06-125. Washington DC, USA.

Gasparatos, A., El-Haram, M. and Horner, M. (2008) A critical review of reductionist approaches for assessing the progress towards sustainability. *Environmental Impact Assessment Review*. 28(2008). p.286-311.

Gitelman V. and Hakker A.S. (2006) *Road Safety Performance Indicators: Manual*. European Commission, Deliverable D3.8 of the EU FP6 project SafetyNet.

Harwood D.W., Fambro D.B., Fishburn B., Joubert H., Lamm R. and Psarianos B. (1995) International sight distance design practices. In: *International Symposium on Highway Geometric Design Practices*. Transportation Research Board, Boston, USA

Hayez Q., De Smet Y. and Bonney J. (2012) D-Sight: A New Decision Making Software to Address Multi-Criteria Problems. *International Journal of Decision Support System Technology (IJDSST)*. IGI Global. 4(4). p.1-23.

IBGE (2012) *Outil d'évaluation de la capacité environnementale des voiries urbaines en Région de Bruxelles-Capitale*. Unpublished report. Bruxelles Environnement – IBGE. Brussels, Belgium.

IBSR (2014) *Baromètre de la sécurité routière : 1er trimestre 2014.* Institut Belge pour la Sécurité Routière. Brussels, Belgium.

IRTAD (2014) *Road Safety Annual Report 2014*. International Traffic Safety Data and Analysis Group. International Transport Forum. April 2014. Paris, France.

Kabir, G., Sadiq, R. and Tesfamariam, S. (2013). A review of multi-criteria decision-making methods for infrastructure management. *Structure and Infrastructure Engineering*. 10(9). p. 1176-1210.

Martensen, H. and Nuyttens, N. (2009) *Rapport thématique Cyclistes : accidents de la route impliquant des cyclistes 2000-2007*. IBSR, Observatoire pour la sécurité routière, Brussels, Belgium.

Moisan, O., Subirats, P., Bisson, O., Cheinisse, D., Chauvin, P. and Violette, E. (2014) A Safer Road With No Accidents – A Case Study. In: *Transport Research Arena 2014*. 14-17 April 2014, Paris, France.

Muench, S.T. et al. (2011). *Greenroads Manual v1.5*. J.L. Anderson, C.D. Weiland, and S.T. Muench, Editions. Seattle, WA: University of Washington, USA.

Noël, N., Leclerc, C. and Lee-Gosselin, M. (2003) CRC Index: Compatibility of Roads for Cyclists in Rural and Urban Fringe Areas. In: *TRB 2003 Annual Meeting*. 12-16 January 2003, Transportation Research Board, Boston, USA.

Nossent, P. (2011) La certification Route Durable : une certification qui donne confiance. In: *Colloque Route Durable*. 31 May 2011, Lille, France.

Office Fédéral de l'Environnement, des Forets et du Paysage (OFEFP) (1995) *Bruit de traffic routier : correction applicable au modèle de calcul du trafic routier*. Collection l'environnement pratique. Switzerland.

OFROU (2003) *NISTRA: Indicateurs du développement durable pour les projets d'infrastructure routière.* Office Fédéral des Routes (ed). Département fédéral de l'environnement, des transports, de l'énergie et de la consummation. Berne, Switzerland.

Organization for Economic Co-operation and Development (1999) *Safety strategies for rural roads*. OECD Publishing. Paris, France.

PIARC (2003) *Manual of Road Safety*, PIARC World Road Association.

Pirdavani, A., Brijs, T. and Wets, G. (2010). Multiple Criterion Decision-Making Approach for Prioritizing Accident Hot Spots in Developing Countries in the Absence of Crash Data. In: *Transportation Research Board 89th Annual Meeting*. January 2010, Washington DC, USA.

ROSEBUD (2006) Framework for the assessment of road safety measures in *Thematic Network* of *ROad Safety and Environmental Benefit-cost and cost-effectiveness analysis for Use in Decision-making*. May 2006, Federal Highway Research Institute, Germany.

Saaty, T.L. (1980) *The Analytic Hierarchy Process.* McGraw Hill International.

Sarrazin, R. and De Smet, Y. (2014) *Design safer and greener road projects by using a multi-objective evolutionary approach*. Technical Report TR/SMG/2014-004, SMG, CoDE, Université Libre de Bruxelles, Brussels, Belgium.

Talbi E.G. (2009) *Metaheuristics : from design to implementation*, John Wiley & Sons.

