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Multiobjective Optimization and Multicriteria Decision Aid Applied to the Evaluation of Road Projects at the Design Stage

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SARRAZIN Renaud

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Yves De Smet et **Claude Van Rooten**

À mon papa.

Foreword

The present PhD thesis is an aggregation of published contributions related to the application of multicriteria analysis to the evaluation of road projects at the design stage. The aim of the two introductory chapters is to offer a synthesised and critical presentation of the scientific contributions that constitute the PhD thesis. The complete version of the journal articles and preprints are found in Chapters 3 to 6. In the appendices, we also provide reprints of conference papers that are usually related to one of the main contributions of the thesis.

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Quand j'ai débuté ma thèse il y a près de cinq ans, on m'a souvent répété que j'allais devoir me préparer à enchaîner des moments de grande euphorie et quelques autres profonds instants de doutes et d'abattement. À l'époque, je n'imaginais pas encore à quel point ce constat s'avèrerait pertinent pour moi, ni qu'il traduirait des joies et difficultés rencontrées ces dernières années - et bien au-delà du cadre de cette thèse. Aujourd'hui, je souhaite donc remercier toutes les personnes qui m'ont accompagné dans cet exercice pour leur soutien, leur implication et leur amitié.

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Par ailleurs, il m'est impossible de dissocier la composante scientifique de cette thèse de sa dimension sociale. À cet égard, je tiens à exprimer toute mon affection et ma reconnaissance envers mes proches qui m'ont continuellement supporté et encouragé. Merci en particulier à ceux qui me font adorer ce pays, à ceux qui l'ont rejoint et à ceux qui sont plus loin (même à Paris). Merci à ma belle belle-famille, aux *Bee Gees*, aux fourbes, aux bretons, aux mélomanes, aux footeux (même pour Paris), aux prénoms équivoques, aux matheux, à ceux du Buis (ça n'en fait toujours pas une adresse), aux Mous, à la *Family* et aux canards.

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Chapter 1
Problem description

1.1 Introduction

Constructing a road is a complex process that may be represented as a series of correlated steps, from the planning to the construction and usage of the new road. At the heart of this process, the preliminary and detailed design stages are key elements that will ensure the quality and the adequacy of the final solution regarding the constraints and objectives of the project. In particular, infrastructure layout and design will have a strong impact on the global performances of the road in operational conditions. Among them, road safety, mobility, environment preservation, noise pollution limitation, economic feasibility and viability of the project, or even its socio-economic impact at the local level. Consequently, it is crucial to offer engineers and road planners some tools and methods that may assist them in designing and selecting the most efficient solutions considering the distinctive features of each design problem.

For that purpose, during the last decades, many European transport policies have considered the improvement of road safety and the recognition of sustainable development as the main challenges for the road sector. In 2001, the European Commission published the White Paper on Transport Policy [38] in which many objectives in favor of road safety were targeted, such as halving the overall number of road deaths in the European Union by 2010. Recently, this challenging objective has been updated and reinforced in the Road Safety Programme 2011-2020 [41]. The European action programme encouraged Member States to adopt national road safety plans in order to cope with these objectives [103]. In particular, the definition of actions to improve road infrastructure and monitor road safety performances were cited as essential topics. Moreover, with the concerns about the environment and the move towards sustainable mobility, the European Commission published in 2008 the Greening Transport Package about strategies to apply in order to strive for a transport system more respectful of the environment [40].

Hence, balancing the safety of the road networks with sustainable concerns is gradually becoming one of the main challenges faced by engineers and planners of the road sector. However, despite an increasing and sustained political support at the national and international levels, few methodologies have been developed to support the preventive assessment of infrastructure projects regarding their safety performances or sustainable nature. To the best of our knowledge, the situation is particularly critical concerning the evaluation of road safety performances while it is mainly done in a reactive approach from the analysis of accidents databases [59, 60]. In Belgium, an extensive black spot treatment programme has led to promising results regarding road safety improvement since 2000 [23] but it essentially consists of curative analysis of the high accident concentration areas. Then, the preventive analysis of road infrastructure from design parameters remains an unexplored research area. Since then, the road design process mostly depends on the expertise of the engineers and the selection of a solution is, most of the time, reduced to a single-criterion decision problem (based solely on global costs).

In this work, a multicriteria analysis methodology is developed to carry out an integrated and preventive assessment of road projects at the design stage by considering both their safety performances and some economic and environmental aspects. Its purpose is to support design engineers in the analysis of their projects and the identification of innovative, consistent and effective solutions. A block diagram of the thesis methodology that is applied in this work is represented in Figure 1.1. It is composed of two main research frameworks. On the one hand, the road design problem is addressed by focusing successively on the structuring of the multicriteria problem, the identification of the approximate set of non-dominated solutions using a genetic algorithm, and the application of the methodology to a real road design project. On the other hand, the methodological development of a multicriteria interval clustering model was performed. Due to the applicability of this model to the studied problem, the interactions between the two frameworks are also analysed.

The first framework of the proposed approach specifically analyses the road design process as a combinatorial optimisation problem that is structured in a multicriteria context. Due to the large size of real design problems and the particular nature of the criteria, a multiobjective evolutionary algorithm is applied to identify the non-dominated solutions. However, if decision making is feasible at this stage in traditional bi-objective optimisation problems, the complexity significantly increases with the number of criteria. To tackle this issue and support decision makers in the understanding and the characterisation of their problems, it is worthwhile to simplify them by using complementary models. This is precisely the aim of the contribution that is developed in the second framework of the proposed approach. For that purpose, a new extension of PROMETHEE to multicriteria interval clustering was developed and analysed. The good results of the model stress the interest of using such an approach to identify groups of similar solutions that support a partial order and then to propose the Decision Maker (DM) a limited set of representative elements. For simplification reasons, note that this step refers in the following of this

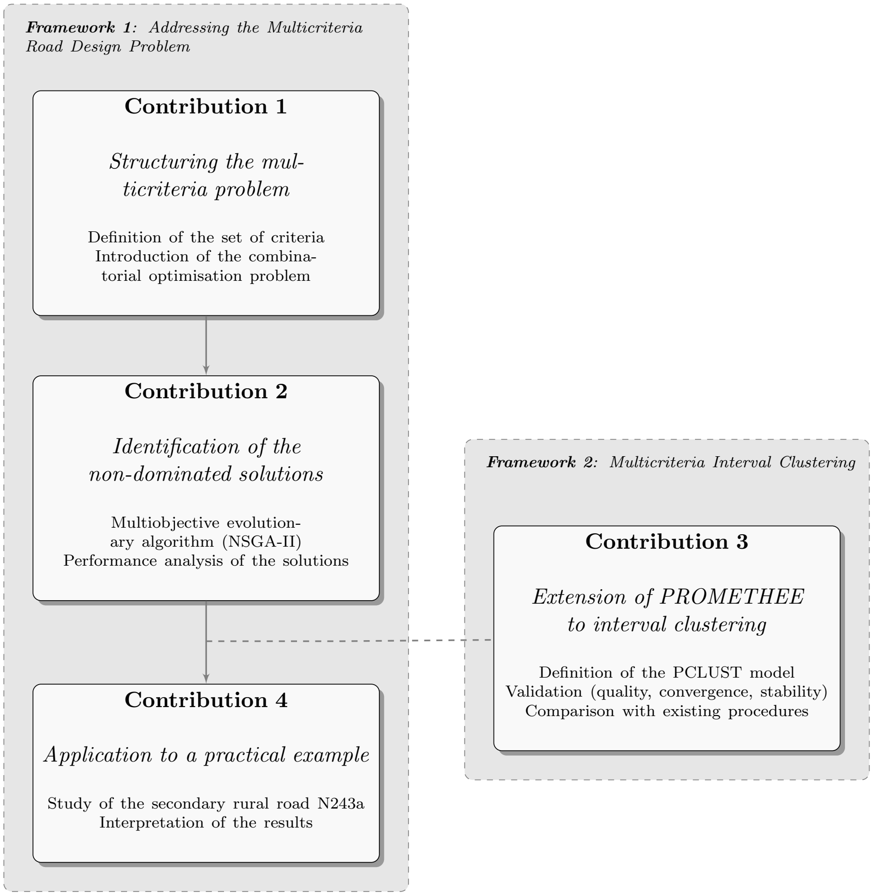

Fig. 1.1 Block diagram of the methodology developed in this thesis

manuscript to the action of *simplifying* the complex multicriteria problem. Finally, the interval clustering model is applied to a practical example that is studied in the fourth contribution of the thesis. The applicability of the global methodology to a real case-study is then presented as a proof-of-concept.

This thesis presents a methodological contribution that aims to provide elements of a response to the road design problem. Its main purpose is to structure and analyse the problem in a context of multicriteria decision aid and multiobjective optimization. However, considering that such real-world decision problems are by nature very complex, the "strict" and precise solving of the road design problem goes beyond the scope of the proposed work. In sum, the methodological approach developed in this thesis can be illustrated by the following quote of Samuel Karlin from the 11^{th} R.A. Fisher Memorial Lecture, "*the purpose of models is not to fit the data* *but to sharpen the questions*".

In the following sections, the list of abstracts of each contribution is given. Then, the research question of this work is precisely described. In Chapter 2, a synthesis of this thesis is provided. Each paper is first described by focusing on the main results and conclusions. The hypotheses, limits and validation of each contribution are then discussed and the general conclusions and perspectives are given. Finally, the four contributions of the proposed thesis are available in the Chapters 3 to 6 of this manuscript.

1.2 List of abstracts

Contribution 1: Structuring the multicriteria road design problem

This contribution is available in the Chapter 3 of this manuscript.

- Sarrazin, R. and De Smet, Y. (2011). *A preliminary study about the application of multicriteria decision aid to the evaluation of the road projects performance on sustainable safety*. In: Proceedings of 2011 IEEE International Conference on Industrial Engineering and Engineering Management, pp. 727-732. (in Appendix)

- Sarrazin, R. and De Smet, Y. (2015). *Applying multicriteria decision analysis to design safe road projects*. Accepted in: European Journal of Transport and Infrastructure Research, vol. 15(4), pp. 613-634, ISSN: 1567-7141.

Abstract: 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. To this intent, 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.

Contribution 2: Identification of efficient solutions by using a multi-objective evolutionary approach

This contribution is available in the Chapter 4 of this manuscript.

- Sarrazin, R. and De Smet, Y. (2015). *Design safer and greener road projects by using a multi-objective evolutionary approach*. Accepted in: International Journal of Multicriteria Decision Making, 15(Z):xxx-yyy.

Abstract: Over the past few years, both recognizing sustainable development and improving road safety have been main issues in policies for transport and mobility in Europe. However, few methodologies have been developed to support actively the road sector in the design of safer and greener roads. Consequently, this research project aimed to develop a multicriteria analysis methodology to carry out an integrated and preventive assessment of the road safety performances and some sustainable aspects of road projects at the design stage. Due to the combinatorial nature of design projects, we have investigated how an evolutionary approach, such as NSGA-II, could help the engineers to identify efficient alternatives. The algorithm was studied by means of well-known performance indicators. These showed the quality of the solutions generated by the algorithm in terms of convergence and diversity. In particular, the binary hypervolume indicator pointed out the quality of the approximation set.

Contribution 3: Development of a multicriteria interval clustering model

This contribution is available in the Chapter 5 of this manuscript.

- Sarrazin, R., De Smet, Y. and Rosenfeld, J. (2014). *An extension of PROMETHEE to interval clustering*. Technical Report TR/SMG/2014-009, CoDE-SMG, Université libre de Bruxelles, December 2014.
  Note. This paper has been submitted to the European Journal of Operational Research in September 2015 after a major revision.

Astract: Multicriteria clustering techniques aim to detect groups of alternatives evaluated on multiple criteria with similar profiles. The preferential partitioning of the data set allows the decision maker to get a better understanding of the structure of his problem. In this paper, we focus on the particular case of interval clustering. This approach allows us to assign alternatives either in individual or interval clusters. To this purpose, we develop a model based on the PROMETHEE I outranking method and the FlowSort sorting procedure. We evaluate its performances on real-world data sets regarding the convergence, the stability and the quality of the clustering. In particular, we analyse the impact of three update functions and two initialization strategies. This analysis has pointed out some promising results that we stress by comparing the performances of the proposed model with the well-known *k*-means procedure and the P2CLUST model.

Contribution 4: Practical application to a case study

This contribution is available in the Chapter 6 of this manuscript.

- Sarrazin, R. and De Smet, Y. (2015). “Solving a multicriteria road design problem: a practical example”. In: *Technical Report TR/SMG/2015-00X*, CoDE-SMG, Université libre de Bruxelles, September 2015.
  Note. This paper has been accepted as a Chapter of the book *Multiple Criteria Decision Making: Applications in Management and Engineering* (Springer) in November 2015.

Abstract: Improving the safety performances of road infrastructures had been a major issue in recent transport policies 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, few methodologies have been developed to support actively the road sector in the design of safer and greener roads: road designing remains mainly a single-criterion decision problem based on the global costs. This study seeks to develop a multicriteria methodology to carry out an integrated and preventive assessment of road projects at the design stage by considering both their safety performances and some economic and environmental aspects. It would support design engineers in the analysis of their projects and the identification of innovative, consistent and performing solutions. To this intent, we consider road designing as a combinatorial optimisation problem to be solved in a multicriteria context. For a given road project, we use an evolutionary approach to identify efficient solutions. Then, we apply a multicriteria clustering technique based on PROMETHEE to detect groups of similar alternatives that support a partially ordered structure. We illustrate the methodology on a real design project of a rural road infrastructure in Belgium.

1.3 Notations

In this manuscript, the following notations are considered.

- $A = \{a_1, ..., a_n\}$ represents the set of actions (or alternatives) of the problem
- $F = \{g1, ..., g_q\}$ represents the set of criteria
- P_k is the preference function associated to $g_k \in F$
- q_k is the indifference threshold associated to P_k
- p_k is the preference threshold associated to P_k
- ω_k are the weights associated to each criterion $g_k \in F$
- $\kappa = \{C_1, C_2, ..., C_K\}$ represents a set of K categories
- $\delta(A, \kappa)$ represents the clustering distribution of A in the categories of κ
- $R = \{r_1, r_2, ..., r_K\}$ represents the set of reference profiles
- r_j is the reference profile associated to the category C_i
- C_i represents a principal category in the clustering distribution
- $C_{i,j}$ represents an interval category in the clustering distribution ($i \neq j$)

1.4 Research question

In this thesis, the road design assessment problem is analysed within the methodological context of multicriteria decision analysis. This research question refers both to the assessment of road infrastructure performances and to the study of real-world decision engineering problems (i.e. the identification of best design alternatives for a given road project). On the one hand, the road design problem was analysed by considering the preventive assessment of road safety and the integration of economic, environmental and social aspects in the design process. On the other hand, the decision problem was addressed by developing a methodological approach that gathers knowledge and material from the fields of multicriteria decision analysis, multicriteria clustering and multiobjective optimisation.

Consequently, the main objective of this thesis is methodological. It relates to the analysis and the improvement of the road design problem by providing elements that will objectify the decision process and by developing models that will support the identification of performing and interesting solutions. Then, the added-value of this work goes over the strict analysis of a practical case-study while it provides a methodological framework for the analysis of complex decision engineering problems - including road design assessment.

In the following, the context of the research problem is described by focusing successively on the road design problem, the scope of the approach and technical assessment of road safety, and the consideration of the sustainable nature of roads in the evaluation process. The main outcomes of the proposed approach are consequently presented.

1.4.1 Road design and decision problem

Designing a road project is not an easy task. As introduced previously, it is a complex process that is constituted of successive stages from the planning to the construction of the new infrastructure project (cf. Fig. 1.2). The development of performing and efficient solutions requires a strong technical expertise. Additionally, it becomes more and more frequent to find in the project specifications some requirements about the analysis of numerous external aspects. Among these aspects, we may cite environmental impacts, economic performances and social values of the project, travel safety and comfort, or even some societal and political aspects. Consequently, the consideration of all these aspects increases significantly the complexity of the road design process. On this basis, several research projects were conducted during the last decades to assess the impact of some road design characteristics regarding road safety [17, 44, 64, 74, 100], vehicle fuel consumption [8, 110], mobility aspects and air pollution [18, 51], safety of pedestrians and cyclists [33, 45, 66, 72, 80, 84] or even noise pollution [82]. Nevertheless, in practical, most of these aspects are often neglected (or addressed separately) due to the lack of tools that might conduct an exhaustive and integrated evaluation of road projects.

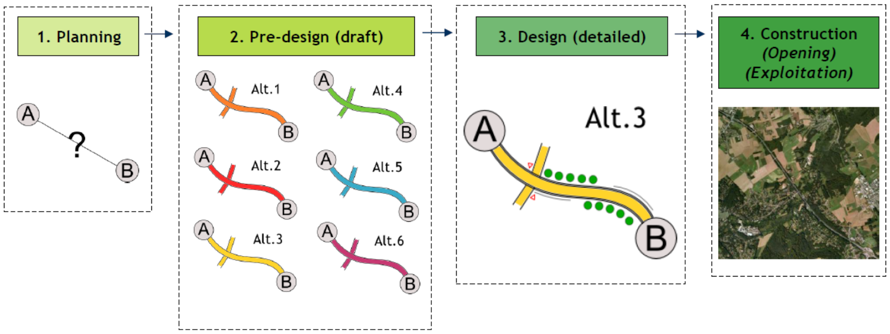

Fig. 1.2 Illustration of the design stage of an infrastructure project

Consequently, it is crucial to develop models and methods that will consider all these topics simultaneously. Such approaches might assist engineers and road planners in the identification of the most efficient solutions considering the distinctive features of each design problem. For this purpose, the use of multicriteria decision analysis seems particularly interesting. Due to their flexibility, these methods are applicable to many kinds of problems in decision engineering [6, 61, 69, 87, 91] while they handle multiple criteria of different nature. Recently, the growing interest of the road sector in the use of multicriteria decision techniques was pointed out in a review paper that indexed approximately 300 contributions about the application of multicriteria decision techniques in the field of infrastructure management in 1980-2012 [63].

From a more practical perspective, multicriteria decision analysis was recently used for the design of the new Ax/A11 motorway project that will connect the Port of Zeebrugge to the E40 and E34 motorways [21]. A limited set of alternatives were considered for the entire trajectory and a multicriteria model was applied to compare their environmental impacts (fauna and flora, geology), social aspects (noise annoyance, expropriations) and mobility performances (access to the port and local communities). This analysis has led to interesting results while it allowed the design engineers to identify conception strategies that balance the interest of environment, public and economical stakeholders from the Zeebrugge area. However, this approach might be criticized on the basis of the restricted number of criteria that were considered and the sample of alternatives that were suggested by the engineers.

In France, the project *A Safer Road with No Accidents* was applied to a 23-km main road between Yvetot and La Mailleraye in Seine-Maritime with the aim to improve road safety significantly by avoiding severe accidents to occur [75, 76].

Concretely, a multidisciplinary approach was applied to consider road safety aspects at the design stage. The accident statistics of the road were analyzed, a diagnostic of the infrastructure was established to prioritize the interventions and finally some solutions were provided for straight sections of road and intersections. In particular, a multicriteria decision analysis was conducted to assess the performances of the roundabouts with regards to road safety, road operations (time lost and saved, overall increase in journey time, influence on traffic micro-flow) and environmental aspects (fuel consumption, emissions, noise). Most of the indicators were defined on the basis of in-situ measurements. The results of this project are particularly encouraging while no accidents have occurred in the sections of the project since 2010. However, if this multidisciplinary approach provides inspiring outcomes regarding the preventive assessment of road design projects, it remains *project-specific*. The evaluation of the criteria requires an intensive collection of local data so that the distinctive features of the project are analysed.

In this thesis, we have developed a methodological approach that aims to support engineers and road planners at the preliminary design stage of a road infrastructure (or pre-design stage in the Fig. 1.2). At this step of the design process, alternatives are modeled by considering essentially their principal characteristics and general design options [71]. This preliminary stage corresponds to a macroscopic evaluation of road design strategies so that the precise analysis of local features is not often required. The main methodological advantage of focusing on this stage of the design process is that we can use general data and parameters to define global criteria that would be applicable to a large range of road projects[1].

Moreover, at the preliminary stage of a classical design process, a limited set of alternatives is modeled. Depending on the size of the road project, the characteristics of the roadside environment or the requirements of the specifications, engineers usually propose between 5 to 15 alternatives to the stakeholders of the project. These alternatives represent different design options such as alternative layouts, different type of intersections or various cross-sections of the roadway. All the others design elements are set by the engineers so that only a few configurations are compared. Consequently, the preliminary design stage is still an subjective process that mainly depends on the technical expertise of the design engineers.

Based on these observations, the proposed methodology was developed with intent to meet two main objectives. First, we aim to conduct a multicriteria evaluation of road design alternatives in order to enrich the design process and support the identification of innovative and performing solutions (cf. Sect. 3.3.2). Secondly, we propose to increase the set of alternatives to all the feasible solutions in order to explore a larger set of design options and then to objectify the decision process (cf. Sect. 4.4).

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[1] As mentioned in the following section, the proposed methodology is appropriate for the assessment of any secondary road project in rural areas

1.4.2 Preventive assessment of rural road safety

In this work, the assessment of the performances of road alternatives at the preliminary design stage refers both to technical and sustainable aspects. The technical performances are closely related to road safety while some environmental, economic and social aspects tend to represent the sustainable nature of road infrastructure projects. The focus on road safety for the technical aspects is motivated by the strong political support in favor of the reduction of road accidents fatalities in the European road network by 2020 [23, 38, 39, 41, 57, 103, 107]. Road safety improvement has then become a priority task for engineers and road planners in Europe so that it is crucial to support them in the conception of performing and preventive infrastructures.

Nowadays, the institutional organisation of road safety in Europe is supported by numerous programs, visions and strategies that define the objectives to reach and the measures to apply to improve road safety [19]. Among the visions of road safety, the Dutch concept of *Sustainable Safety* [1] and the Swedish *Vision Zero* [104] are probably the most famous examples while they inspired many national safety policies. These two global concepts aim to avoid road crashes or to reduce the severity of the accidents if they occur. These visions define the framework of a global road safety system through guidelines and principles. However, they do not convey a specific assessment of road infrastructure in relation to road safety.

The evaluation of the safety performances on an infrastructure is still mainly correlated to the analysis of accident statistics [59, 60], the identification and treatment of black-spot areas [23, 86] or the ex-post evaluation of road projects [4]. Recently, the RiPCORD-iSEREST project had conducted an intense review of methodological approaches that support a preventive assessment of road projects in relation to road safety [36, 71]. In particular, the concepts of Road Safety Impact Assessment (RIA) and Road Safety Audits (RSA) were presented. However, the RIA approach refers essentially to accident prediction models while the RSA consists of an in-situ evaluation of the road infrastructure at different stages of the project (cf. Fig. 1.3).

In the proposed methodology, we aim to develop a new approach for the preventive assessment of road safety by evaluating the impact of numerous design parameters and strategies at the preliminary stage. However, the relations between the road design elements of an infrastructure and its road safety performances still remains incomplete [103]. Consequently, the development of consistent road safety criteria was a strong challenge that required an intense literature review and an important stage of modeling and creation of data (cf. Sect. 3.3.2). To our knowledge, the proposed set of road safety criteria is the first contribution in the field of preventive road safety assessment while it refers to safety aspects such as visibility, protection of vulnerable road users, quality of road surface materials, or even the adequacy of the intersections. As a consequence, some improvements should still be made on

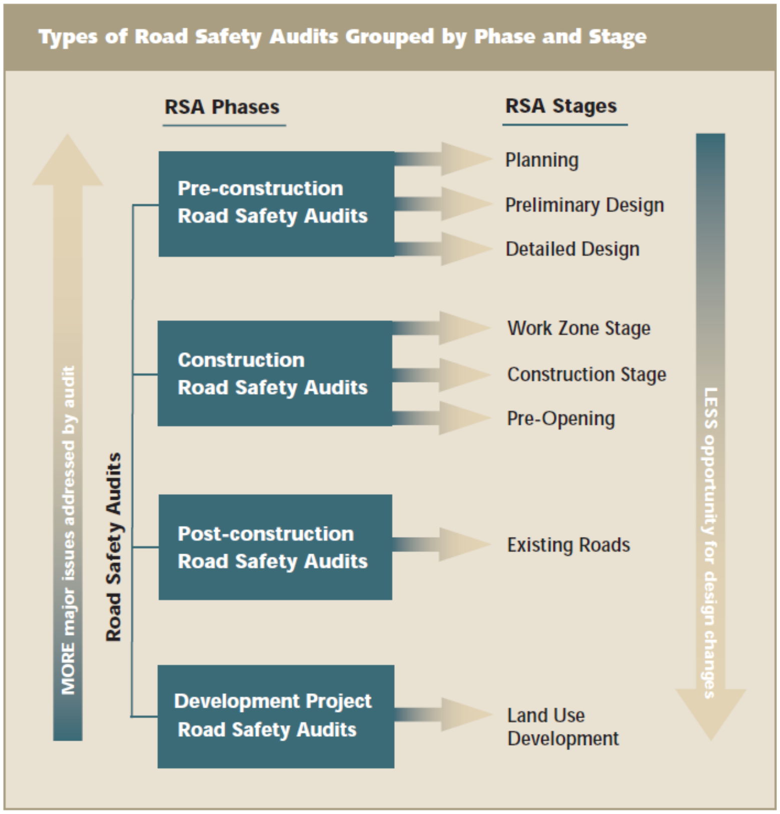

Fig. 1.3 Diagram of types of Road Safety Audits grouped by phase and stage [108]

the criteria and the proposed set must be seen as a proof-of-concept.