Tingvall, C. and Haworth, N. (1999) Vision Zero: an ethical approach to safety and mobility. In: *The 6th Institute of Transport Engineers International Conference of Road Safety and Traffic Enforcement: Beyond 2000*. 6-7 September 1999, Melbourne, Australia.

TRB (2010). *Highway Capacity Manual 2010 (HCM2010)*, Volumes 1 to 4. Transportation Research Board, Washington D.C., USA.

Vincke P. (1989) *L'aide multicritère à la décision*, Statistiques et mathématiques appliquées, Editions de l'Université Libre de Bruxelles. Brussels, Belgium.

Weekley, J., Ni Nuallain, N.,Sarrazin, R. and Wennström, J. (2014) The STARs evaluation tool: optimising network performance, road worker safety and road user safety during roadworks and maintenance. In: *Transport Research Arena 2014*. April 2014, Paris, France.

Zegeer C., Steward R., Council F. and Neuman T. (1994) Accident Relationships of Roadway Width on Low-Volume Roads. *TRB Record 1445*, Transportation Research Board.

Zhao, Y., Tian, Z. Z. and Hernandez, A. (2013). A Multi-Criteria-Based Guideline for Marked and Unmarked Pedestrian Crosswalks at Unsignalized Intersections. In: *Transportation Research Board 92nd Annual Meeting*, No. 13-1282. 13-17 January 2013, Washington DC, USA.

# Appendix A. Additional information on the multicriteria problem

Hereinafter, we describe the meaning of the parameters' evaluation from the Table 5.

- *intertype*: {1;2;3;4} = {give way to right; through road; traffic signals; roundabout}
- *cp_nat*: {2} = marked cycle lane on the road – width = 1m
  {3} = shared lane (mixed traffic)
  {6} = separated cycle lane – width = 1,5m – no separation
  {7} = separated cycle lane – width = 1,5m – delineators
  {8} = separated cycle lane – width = 1,5m – barriers

# Appendix B. The PROMETHEE methods

The PROMETHEE methods had been developed in 1982 by J.P. Brans (Brans and Mareschal, 2002) and they offer the decision maker (DM) a support for the problems of multicriteria choice (PROMETHEE I and II) and the problems of multicriteria ranking (PROMETHEE II). These outranking methods are based on three main principles: the enrichment of the preference structure, the enrichment of the dominance relation and decision aiding.

Concerning the enrichment of the preference structure, the PROMETHEE methods introduces the preference function which allows us to take into account the amplitude of the variance between the evaluations of each criteria. Indeed, giving that the dominance relation is quite weak, we enrich it by using the function *Pj(a,b)* which supplies the preference degree for the alternative *a* over the alternative *b* (A.1) :

$$P_j(a,b) = P_j\left[d_j(a,b)\right] \qquad \text{(A.1)}$$

$$0 \leq P_j(a,b) \leq 1 \qquad \text{(A.2)}$$

While $d_j(a,b) = f_j(a) - f_j(b)$ is the variance between the evaluations $f_j(a)$ and $f_j(b)$. Thus, we can define different types of preference functions depending on the preferences of the decision maker (i.e. the preference threshold *p* and the indifference threshold *q*). Considering a multicriteria problem and the preference function *Pj(a,b)* associated to each criteria, we can define the multicriteria preference index $\pi(a,b)$ and the ingoing $\Phi^+(a)$ and outgoing flows $\Phi^-(a)$ for each action by using the weights defined by the DM. By using these outranking flows, we are able to transform the local information on each action and criterion into global information:

$$\pi(a;b) = \sum_{j=1}^{k} P_j(a,b) \times w_j \qquad \left(\text{and} \sum_{j=1}^{k} w_j = 1\right) \qquad \text{(A.3)}$$

$$\phi^+(a) = \frac{1}{n-1} \sum_{x \in A} \pi(a,x) \qquad \text{(A.4)}$$

$$\phi^{-}(a) = \frac{1}{n-1} \sum_{x \in A} \pi(x, a) \quad \text{(A.5)}$$

While A is the set of actions, *a* the actions on *A*, *n* the number of actions, *k* the number of criteria and $w_j$ the weight of criterion *j* ($w_j > 0$ *for* $j=1 \ldots k$). Finally, these two flows are combined to obtain a single net flow:

$$\phi(a) = \phi^{+}(a) - \phi^{-}(a) \quad \text{(A.6)}$$

Then, on the basis of these flows, we can rank all the actions of the problem. In PROMETHEE II, we use the net flow to obtain a complete ranking of the actions.