In addition, the scope of the proposed methodology covers the evaluation of secondary roads in rural areas. Indeed, when addressing the problem of road safety assessment, it is important to differentiate urban and rural roads while they have very different characteristics. In urban areas, high density of traffic and road functions are encountered, a wide range of transport modes are represented, and the roadside environment is highly heterogeneous [103]. In rural areas, the average operating speed is significantly higher while the traffic volumes are lower, but the road environment is constituted of changing situations and inconsistent design characteristics[2] [84]. In addition, rural roads are characterized by strong speed variation among users due to the presence of slower modes such as buses, trucks, agricultural vehicles or even bicyclists. Consequently, rural road accidents are closely related to inappropriate and excessive speeds and unsafe design configurations. Rural road safety is then com-

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[2] Inadequate visibility distance, narrow road lanes or shoulders, dangerous obstacles along the roadway, etc.

pletely different than urban road safety so that it requires a separate management approach.

1.4.3 Consideration of the sustainable nature of roads

As mentioned previously, the preventive assessment of road safety at the preliminary design stage constitutes already a promising added-value for the engineers and road planners. In addition, the use of a multicriteria decision aiding approach may support the project stakeholders in the evaluation, the understanding and the comparison of their solutions regarding road safety. However, due to the collective nature of road infrastructures and their multiple impacts on their surroundings, the assessment of road project cannot be limited to technical aspects only.

During the last decades, numerous research papers and technical reports were published and pointed out the growing interest of the road sector in the analysis of these external aspects. They refer notably to life-cycle assessment of road pavements [55, 92, 102] and lighting equipments [98], the interactions of environmental and safety measures for road transportation [68], the evaluation of the environmental efficiency of the road transport system [2, 56], noise disturbance [7, 82], land use or preservation of the soil quality and the water balance [77] or even the social impact assessment of roads [35, 97].

Based on these observations, the proposed methodology integrates the evaluation of some environmental, social and economic criteria. They were selected on the basis of their correlation with the road design problem. Concretely, we focused on the aspects that were directly related to design options and infrastructure parameters (e.g. the global costs of the road project, the emissions and noise pollution due to the road pavements and road layout, etc.). Then, if the proposed set of criteria only represents a partial vision of the sustainable nature of roads, we assume that it might still give decision makers an interesting outcome to enrich the decision problem at the design stage. In particular, it might allow engineers and road planners to support the selection of more social or environmental-friendly alternatives and to motivate this choice to the stakeholders with robust and quantitative arguments.

1.4.4 A support to engineers and road planners

To conclude, the proposed methodology that is developed in this thesis can be seen as the methodological framework for the preventive and multicriteria analysis of road alternatives at the design stage. This innovative approach may enrich the preliminary design process by increasing significantly the number of alternatives to be compared and by evaluating them on multiple criteria related to road safety and some environmental, social and economic aspects.

Additionally to the technical support that the proposed methodology may provide to the design engineers, such a methodological framework may also improve the communication with the stakeholders and the promotion of new and striking solutions. In particular, by integrating the preferences of different stakeholders in the multicriteria decision model, different profiles of alternatives could arise so that the best compromise between the actors of the project could be identified.

Chapter 2
Synthesis

2.1 Brief overview of the contributions

In this section, a brief synthesis of the thesis is provided. Each paper is described by focusing on the main results and conclusions.

2.1.1 Structuring the multicriteria road design problem (Contribution 1)

This contribution is available in the Chapter 3 of this manuscript. A preliminary paper that was submitted in the Proceedings of the IEEE conference is also available in the Appendix.

> Sarrazin, R. and De Smet, Y. (2015). *Applying multicriteria decision analysis to design safe road projects*. Accepted in: European Journal of Transport and Infrastructure Research, vol. 15(4), pp. 613-634, ISSN: 1567-7141.

As mentioned in the introduction, considering sustainable development and improving road safety have been two majors concerns in mobility and transport policies in Europe over the last decades. Several reports and directives were published by the European Commission about the improvement of the safety level on the European road network and strategies to apply in order to strive for a transport system more respectful of the environment. In Belgium, the Federal Commission for the Road Safety was formed in 2002 with the intent to fulfil the European objectives. During the last decades, several initiatives have been launched so that actions and campaigns have been conducted to make the road users sensitive to road safety issues. 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. Additionally, the quantification of the sustainable nature of road projects is not systematically provided at the design stage neither supported by integrated methods or guidelines.

As a consequence of this observation, this contribution relates to the structuring of the multicriteria road design problem. In particular, we aim to conduct a preventive assessment of road design alternative with regards to safety performances and some sustainable concerns. In order to do this, a new technical approach of sustainable road safety is defined and a complete set of 12 different criteria is developed (cf. Table 2.1). They are completely described in the Sect. 3.3.2 of the third chapter.

Table 2.1 List of criteria that represent the concept of sustainable road safety

Dimension	Code	Name
Infrastructure	INF1	Visibility of the infrastructure
Infrastructure	INF2	Road design and road safety equipment
Infrastructure	INF3	Quality of the road pavement materials
Infrastructure	INF4	Protection of the vulnerable roads users (VRU)
Infrastructure	INF5	Intersections
Infrastructure	INF6	Safety on road works
Services	SRV1	Information and intervention services[a]
Environmental	ENVI1	Reduction of greenhouse gases emissions
Environmental	ENVI2	Limitation of noise pollution
Social	SOC1	Ensure mobility of all
Economic	ECO1	Limitation of the construction costs
Economic	ECO2	Limitation of the maintenance costs

[a] Due to the complexity of this topic, the criterion was finally not developed

From a methodological point of view, the definition of this set of criteria was a strong challenge. It required to respect the constraint of using exclusively data and parameters that are available at the design stage. Among the parameters that may not be used at this stage, we may cite the real traffic volumes and composition resulting from counting campaigns, the operational speed on the roadway, accident statistics, *in situ* pavement assessment data, data from noise measurement campaigns, etc. At the same time, it was crucial to ensure the precision of the criteria evaluation to support the identification of discriminated and efficient solutions. For that purpose, an important stage of creation and modeling of data was necessary. The key factors and parameters related to each criterion were then identified.

The application of the proposed multicriteria model to an illustrative case study has shown the interest of using such an approach (cf. Sect. 3.4). A simple road design problem was considered so that 10 different alternatives were defined and evaluated on a restricted set of 6 criteria due to the nature of the problem and the availability of the data. We applied the PROMETHEE II method to characterise the problem and identify performing solutions. It allowed us to observe the diversity of profiles among the best solutions and the relative robustness of the final ranking regarding the preferences of the DM.

2.1.2 Identification of non-dominated solutions (Contribution 2)

This contribution is available in the Chapter 4 of this manuscript.

> Sarrazin, R. and De Smet, Y. (2015). *Design safer and greener road projects by using a multi-objective evolutionary approach*. Accepted in: International Journal of Multicriteria Decision Making, 15(Z):xxx-yyy.

Once a complete set of criteria has been developed, the next step was to identify all efficient solutions of the problem. However, due to the combinatorial aspect of the road design problem and the nonlinear nature of the criteria, the development of an exact algorithm seemed to be unrealistic. In this contribution, we have studied how the use of a multiobjective evolutionary algorithm may help in the identification of Pareto optimal solutions.

We used the multiobjective evolutionary algorithm NSGA-II. It is presented in the Sect. 4.4.2 of the fourth Chapter of this manuscript. The main idea of this genetic algorithm lies in the iterative improvement of a limited subset of solutions by applying successive crossover and mutation operations. When the model converges, the set of non-dominated solutions is finally identified. Table 2.2 contains the results of the simplified problem introduced in the Section 4.4.1 of the Chapter 4. The initial population was composed of 50 alternatives randomly selected and 50 generations have been conducted in NSGA-II. A limited set of 8 criteria has been considered. The respect of the maximum width available was set as the only constraint of the model. At the end of the process, we observe that 186 non-dominated solutions have been identified. Considering the size of the population and the number of generations, we finally analysed a problem of 2500 solutions which corresponds to only 0.1% of the complete set. This remarkable reduction of the decision space points out the strong interest of using a multiobjective evolutionary approach to handle road design problems.

The interesting results shown in Table 2.2 illustrate the utility of using a multiobjective evolutionary algorithm to characterise the properties of the problem. It allows us to identify an approximate set of non-dominated solutions in a limited calculation time, so that it is particularly efficient when dealing with large and complex decision problems. However, it is crucial to analyse the quality of the approximate set at the end of the evolutionary process in order to ensure the reliability and validity of the final results. To this purpose, we analysed the properties of the design space and the quality of the approximate set of non-dominated solutions by using

Table 2.2 Amount of Pareto solutions obtained after applying NSGA-II

Variables	Values	Description (unit)
alt	2350080	Total amount of feasible alternatives
initial_pop	50	Size of the initial population for NSGA-II
gen	50	Number of generations in NSGA-II
time	25.8	Time required to compute the Pareto frontier (s)
pareto_sol	**186**	**Size of the approximate Pareto front**

performance indicators. We used classical indicators from the literature in order to evaluate the convergence of the model (cf. Sect. 4.5.1), the diversity of the non-dominated solution set (cf. Sect. 4.5.2) or both convergence and diversity (cf. Sect. 4.5.3) [99].

The evaluation of the model with performance indicators allowed us to describe the properties of the design space. In particular, we verified that the solutions of the approximate set were both well-performing and diversified. This demonstrates the methodological interest of applying the NSGA-II algorithm to our multicriteria problem. To conclude, let us note that the aim of this contribution was neither to parametrise completely the multiobjective evolutionary algorithm nor to identify the most efficient one regarding the nature of the problem, but to present a proof of concept that demonstrate the interest of using such an approach in road design assessment (cf. Sect. 4.6).

2.1.3 Development of an interval clustering technique (Contribution 3)

This contribution is available in the Chapter 5 of this manuscript. Note that this paper has been submitted to the European Journal of Operational Research in September 2015 after a major revision.

> Sarrazin, R., De Smet, Y. and Rosenfeld, J. (2014). *An extension of PROMETHEE to interval clustering*. Technical Report TR/SMG/2014-009, CoDE-SMG, Université libre de Bruxelles, December 2014.

When dealing with large multicriteria problems with several criteria, the nature of the Pareto front may be so complex that decision making can be very difficult (even impossible). To tackle this issue and support the DM in solving their multicriteria problems, it is crucial to simplify the decision process. In this contribution, we developed the PCLUST model that is an extension of the PROMETHEE method to interval clustering (cf. Sect. 5.2.3).

The proposed model is based on the principles of FlowSort (cf. Sect. 5.2.2) and PROMETHEE methods (cf. 5.2.1). It is completely described in the Sect. 4.3 of the present manuscript. The aim of this model is to solve a multicriteria clustering problem by defining a set of categories κ^* that could be divided in two groups: the principal categories C_i and the interval categories $C_{i,j}$, $\forall i,j \in \{1 \dots K\}$ and $i \neq j$. The principal categories are ordered and respect the dominance condition (cf. Condition 1 in Sect. 4.2.2) while the interval categories $C_{i,j}$ are located ”between” the principal categories C_i and C_j. Considering the preference relation of PROMETHEE, it means that the profile $r_{i,j}$ is incomparable with r_i and r_j.

In this contribution, we have studied the impact of three different update functions (cf. Sect. 5.3.3) and two initialization strategies (cf. Sect. 5.3.1) on the final distribution of the clustering. The validation of the model was conducted on two structured data sets from the literature, as described in Sect. 5.4. In particular, we analysed the quality of the clustering distribution (cf. Sect. 5.4.1), the convergence of the model (cf. Sect. 5.4.2) and the stability of the clustering procedure (cf. Sect. 5.4.3). Interesting results were globally observed.

So, we decided to compare the performances of the proposed model with the well-know k-means procedure [9, 11, 65] and the P2CLUST model [24] that is the first extension of PROMETHEE II to totally ordered clustering. The results are shown in the Section 5.5. In particular, we observed particularly good results of the PCLUST model with regards to the quality and stability of the clustering distribution. As regards the convergence of the model, PCLUST obtains acceptable results even if it requires slightly higher calculation time in comparison with the P2CLUST model.

In the field of decision aid, the proposed interval clustering model seems to bring an interesting added-value to support the solving of particular multicriteria problems. Indeed, the interval categories give a different information compared to the principal categories. The particular nature of the interval categories may help the DM to identify alternatives with a singular profile. In real-world multicriteria problems such as the road design problem, we assume that the data distribution promotes the use of multicriteria interval clustering.

2.1.4 Practical application to a case study (Contribution 4)

This contribution is available in the Chapter 6 of this manuscript. This paper has been accepted for publication as a Chapter of the book “Multiple Criteria Decision Making: Applications in Management and Engineering” (Springer) in November 2015.

Sarrazin, R. and De Smet, Y. (2015). “Solving a multicriteria road design problem: a practical example”. In: *Technical Report TR/SMG/2015-00X*, CoDE-

SMG, Université libre de Bruxelles, September 2015.

The final contribution of this work relates to the application of the complete methodology to a practical case study. The main aim was to illustrate practically how the proposed methodology could assist decision makers in addressing the road design problem. The case study we have analysed concerns the reconstruction of the national road N243a in the rural area of Walhain in Belgium. Its complete description is given in the Sect. 6.4.1 of the Chapter 6.

In order to solve the road design problem of the N243a, we applied successively the multiobjective evolutionary algorithm and the interval clustering model that we introduced in the previous contributions. First, we defined the parameters and constraints of the project in order to support the definition of the alternatives of the multicriteria problem (cf. Sect. 6.4.1). Next, we used the NSGA-II algorithm to identify an approximate set of non-dominated solutions (cf. Sect. 6.4.2). Finally, we handled the solving of the multicriteria decision problem by using the PCLUST model (cf. Sect. 6.4.3).

The application of the multiobjective evolutionary algorithm to the design problem of the N243a rural road allowed us to identify an approximate set of 169 non-dominated solutions among more than 2×10^6 possible designs. To support the DM in the identification of the alternatives that would be the most performing and adapted to the constraints and distinctive features of the project, we used the PCLUST model. We arbitrarily set the number of clusters to $k = 10$. Table 6.5 shows the evaluations of the reference profiles of each principal category of the clustering structure. The complete clustering distribution is available in Sect. 6.4.3. A good distribution of the solutions within the different clusters was globally observed.

Table 2.3 Objective functions values of the reference profiles r_i ($k = 10$)

	INF1	INF2	INF3	INF4	INF5	ENVI1	ENVI2	ECO1
r_1	1.000	0.162	1.852	5.627	1.000	4.2552	2.6957	$7,14 \times 10^4$
r_2	1.000	0.173	1.852	5.671	1.000	4.2582	2.6957	$9,99 \times 10^4$
r_3	1.000	0.176	1.852	7.000	1.000	4.2653	2.6957	$1,36 \times 10^5$
r_4	1.109	0.211	1.852	11.000	1.066	4.2659	2.6957	$1,67 \times 10^5$
r_5	1.205	0.256	1.852	23.538	1.154	4.2670	2.6957	$1,99 \times 10^5$
r_6	1.421	0.282	1.852	28.667	1.316	4.2685	2.6957	$2,17 \times 10^5$
r_7	1.556	0.341	1.852	33.579	1.833	4.2696	2.6957	$3,25 \times 10^5$
r_8	1.667	0.343	1.859	40.125	2.000	4.2697	2.6957	$4,62 \times 10^5$
r_9	2.000	0.388	1.880	40.750	2.000	4.2703	2.6998	$4,91 \times 10^5$
r_{10}	2.152	0.491	2.083	45.112	2.000	4.2710	2.7098	$1,27 \times 10^6$

The analysis of the Table 6.6 indicates that several design options were represented. The local and variable parameters of the N243a design project are described in Tables 6.1 and 6.2 in the Section 6.4.1 of the related contribution. When focusing on the roadway lanes (width and number), many configurations are represented : 2×2.5, 2×3.0, 2×3.5. In addition, four different solutions for the cycling equipment are also represented and correspond to a mixed traffic on the roadway ($cp\_nat = 1$), a marked lane on the roadway ($cp\_nat = 2$) and a cycle lane separated from the roadway without physical separation ($cp\_nat = 6$) or delineators ($cp\_nat = 7$). Similarly, the nature of the equipments for the road signs and the marking differs from a category to another. However, the maximum speed limit is set to 50 km/h for each representative solution, essentially because we did not considered the mobility criterion in this example (mainly due to a lack of data that are necessary to compute this objective function).

Table 2.4 Decision variables values of a the non-dominated solutions that are the closest to the reference profiles of each non-empty principal category of the clustering structure

C_i	id	w_l	n_l	w_{sh}	b_{sh}	cp_nat	w_{med}	mat_nat	r^a	m^a	l^a	it^a	v
C_2	130	2.5	2	3	0	7	0	6	2	2	3	3	50
C_3	19	3.5	2	3	0	6	0	6	2	2	3	3	50
C_4	67	2.5	2	3	0	7	0	6	2	1	3	3	50
C_5	158	2.5	2	3	0	6	0	6	1	2	3	1	50
C_6	114	3.0	2	3	0	7	0	6	2	1	3	1	50
C_7	107	2.5	2	1	0	1	0	6	2	1	3	1	50
C_8	163	3.5	2	1	0	2	0	6	1	1	3	1	50

[a] r = rsign ; m = marking ; l = lighting ; it = intertype

Consequently, based on the results of the multicriteria clustering problem, we were able to identify that a performing solution for the reconstruction of the N243a should consider an efficient and safe cycling facility (with a physical separation from the roadway). In addition, the better are the road signs, marking and lighting equipments, the better is the global performance of the designed solution. Moreover, we observed that the construction of wide shoulders was strongly recommended. However, increasing the operational speed limit appeared to be unnecessary. These first conclusions provide the basis for a strategic discussion between the DM and the others actors of the project at the end of the pre-design stage. In particular, they convey preliminary information and guidelines to refine the search of a performing and consistent solution (e.g. by eliciting the weights associated to each criterion more precisely). The design of a road project may then be considered as an iterative process that would involve the different actors of the project at the end of each stage. This would support the development of performing compromise solutions.

2.2 Discussion

The development of the methodology that we describe in this work has led to numerous methodological and practical interesting observations. Among them, the application of the proposed methodology to a real example pointed out the interest of applying such a strategy to address the road design problem (cf. Sect. 6.5). We assume that considering the preliminary design process as a combinatorial optimisation problem evaluated on a complete set of criteria constitutes the first added-value of this work (cf. Sects. 3.3.2 and 3.3.3). In addition, the combined use of a multiobjective evolutionary algorithm (cf. Sect. 6.4.2) with a multicriteria interval clustering technique (cf. Sect. 6.4.3) leads to our point of view to promising results. This seems to be efficient and appropriate to handle, characterise, simplify and finally solve large and complex multicriteria decision problems.

Nevertheless, each contribution of the proposed approach is based on a number of hypotheses, constraints and limits that we should analyse to motivate the validity and reliability of the methodology on the one hand, and to identify the prospects for further research on the other hand. In the following section, we describe successively the hypotheses of the proposed methodology, the limits resulting either from these hypotheses or from the nature of the problem, and the validation procedures that ensure the overall pertinence of the methodology. Finally, some perspectives are presented in the following Section.

2.2.1 Hypotheses

As mentioned in the introduction of this Chapter, the proposed methodology is composed of 4 main *blocks* that are separated into two *frameworks* (cf. Fig 1.1). The first framework contains the analysis of the road design problem from a combinatorial optimisation perspective while the second relates to the methodological development of an interval clustering algorithm. Therefore, even if the structure of the proposed approach is not strictly linear, interactions exist between these two frameworks so that the global methodology forms a coherent whole. However, before we describe the reliability of the approach and the consistency of the results, it is crucial to first focus on the hypotheses of the different *blocks* of the methodology.

Structuring the multicriteria road design problem

First, when structuring the multicriteria road design problem, we stated numerous hypotheses both for defining the criteria and describing the design process as a combinatorial optimisation problem (cf. Sect. 3.3). To constitute the set of criteria, we conducted an intensive review of the literature on several technical topics such as road design process, road safety assessment, secondary rural roads, sustainable safety, road pavement materials, legibility and visibility of the infrastructure, protection of vulnerable road users, or even configuration of intersections. In order to consider the sustainable nature of road infrastructure projects, we also focused on the preliminary developments in sustainable safety and on complementary studies about road emissions, noise pollution, societal acceptability, accessibility of the road network or even economic performances (cf. Sect. 3.3.2). A large part of the references we used are cited in the second Chapter of this work. They are composed of national and European research reports, scientific papers, academic works, standards and guidelines, manuals, technical reports and statistics databases. Table 2.5 describes the nature of the criteria that structure the road design problem.

Table 2.5 Nature of the criteria that represent the concept of sustainable road safety

Criteria[a]	Evaluation	Nature	Scale	Units
INF1	Qualitative	Discrete	Ordinal	-
INF2	Quantitative	Non-linear	Ratio	Acc.[b] per veh.km
INF3	Qualitative	Discrete	Ordinal	-
INF4	Quantitative	Non-linear	Ratio	-
INF5	Qualitative	Discrete	Ordinal	-
INF6	Quantitative	Non-linear	Ratio	Acc.[b] per km.day
SRV1	Qualitative	Discrete	Ordinal	-
ENVI1	Quantitative	Non-linear	Ratio	μg per m^3.year[c]
ENVI2	Quantitative	Non-linear	Interval	dB(A)[c]
SOC1	Quantitative	Discrete	Ordinal	Level of service
ECO1	Quantitative	Linear	Ratio	Euros
ECO2	Quantitative	Linear	Ratio	Euros

[a] Refer to Table 2.1 for further information
[b] Acc. = Accidents
[c] Normalized

Complementary, several discussions were organized with experts and actors of the road sector. Those allowed us to criticize the criteria of the proposed set, to refine some of them, or even in a few case to develop new objective functions. Regarding the content of the criteria, we may refer to the profitable talks and share of technical resources with the scientific staff of the Belgian Road Research Center which continuously provided this work with interesting inputs. In particular, let us cite the numerous interactions with X. Cocu, W. Debauche, F. Debelle, O. Van Damme, K. Redant and L. Goubert. In addition, a 3-month internship at the German Federal Highway Research Institute (BASt) allowed us to take advantage of their expertise in the field of road safety assessment and transportation research (K-J Höhnscheid, A. Lüdeke, H. Holdik). The preliminary developments of this work were also regularly presented during the Technical Committee in Road Safety organized by the Belgian Road Research Center. Finally, our involvement in other research projects for the duration of this work developed our knowledge of topics such as safety at roadworks, noise pollution and road traffic emissions. Regarding the methodological nature of multicriteria analysis, we benefited from the strong expertise of the researchers of the CoDE-SMG laboratory. In particular, many interesting outputs resulted from discussions and research collaborations with Y. De Smet, A.V. Doan, S. Eppe, J. Rosenfeld, K. Lidouh, D. Van Assche and M. Bagheri. Additionally, this work was regularly presented in international conferences and European working groups in multicriteria decision analysis.

About the definition of the alternatives, the main methodological hypothesis is to consider the road design process as a combinatorial optimisation problem (cf. Sect. 3.3.3). Indeed, we define a set of actions $a_i \in A$ from a finite set of variables $X = \{x_1, ..., x_m\}$ and the sets of domains $D_i = \{d_1, ..., d_p\}$ that are associated to each variable x_i. In this problem, each domain is constituted of a finite number of elements (but they could be infinite). The size of the decision space corresponds to the cartesian product of all the domains $A = D_1 \times D_2 \times ... \times D_m$. Hence, the cardinality of A can be potentialy very large while it increases exponentially with the number of variables. To solve the combinatorial problem, we aim to identify a discrete set of solutions $S \subset A$ which minimise[1] the evaluations of each objective function. If the combinatorial optimisation problem is solved under constraints, we must define those in the problem so that the set S is strictly composed of *feasible* solutions.

The combinatorial nature of the studied problem allows us to parametrise completely the design process and to generate easily all the alternatives of the road project. In order to respect the feasibility of the alternatives, let us note that we define a constraint related to the maximum width available (i.e. road right-of-way). The local and variable parameters of a *classical* road project were identified by analysing the recurrent parameters in the objective functions and by consulting the guidelines and technical manuals about road design. In addition, a few meetings were organized with design engineers and road planners of the Walloon Region in order to conduct a complementary field survey about the data that are available and the parameters that are usually considered at the preliminary design stage.

Identification of the non-dominated solutions

Due to the size of the multicriteria road design problem and the non-linear and complex nature of some criteria of the set, solving the problem with an exact method seems to be highly intractable. To tackle this issue, we decided to use a multi-objective evolutionary approach to characterise the problem and identify the non-dominated solutions (cf. Sect. 4.4). The selection of the NSGA-II algorithm was done mainly because of the good referencing of this method in the literature, its good performances when handling problems with numerous objectives, the possibility of integrate constraints, and the fact that NSGA-II is able to deal with discrete

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[1] In this problem, the optimal solution is the solution that minimise all the objective functions

and continuous evaluations of the criteria (which is the case in our problem).

Concerning the parametrisation of the algorithm, we used classical genetic operators from the literature (i.e. *Simulated Binary Crossover* and *Polynomial Mutation*) (cf. Sect. 4.4.2). The value of the spread factor as well as the probabilities of crossover and mutation were defined on the basis of values that are frequently found in the literature.

Development of an interval clustering technique

The development of the PCLUST model follows on from the preliminary work that was made on the extension of PROMETHEE II to totally ordered clustering in the CoDE-SMG laboratory [24]. This is a methodological contribution in multicriteria clustering analysis but clear interactions exist with the road design combinatorial problem that we are dealing with. In particular, we assume that such an approach may simplify the multicriteria problem so that it may help the DM in the identification of the representative solutions of the (approximate) Pareto front. The originality of this approach lies on the use of preference information among alternatives given by the PROMETHEE I method to solve the multicriteria interval clustering problem (cf. Sect. 5.2.3). This limits the loss of preference information during the solving process so that it ensure the global quality and reliability of the final clustering distribution.

For the algorithm of the proposed model, we decided to use the PROMETHEE methods because of the great expertise of our laboratory regarding this methodology (cf. Sect. 5.2.1). The PROMETHEE methods were developed at the ULB by J.P. Brans in the early 80s and since then, the CoDE-SMG laboratory remains very active in multicriteria decision research, particularly in the developments of this method.

In the PCLUST model, we developed three different functions to update the reference profiles (cf. Sect. 5.3.3) and two initialisation strategies (cf. Sect. 5.3.1). The main difference between these functions lies on the nature of the information that is used to update the reference profiles. In the first update function *Upd1*, the alternatives that belong to the interval categories are only considered to update reference profiles of extreme and empty principal categories. This restrictive use of the preference information from the interval categories is justified by the singular nature of the alternatives that belong to these *in-between* categories. To our point of view, the interval categories mostly contain alternatives with complex profiles i.e. alternatives that have some evaluations that are too good to authorize an assignment to a given category but some others that are too weak to authorize an assignment to a better one. From a decision making perspective, knowing the existence and the composition of these interval categories constitute an informative output but we assume that the composition of the best principal categories (or category) would most probably be the most interesting knowledge for the DM. On the basis of these observations, we decided to update the reference profiles of the principal categories as far as possible with the evaluations of the alternatives that belong to these categories. In the second update function *Upd2*, we refined the assignment rule of the extreme and empty principal categories by only considering the alternatives from the interval categories that are the *"closest"* (regarding the net flows) to the considered principal category. In the third function *Upd3*, we simply extended the application of this rule to the non-extreme and empty principal categories.

Practical application to a case study

Most of the hypotheses of this contribution were cited in the previous Sections. Regarding the application, we defined the local parameters of the project on the basis of all the data we get about the N243a rural road (cf. Sect. 6.4.1). Recently, a precise analysis of the project was conducted at the Belgian Road Research Center training session for road safety auditors so that many data were available, among which the traffic volumes and composition, intersection configuration, presence of obstacles along the roadway, etc. The variables were set so that their values were technically relevant (e.g. lane width of 2.5, 3 or 3.5 m).

In this practical road design problem, we did not consider the criteria about the safety at roadworks, the intervention services, the mobility performance on the infrastructure and the maintenance costs (cf. Sect. 6.4.2). This is mainly due to lack of information and data about these concerns on the N243a project. Consequently, we preferred not to evaluate the alternatives on these criteria rather than evaluate them with inconsistent values.

Finally, when applying the interval clustering model, we decided to set arbitrarily the number of categories to 10 (cf. Sect. 6.4.3). This seemed to be a good compromise between the number of alternatives of the set (169) and the maximum size of the clustering structure that we may allow to give a sound and useful output to the DM.

2.2.2 Limits

Structuring the multicriteria road design problem

Concerning the definition of the set of criteria, we consider that it constitutes a promising added-value in the field of road design regarding the state of the art in preventive safety assessment. However, some criteria of the set still suffer from approximations (cf. Sect. 3.3.2). In particular, some evaluations remain imprecise or highly qualitative, mainly due to an important lack of information or knowledge about several topics related to the preventive assessment of road safety. For instance, the evaluation of roadway elements and equipments regarding the visibility remains an unexplored research area, so that we had to define an ordinal scale on the simple basis of our own expertise. Concerning the evaluation of the economic performance of road projects, precise data are not always available (or very difficult to obtain due to privacy reasons) so that the evaluation is quite rough at this stage. Then, given that this approach relates to the assessment of road project at the preliminary design stage, this relative imprecision in the evaluation of some criteria does not question the global relevance of the proposed approach, but it should be seriously taken into consideration when analysing the final solutions or allocating the weights to the criteria.

In addition, among the approximations of the proposed set of criteria, we may cite the calculation method of the criteria INF1, INF3 and INF5 (cf. Sect. 3.3.2). Those measures the average performance of a set of elements by considering the arithmetic mean of their evaluations. However, considering that each element is evaluated on the basis of an ordinal scale, we might wonder about the precision of this aggregation procedure. In particular, the phenomenon of compensation between *good* and *bad* values should be carefully analysed.

Another limit of the structuring stage lies on the nature of combinatorial design problem (cf. Sect. 3.3.3). Due to the methodological constraint of the proposed approach that is to use exclusively the design parameters of road project to define the criteria and alternatives of the design problem, it is very complex to handle the specific nature of a given road project with our methodology. Consequently, the proposed approach must be considered as a high-level description of the road project performances at the preliminary design stage. Given that it is not obvious how to *generalize* the preventive evaluation of road safety for every project, most of the criteria have then been defined on the basis of systemic features.

Identification of the non-dominated solutions

Concerning the implementation of the multiobjective evolutionary algorithm to the road design problem, we faced some difficulties when considering decision variables with discrete values in NSGA-II. Due to the construction of some objective functions, continuous variables were not acceptable. To tackle this issue, we had to develop some corrective operators in the algorithm that we applied after the mutation of the solutions. This allowed us to ensure the reliability of the solutions that were generated by the NSGA-II algorithm, but it most probably affect the efficiency of the model regarding the diversity of the Pareto frontier.

In addition, some problems may arise when using multiobjective genetic algorithms in real-world engineering optimisation problems with a large number of complex objective functions and constraints. The identification of a good approximate set may cost a lot of computational time or require complex genetic operators to define feasible solutions. Concerning the quality of the approximate set, we may have difficulties to maintain the diversity of the Pareto front solutions due to the discrete nature of the front or the non-uniform distribution of the solutions [28]. Consequently, we may question the pertinence of using such an approach if we aim to further improve the objective functions of the set of criteria - or eventually to add new criteria in the set.

Finally, let us note that the multiobjective algorithm was completely developed in MATLAB due to its ease of use, interactive environment and large referencing. Nevertheless, from a computational perspective, this high-level language is not the most efficient. If we aim to apply the proposed methodology to bigger problems with a more complex structure, it may be worthwhile to export the model on other languages such as C++.

Development of an interval clustering technique

The use of an interval clustering technique in order to provide a simplified representation of complex multicriteria data sets had led to promising and interesting results. However, a number of limits or challenges must be mentioned. First, the definition of the number of categories remains a tedious task when addressing the multicriteria clustering problem. In the proposed approach, we analysed the quality of the clustering distribution depending on the number of categories and we clearly observed strong differences (cf. Sect. 5.4.1). In particular, the best quality of clustering was always observed for the EPI[2] and CPU[3] data sets with the lowest number of categories while it is not intuitively obvious regarding the maximisation of the homogeneity intra-category. Consequently, the definition of the number of categories may have a strong influence on the global quality of the final clustering distribution. Given that the aim of such an approach is to support the DM in the simplification of the decision process, it may be questionable to let him select arbitrarily this number.

Moreover, the analysis of three different update procedures for the PCLUST model pointed out the limited interest of using the preference information from the interval categories (cf. Sects. 5.4.1, 5.4.2 and 5.4.3). This observation probably needs to be confirmed by further research and by testing the model on data sets with a more complex structure. In addition, we studied the impact of the equidistributed and random initialization strategies on the performance of the model. It emerges from this analysis that the equidistributed initialization of the reference profiles led to more stable clustering while the random initialization allows the model to converge faster. Again, it may be worthwhile to analyse more precisely these observa-

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[2] Environmental Performance Index 2014

[3] Central Processing Units evaluation from the UCI repository

tions on additional data sets with different structures and sizes.

Regarding the global quality index, if the calculation of the penalties seems to give relevant and consistent results, all the pairwise comparisons between alternatives and reference profiles are not considered (cf. Sect. 5.4.1). In particular, we do not consider the penalties calculation between the alternatives of an interval category and the reference profiles of principal categories that have no relation with the latter. Also, we do not consider the penalties calculation between the alternatives of an interval category and the reference profiles of others interval categories. Given that the dominance relation should always be verified due to the construction of the categories, this might not alter the calculation of the global quality index. However, we decided not to consider these specific pairwise comparisons due to the difficulties we encountered to define the related penalty rules.

Similarly to the multiobjective algorithm, the PCLUST model was completely developed in MATLAB. To compute our problem, the computation times and efficiency were not very good. It may then be worthwhile for further research to export the model on other languages. It may certainly improve its computational performances and allow us to handle efficiently more complex clustering data sets.

Finally, we may consider that the use of PROMETHEE constitutes in some way a limit of the interval clustering model (or at least a challenge). Indeed, this requires a relative expertise from the DM to select the preference functions for criteria and to define the preference and indifference thresholds. In particular, the use of the difference of the evaluations may induce some difficulties for a DM that is not familiar with the PROMETHEE methods.

Practical application to a case study

If the proposed methodology conveys interesting information to the DM at the end of the preliminary design stage, some limits exist regarding its application to a practical example. Those mainly refer to the relative imprecision of the results. The number of variables is quite limited at this stage and their interpretation is relatively macroscopic so that the final output may not give inspiring information to the DM (cf. Table 6.6 in Sect. 6.4.3). To our point of view, it would be interesting to refine the criteria of the problem in order to identify more precisely which are the parameters that affect the performances of the road design alternative (and how they do). By doing so, we might enrich the list of variables of the problem, and consequently the quality of the final outputs of the combinatorial optimisation problem might be improved. In particular, we might imagine that some of the distinctive features of road design projects could be taken into consideration.

2.2.3 *Validations*

Structuring the multicriteria road design problem

As previously mentioned in the Sect. 2.1.1 of this Chapter, the definition of the criteria was supported by a large literature review and by some discussions with design engineers, road planners, researchers and experts in the fields of road safety assessment, noise pollution quantification, environmental impact of roads, protection of vulnerable road users, mobility, multicriteria decision analysis or even transport research. All these interactions allowed us to analyse the proposed approach and to identify its actual limits. From a methodological perspective, the multicriteria problem is consistent and reliable but the precision of its results is restricted due to the nature of some criteria.

Concerning the definition of the alternatives, we applied a top-down approach from the review of the different topics related to sustainable road safety to identify which are the key parameters of a road design alternative (i.e. the parameters that influence the performances of the road design project). Then, we applied a bottom-up strategy from the analysis of practical case studies - and discussions with design engineers and road planners - to stress which are the recurrent parameters in road design projects, which data are available, which parameters are considered as local or variable elements, etc. This complementary approach allowed us to structure the set of local and variable parameters of the multicriteria road design problem that constitute the basis of the combinatorial optimisation approach.

Finally, note that the content of this work had been regularly presented throughout the PhD thesis in international conferences, working groups and workshops such as MCDM 2011, 2013 and 2015[4], IEEM 2011[5], MCDA 74 and 76[6], ORBEL 28[7], IMW 2014 and 2015[8], OPDE 2013[9], BIVEC-TRD 2013[10]. We also participated in two Doctoral Schools[11] and we did a 3-month internship at the Federal Highway Research Institute. Those numerous presentations allowed us to appraise the validity and pertinence of our developments in front of experts and researchers from the fields of multicriteria decision analysis, road safety analysis and transport research.

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[4] 21st, 22nd and 23rd International Conference on Multiple Criteria Decision Making

[5] International Conference on Industrial Engineering and Engineering Management 2011

[6] European Working Group on Multicriteria Decision Aiding 74 and 76

[7] 28th Conference of the Belgian Operations Research Society

[8] 1st and 2nd International MCDA Workshop on PROMETHEE

[9] Colloque Outils Pour Décider Ensemble 2013

[10] 2013 Benelux Interuniversity Association of Transport Researchers - Transport Research Day

[11] Cost IC0602 International Doctoral School 2011 and MCDM Summer School 2013

Identification of the non-dominated solutions

Given that we have completely developed our code for the computation of the genetic algorithm, we wanted to verify the reliability of the results given by our algorithm. For that purpose, we computed several benchmark tests. We applied the algorithm on smaller decision problems so that we solved them both exactly and by using our metaheuristic. The characterisation of the approximate Pareto frontier from the analysis of performance indicators was then facilitated. In particular, we used the hypervolume metric in its binary form (cf. Sect. 4.5.3). It measures the portion of the graph that is dominated by the exact Pareto frontier but not by the approximate one. This metric has to be minimized so that the closest is the ratio to 0, the better is the approximate front. Figure 2.1 shows the results obtained on this binary hypervolume metric during one of our benchmark test. We clearly observe that the hypervolume metric completely converges after 30 generations which highlights the reliability of the results and the validity of the genetic algorithm.

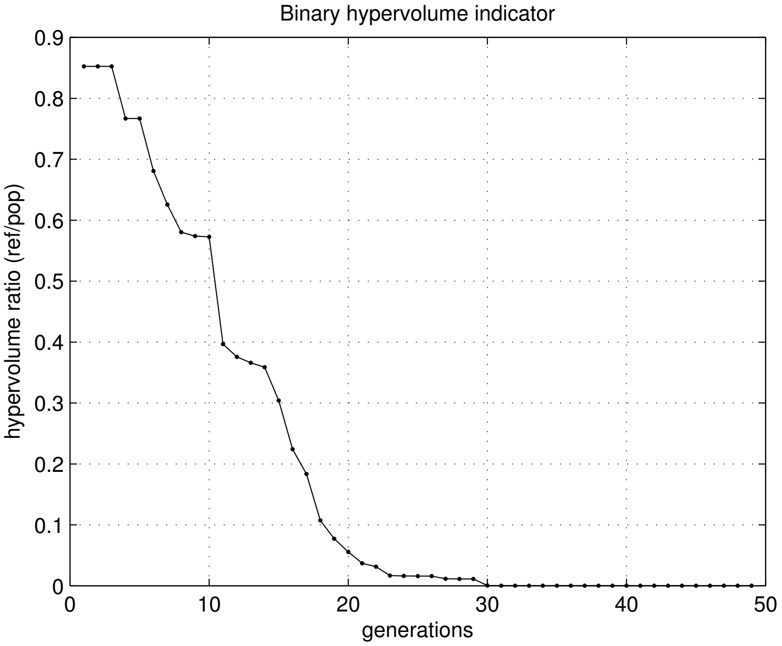


Fig. 2.1 Evolution of the binary hypervolume values with the number of iterations of NSGA-II.

Development of an interval clustering technique

In order to analyse the PCLUST model, we defined our own performance metrics (quality, stability, convergence) while no work has ever been done previously - to our knowledge - on interval clustering. To measure the quality of the clustering distribution, we defined a quality index that is based on the calculation on inconsistent assignment penalties (cf. Sect. 5.4.1). Concretely, it is commonly accepted in the field of multicriteria clustering that a high quality clustering would assign the alternatives to the categories so that the inter-distance between the categories is the highest and the intra-distance within each category is the lowest. This common rule refers to the homogeneity intra-category and the heterogeneity inter-categories. Concerning the interval categories, we assume that they should be at *"equal distance"* from the principal categories they are associated with. In that case, the notion of distance between two alternatives is related to their preference index. The most the alternatives are similar, the lowest is the value of the preference index (i.e. the *"closest"* are the alternatives). The calculation of the penalties intra- and inter- principal categories is quite obvious, while it simply considers a strong dominance relation. Concerning the calculation of the penalties between alternatives that belong to an interval category and the reference profiles of the associated principal categories, we consider that we should be in a situation of equi-preference (i.e. the two reference profiles are equally preferred regarding the preference index).

The calculation of the convergence of the model is simply based on the number of runs and calculation time that are necessary to converge. The quantification of the differences in the clustering distribution between two successive iterations (cf. Fig. 5.6 in Chapter 5) is used to observe the shape of the convergence process.

About the stability of the clustering procedure, we decided to calculate the proportion of occurrence of the most represented clustering distribution after 100 runs of the model (cf. Sect. 5.4.3). This gives a first information about the global performance of the model regarding the stability of the clustering. Then, we completed this metric with the calculation of the percentage of dissimilarity between the most represented clustering distribution and the other ones. This notion of dissimilarity considers any assignment differences of every alternatives between two distributions (but not the intensity of this difference). The percentage of dissimilarity allows us to quantify the importance of the difference between the different distributions obtained by the model. Consequently, we might define a percentage of dissimilarity that is satisfying regarding the stability (e.g. between 1 and 5%) so that two distributions with a small proportion of assignment differences might be considered as similar.

In addition, we decided to compute the validation process of the PCLUST model by applying the proposed algorithm to two data sets from the literature that are *a priori* structured for totally ordered clustering (cf. Sect. 5.4). The CPU data set was used in its original form. Concerning the EPI data set, the aggregated version on two criteria was used. The use of structured data sets from the literature allows use to analyse the performances of the model on real-world problems. To our point of view, this contributes to the global reliability of the validation process. Indeed, we might have designed a virtual data set with a structure more compatible with interval clustering, but we assume that it would have induce subjectivity (or at least suspicion of subjectivity) regarding the validation of the proposed model. Moreover, the parametrisation of the multicriteria problem regarding the preference functions (i.e. definition of the indifference and preference thresholds) was made by considering common practices and by analysing the data of each problem. The weights of the EPI data set correspond to the real weights while equal weights were arbitrarily considered for CPU due to the lack of information.

Finally, we concluded the validation process of the PCLUST model by comparing its performances with the *k*-means procedure and the P2CLUST model formerly developed (cf. Sect. 5.5). The use of the *k*-means algorithm was strictly illustrative while it is not a relational clustering technique. The aim was also to point out that even if the structure of PCLUST seems similar to *k*-means, the differences in the assignment rules lead to completely different clustering distributions. Concerning the comparison with the P2CLUST model, the main motivation was to compare an extension of PROMETHEE to multicriteria relational clustering. This is precisely why we did not considered the PROMETHEE CLUSTER method while it is a non-relational multicriteria clustering technique. As an illustration of this difference, Figure 2.2 shows the results of the P2CLUST (left) and PROMETHEE CLUSTER (right) algorithms applied to a virtual bi-objective problem. We clearly observe that the P2CLUST model generates a clustering distribution that support an ordered structure while the PROMETHEE CLUSTER algorithm partitions the decision space without considering the preferential relation between alternatives.

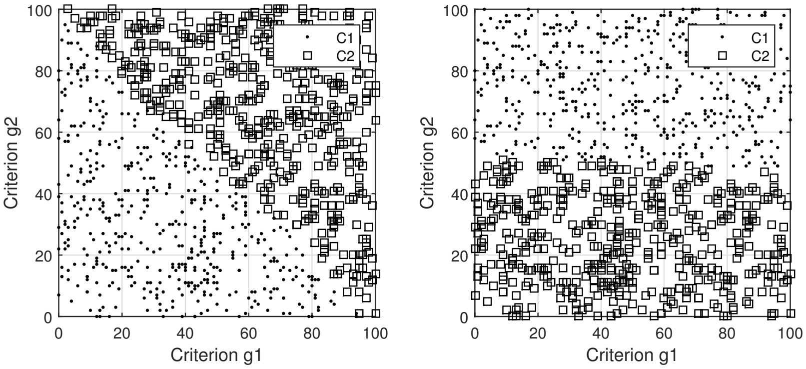


Fig. 2.2 Clustering distribution of the alternatives in the decision space after applying P2CLUST (left) and PROMETHEE CLUSTER (right) to a simple bi-objective problem.

2.3 Perspectives and conclusions

In this work, we presented an *multidisciplinary approach* that gathers knowledge, material and models from the fields of multicriteria decision analysis, multiobjective optimisation and multicriteria clustering. The analysis of these numerous subjects allowed us to identify and suggest beneficial connections between them. This led to the development of the proposed methodology that we assume to be added-values in the fields of road design assessment and multicriteria decision analysis.

As part of road design assessment, the combinatorial nature of the proposed approach allowed us to enrich the preliminary design process by expanding the size of feasible solutions to a significantly higher number. In addition, the integration of the problem into a multicriteria decision approach might encourage the identification of more efficient and *customised* solutions considering the constraints and distinctive features of each project. The combined use of a multiobjective evolutionary algorithm and a multicriteria clustering technique support respectively the handling of the expanded design problem and the identification of representative solutions to solve the multicriteria decision problem.

However, we identified some limits in the different steps of the proposed methodology that may be considered as suggestions for further research. Among them, let us cite first the improvement of the set of criteria and the expansion of the variable parameters set that structure the combinatorial optimisation problem. In particular, we observed from the analysis of the problem, the review of the literature and discussions with actors of the road sector that uncertainty is a recurrent concept in the road design process. It relates both to the organisational uncertainty regarding the availability of the data at the design stage and to the analytical uncertainty regarding the impact of some parameters on the criteria evaluations. To tackle this issue, it might be particularly interesting to integrate some probabilistic analysis within the decision process in order to allow decision making under uncertainty.

In addition, the extension of the proposed set of criteria to temporal evaluations might be particularly interesting to enrich the decision process. Given that the transport system is constantly evolving, it seems reasonable to consider that the values of some parameters related to the road design problem might evolve during the lifecycle of the infrastructure. Among them, let us cite for instance the volume and composition of traffic flows (including cyclists and pedestrians), the degree of road pavement deterioration, the nature of the roadway environment, the performances of the lighting equipments, etc. Then, the use of temporal evaluations of the criteria might support the integration of predictive models within the decision process that would consider the dynamic nature of some parameters. Consequently, it would support the DM in the analysis of both the short-term and long-term performances of his solutions.

From an algorithmic perspective, the transposition of the multiobjective evolutionary algorithm and multicriteria clustering model into a more efficient programming language might be viewed as an opportunity to improve the performances of the global methodology. However, we may also think about the development of a metaheuristic that might handle better the distinctive nature of the proposed set of criteria. Regarding the interval clustering model, the analysis of the validation results pointed out that the number of categories may influence significantly the quality of the final clustering distribution. Consequently, it might be interesting to consider this parameter as a variable of the PCLUST model. For instance, we may study the opportunity of integrating the interval clustering model into a multiobjective approach by considering the number of categories as decision variables, the quality, stability and convergence of the clustering distribution as objectives, and eventually the minimum and maximum numbers of categories as constraints of the multiobjective model. This approach is probably complex to develop from a computational perspective but it would support better the DM in the analysis of his multicriteria problem.

Another interesting perspective for further research refers to the nature of the decision process in road design assessment. Design engineers and road planners are involved regarding the technical assessment of the project, but due to the collective nature of road infrastructures, the decision process may also include numerous actors such as the local authorities and communities, administrative agents, residents, diverse associations and organizations, transport public companies, etc. As a consequence of this observation, the identification of the best solution(s) for a given road design project may differ from an actor to the other so that seeking a compromise solution may be difficult. To tackle this issue, it might be interesting to analyse the opportunity of applying a specific methodology such as the Multi Actor Multi Criteria Analysis (MAMCA) to handle the multicriteria road design problem with several stakeholders.

Concerning the practical application of the proposed approach, we do think that it may be transposed to several topics while the gain of interest of the road sector regarding the multicriteria decision aiding analysis is continuously growing. For instance, similarly to the black spot treatment programme that was conducted in Flanders recently, we may think about analysing the road network in order to cluster road segments on the basis of their performances and then to prioritize the interventions. In the field of road pavement research, the proposed approach might help in the identification of the most suitable material regarding the composition of the internal structure of the road, the ground performances, the local environmental characteristics, etc. Regarding mobility strategies, we may think about defining the areas of a given region regarding multiple criteria such as their accessibility, the profiles of the road transport users, the development of the public transport offer, the density of the road network or even the proportion of commercial and industrial activities. Then, we could use the proposed approach to measure the efficiency of different modes of transport (e.g. car, bus, train, metro, walk, cycle) in all the areas of the studied region and then to cluster the areas regarding the strategies to apply to improve the mobility from, within and towards each area, to connect areas in the same clusters, etc.

To conclude, the development of the multidisciplinary approach proposed in this work to assess both the road safety and the sustainable performance of a project at the design stage has led to interesting results. In particular, the consideration of the road design process as a combinatorial optimisation problem and the use of an ordered clustering approach seem fully appropriate to solve this multicriteria decision problem. We also pointed out the interest of applying successively a multiobjective optimisation approach and a multicriteria clustering technique to assist the engineers during the design process of an infrastructure. Even if we identified several opportunities to improve the proposed approach, we assume that it is scalable to numerous decision problems of different natures.

Chapter 3

Contribution 1: Structuring the Multicriteria Road Design Problem

Sarrazin, R. and De Smet, Y. (2015). *Applying multicriteria decision analysis to design safe road projects*. Accepted in: European Journal of Transport and Infrastructure Research, vol. 15(4), pp. 613-634, ISSN: 1567-7141.

Abstract 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.

3.1 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 [38] 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 [41]. 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 [39]. 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 [40].

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 [57]. Several actions and campaigns have then been conducted to make the road users sensitive to road safety issues (e.g. speed enforcement, seat belt, 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 [107].

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 [60, 59]. In Belgium, an extensive black spot treatment programme had led to promising results regarding road safety improvement since 2000 [23]. 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 [20] or aggregated indices [4] 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 [86] or evaluating the safety performances of pedestrian crosswalks [112]. 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 [89]. 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 [63]. 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 [34]. 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 [67]. 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 [15]. 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.

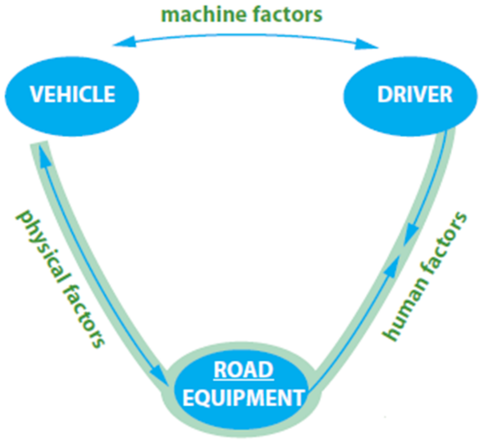
In this paper, we start with a description of the theoretical concept of sustainable road safety and we address the multicriteria problem by detailing the set of considered criteria. Next, we illustrate the multicriteria approach on a case study. Then, the current and future developments on the multiobjective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

3.2 Research motivation

3.2.1 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. Fig. 6.1). 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).

Fig. 3.1 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 the Organization for Economic Co-operation and Development (OECD), from 18% to 28% of the accidents are due to an unsafe road environment or infrastructure [84]. 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.

3.2.2 *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 [43].

Regarding the environment, the road sector has close links with sustainable topics such as energy consumption [42], noise disturbance [82, 7], land use or preservation of the soil quality and the water balance [77]. 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).

3.2.3 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. Fig. 3.2). 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.

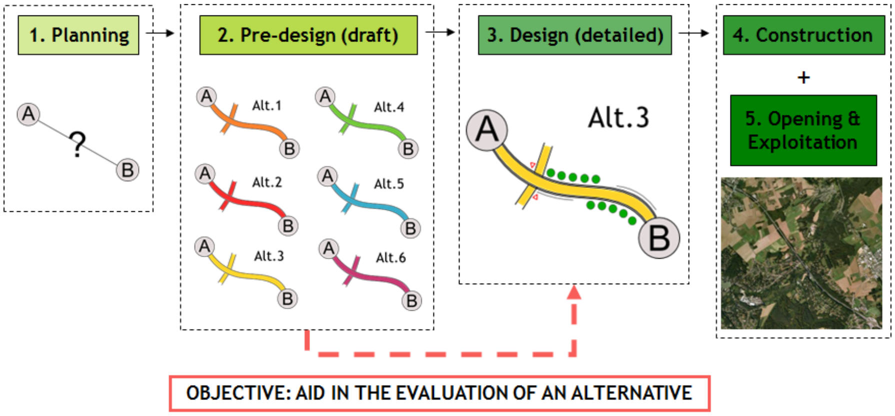


Fig. 3.2 Design stage of an infrastructure and objective of the project

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).

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.

3.3 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.

3.3.1 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 [20, 50, 84, 111], we define the eight following topics, spread in the dimensions Infrastructure (INF) and Services (SRV).

Table 3.1 Topics related to the road safety criteria

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

[a] This criterion was finally abandoned in the following of the work

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 [77], NISTRA [83], or the French approaches Routes durables [81] and Grille RST02 [10]. Additionally, the concept of sustainable safety was introduced in the projects Vision Zero [104] and Sustainable Safety [1]. 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 3.2 List of criteria that represent the concept of sustainable road safety

Dimension	Code	Name
Environmental	ENVI1	Reduction of greenhouse gases 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 (cf. Tables 3.1 and 3.2) 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.

3.3.2 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 drivers 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 [84]. 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 [85], 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 85^{th} 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 (%).

$$DVA_{op} = \frac{V_i \times t}{3.6} + \frac{V_i^2}{254(f_l \pm \frac{G}{100})} \tag{3.1}$$

The measure of sight distance as a criterion to evaluate the legibility of a road has been introduced in many studies [84, 44]. 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 (3.2).

$$C_{LC} = \frac{1}{n}\sum_{i=1}^{n} min(1; \frac{DVA_{i,op}}{DVA_{i,th}}) \tag{3.2}$$

In this equation, $DVA_{i,op}$ is the operating sight distance (3.1) 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 [52]. 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 α_k of the m roadway elements and equipment (3.3). The coefficient α_k is an integer between 0 (very bad) and 10 (very good) which is attributed by the expert to each 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.

$$C_V = \frac{1}{m} \sum_{k=1}^{m} \alpha_k \tag{3.3}$$

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 [80] and the Pedestrian and Bicyclist Safety Indices at Intersections $P/BSII$ [45], we have defined a global index C_{BSI} which expresses the global level of safety of a bicycle equipment on a road (3.4).

$$C_{BSI} = 0.5 \times C_{BSI,segment} + 0.5 \times C_{BSI,inters} = 0.5 \times CRCI + 0.5 \times BSII \tag{3.4}$$

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 [70], 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 [84]. 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 (3.5) based on the indexes *CBSI* and *CPSI* defined above. The actual weights were defined on the basis of the probabilities of accidents of pedestrians and bicyclists on rural roads in Belgium in 2012 [32].

$$C_{VRU} = 0.52 \times C_{BSI} + 0.48 \times C_{PSI} \tag{3.5}$$

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 [20, 22], 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}.

$$C_{RS} = 0.45 \times (0.7 \times PI_R + 0.3 \times PI_D) + 0.4 \times PI_F + 0.15 \times PI_{WC} \tag{3.6}$$

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 [111].

$$C_{SE} = c_0 \times AADT^{c_1} \times c_2^{LW} \times c_3^{PS} \times c_4^{UP} \times c_5^{RS} \times c_6^{TER1} \times c_7^{TER2} \tag{3.7}$$

In Equation (3.7), 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 [109], 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 [49]. 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 [56].

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 (3.8) 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.

$$C_{EM} = \frac{|c_{PM}|^2 + |c_{NO}|^2}{|c_{PM}| + |c_{NO}|} \tag{3.8}$$

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 [82]. 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 (3.9). 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.

$$L = A + 10\log\left[1 + \left(\frac{v}{50}\right)^3 + \left(1 + B \times \eta \times \left(1 - \frac{v}{150}\right)\right)\right] + 10\log(M) + \triangle R \tag{3.9}$$

In Equation 3.9, 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), η is the proportion of heavy trucks and $\triangle R$ 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. The level *Lden* is calculated as follows (3.10).

$$Lden = 10\log_{10}\left[\frac{\left(12\times 10^{\frac{Ld}{10}} + 3\times 10^{\frac{Le+5}{10}} + 9\times 10^{\frac{Ln+10}{10}}\right)}{24}\right] \tag{3.10}$$

The values *Ln* (3.11) and *Lden* (3.12) in dB(A) are normalized on a scale from 0 to 5 as follows. Finally, we obtain the criterion C_{NP} (3.13) which must be minimized.

$$|Ln| = \begin{cases} 0 & if: Ln < 30 \\ 2.5\times Ln/30 - 2.5 & if: 30 \le Ln < 60 \\ 2.5\times Ln/50 - 0.5 & if: 60 \le Ln < 110 \\ 5 & if: Ln \ge 110 \end{cases} \tag{3.11}$$

$$|Lden| = \begin{cases} 0 & if: Lden < 30 \\ 5\times Lden/80 - 1.875 & if: 30 \le Lden < 110 \\ 5 & if: Lden \ge 110 \end{cases} \tag{3.12}$$

$$C_{NP} = \frac{|Ln|^2 + |Lden|^2}{|Ln| + |Lden|} \tag{3.13}$$

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 [105], 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 travellers perspective]" [105]. 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.

3.3.3 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 [106]. The efficient solutions could be defined as the best candidates to solve the problem. From a theoretical point of view, a solution a_i is called efficient if there is no solution s_j in the set such that a_j is at least as good as a_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 3.3 shows that even for a simplified case study with only 11 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 Sect. 3.5, we will see how the use of a genetic algorithm would support us in the identification of the non-dominated solutions.

Table 3.3 Amount of alternatives for a simplified problem

Variable	Values	Description (unit)
w_{max}	14	Maximum width of the roadway lane (m)
w_l	{2.5;3;3.5}	Width of the roadway lane (m)
n_l	{2;3;4}	Number of lanes
w_{sh}	{0;1;2;3}	Width of the shoulder (m)
b_{sh}	{Y;N}	Physical separation with the shoulders
cp_nat	{1–17}	Type of cycling facility
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}	Operational speed limit (km/h)
alt	**1,175,040**	**Amount of feasible alternatives**

3.4 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.

This case study concerns the redevelopment of a secondary road in a rural area with a multimodal traffic (cf. Table 3.4). 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[1]. A simplified version of the

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[1] Those are INF3, INF6, INF6, ENVI1, ENVI2 and ECO1

Table 3.4 Description of the case study

Parameters	Values
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)

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 3.5) 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 Appendice 3.6. 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 (cf. Table 3.6).

Table 3.5 Definition of the alternatives of the case study

Variables	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}
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

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 [14, 12, 13]. 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

Table 3.6 Evaluation table of the multicriteria problem

	g_1 VRU	g_2 Design	g_3 Intersec.	g_4 Emissions	g_5 Noise	g_6 Costs
a_1	37	0.32377	3	4.2842	2.8649	132,450.0
a_2	7	0.32844	3	4.2867	2.6951	432,780.0
a_3	12	0.32377	3	4.2842	2.7674	932,770.0
a_4	22	0.53063	1	4.2884	2.6951	961,980.0
a_5	42	0.49842	3	4.2856	2.6951	102,030.0
a_6	12	0.36597	2	4.2856	2.7674	931,780.0
a_7	22	0.49978	2	4.2897	2.6951	162,200.0
a_8	37	0.36597	3	4.2856	2.8649	122,310.0
a_9	50	0.81102	2	4.2884	2.7674	169,200.0
a_{10}	45	0.81102	1	4.2884	2.6951	179,270.0

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 Appendice 3.6. 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 Fig. 3.3 [53].

Table 3.7 and Fig. 3.3 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 a_2, a_3 and a_6 are the preferred solutions of the problem according to the preferences of the decision maker. Table 3.8 represents the stability of the alternative a_6 as the first ranked solution of the problem.

Based on the stability intervals of each criterion [12], 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

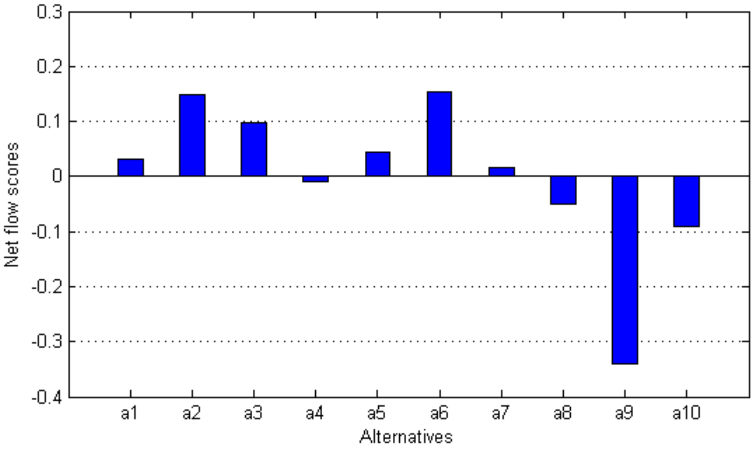


Fig. 3.3 Ranking of the alternatives based on PROMETHEE II net flow scores

Table 3.7 PROMETHEE II net flow scores

Alt.	Rank	Net flow	Flow+	Flow-
a_1	5	0.031727	0.37102	0.33929
a_2	2	0.14815	0.44444	0.2963
a_3	3	0.097312	0.41213	0.31481
a_4	7	-0.0096316	0.38889	0.39852
a_5	4	0.044889	0.3597	0.31481
a_6	1	0.15306	0.44936	0.2963
a_7	6	0.0174	0.39163	0.37423
a_8	8	-0.050955	0.32239	0.37335
a_9	10	-0.34069	0.22321	0.5639
a_{10}	9	-0.091259	0.33333	0.42459

Table 3.8 Stability intervals for the first ranked alternative

Criteria	Min weight	Weight value	Max weight
g_1	8.6%	16.7%	100.0%
g_2	5.1%	16.7%	100.0%
g_3	16.2%	16.7%	35.5%
g_4	15.7%	16.7%	24.3%
g_5	0.0%	16.7%	17.1%
g_6	0.0%	16.7%	17.6%

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 [90].

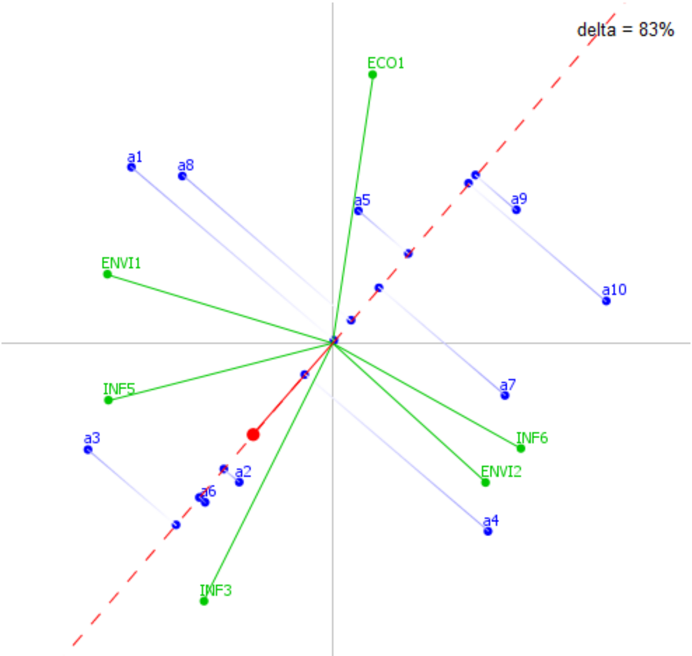


Fig. 3.4 Visual representation of the problem on the GAIA plane

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 3.4 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 a_6 and a_2 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 a_8 performs significantly well on the economic and noise criteria but suffers from bad evaluations on the criteria related to the infrastructure performances (except INF5).

Moreover, the ranking on the Fig. 3.3 shows that the alternatives a_2 and a_3 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.

3.5 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 Sect. 3.3.3, we have seen that even a simplified road design project, the set of alternatives could rapidly reach 10^6 items (cf. Table 3.3). 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 [31]. 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 3.9 Amount of Pareto solutions obtained after NSGA-II (150 generations)

Variables	Values	Description
alt.	1,175,040	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 3.9 contains the results of the simplified problem introduced in Sect. 3.3.3 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 3.5 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.

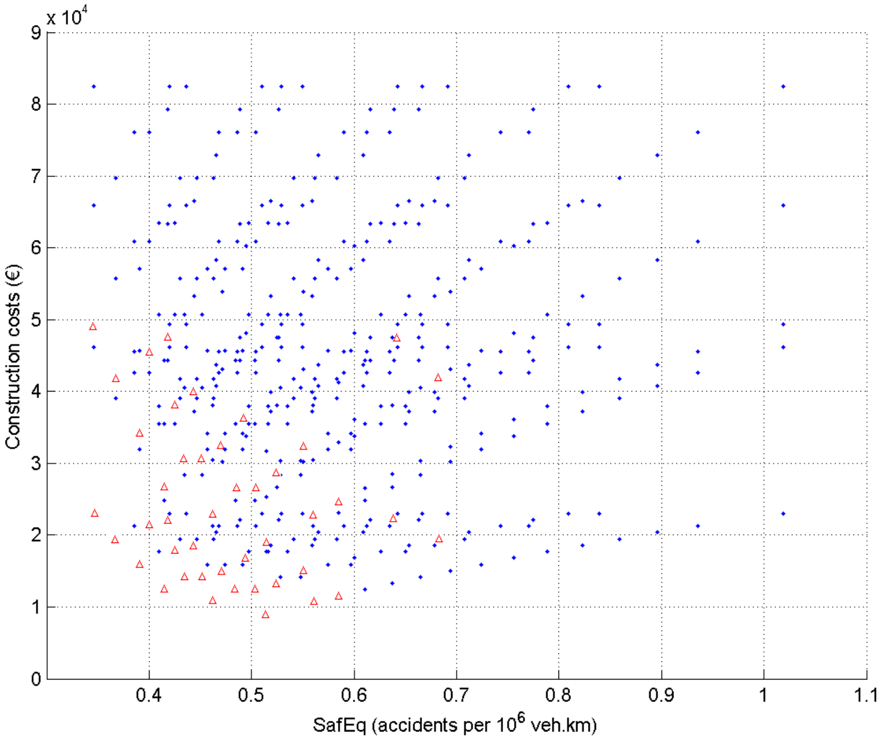


Fig. 3.5 Two-axis projection view of the dominated and non-dominated solutions

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 Fig. 3.5, 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 -indicator, binary hypervolume indicator) [99].

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 (cf. Chapt. 4).

3.6 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.

Appendices

Additional information on the multicriteria problem

Hereinafter, we describe the meaning of the parameters evaluation from the Table 3.5.

- intertype =
  - $\{1\}$: give way to right
  - $\{2\}$: through road
  - $\{3\}$: traffic signals
  - $\{4\}$: 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

The PROMETHEE methods

The PROMETHEE methods had been developed in 1982 by J.P. Brans 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 $P_j(a,b)$ which supplies the preference degree for the alternative a over the alternative b (3.14).

$$P_j(a,b) = P_j\left(d_j(a,b)\right) \tag{3.14}$$

$$0 \leq P_j(a,b) \leq 1 \tag{3.15}$$

In Equation (3.14), $d_j(a,b) = g_j(a)g_j(b)$ is the variance between the evaluations $g_j(a)$ and $g_j(b)$. 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 $P_j(a,b)$ 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:

$$\pi(a,b) = \sum_{j=1}^{k} P_j(a,b) \times \omega_j \tag{3.16}$$

$$\sum_{j=1}^{k} \omega_j = 1 \tag{3.17}$$

$$\phi^+(a) = \frac{1}{n} \sum_{x \in A} \pi(a,x) \tag{3.18}$$

$$\phi^-(a) = \frac{1}{n} \sum_{x \in A} \pi(x,a) \tag{3.19}$$

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

$$\phi(a) = \phi^+(a) - \phi^-(a) \tag{3.20}$$

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.

Chapter 4
Contribution 2: Identification of Efficient Solutions by Using a Multi-objective Evolutionary Approach

Sarrazin, R. and De Smet, Y. (2015). *Design safer and greener road projects by using a multi-objective evolutionary approach*. Accepted in: International Journal of Multicriteria Decision Making, 15(Z):xxx-yyy.

Abstract Over the past few years, both recognizing sustainable development and improving road safety have been main issues in policies for transport and mobility in Europe. However, few methodologies have been developed to support actively the road sector in the design of safer and greener roads. Consequently, this research project aimed to develop a multicriteria analysis methodology to carry out an integrated and preventive assessment of the road safety performances and some sustainable aspects of road projects at the design stage. Due to the combinatorial nature of design projects, we have investigated how an evolutionary approach, such as NSGA-II, could help the engineers to identify efficient alternatives. The algorithm was studied by means of well-known performance indicators. These showed the quality of the solutions generated by the algorithm in terms of convergence and diversity. In particular, the binary hypervolume indicator underlined the quality of the approximation set.

Keywords: Multi-objective optimization, NSGA-II, Performance indicators, Road design, Road safety

4.1 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 had published several reports and directives about the improvement of the safety level on the European road network. In the European White Paper on Transport Policy [38], an objective of halving the overall number of road deaths in the European Union by 2010 had been targeted. This challenging objective has been updated and reinforced in the Road Safety Programme 2011-2020. It has been completed with several strategic objectives and principles such as the development of an integrated approach to road safety [41]. In 2003, the European Road Safety Charter had been 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 2008, the European Commission had published the Greening Transport Package about strategies to apply in order to strive for a transport system more respectful of the environment [40].

In Belgium, the Federal Commission for the Road Safety had been formed in 2002 with intent to fulfill the EC objectives. In 2011, the initiative ”Go For Zero” has been launched by the State Secretary for Mobility and the Belgian Institute for Road Safety. It conducts several actions to make the road users sensitive to road safety issues (e.g., speed, seatbelt, alcohol and driving, etc.) [57]. In Wallonia, the government reaffirmed its willingness to promote sustainable mobility for every road user in its declaration of regional policy for the period 2009-2014 [107].

However, it has become essential to take more practical and effective actions to meet these objectives of improving road safety and considering more significantly the sustainable character of the road transport infrastructure. In particular, we should develop new preventive and innovative tools which may be used during the design stage to assess the technical and sustainable performances of a project. In the long run, these tools would allow us to design innovative road infrastructure projects and to promote solutions more consistent with the sustainable transport policies.

But to date, the assessment of the road safety performances of an infrastructure is essentially based on reactive approaches such as the evaluation of databases containing accident statistics. These offer the administration a support in the identification of the areas or routes with high accident concentration - also called black spots. These methods consist of curative analysis and handling of the high accident concentration areas. Moreover, the selection of project alternatives at the design stage is still mainly motivated by the economic aspect while the environmental and the social aspects are often neglected. Based on these observations, we have initiated the development of a preventive analysis of the sustainable and safety performances of a road project at the design stage.

The structure of this paper is as follows. It starts with a description of the research questions where we briefly discuss about the evaluation of road safety and the integration of sustainability assessment in the design process of a road project. Next, the concept of sustainable road safety is introduced to structure the multicriteria methodology. Thereafter, the method used is outlined. The problem and the genetic algorithm are introduced. Then, the results are presented with an analysis of several performance indicators. Finally, a discussion and some conclusions are provided.

4.2 Research questions and motivation

4.2.1 Towards a preventive evaluation of road safety

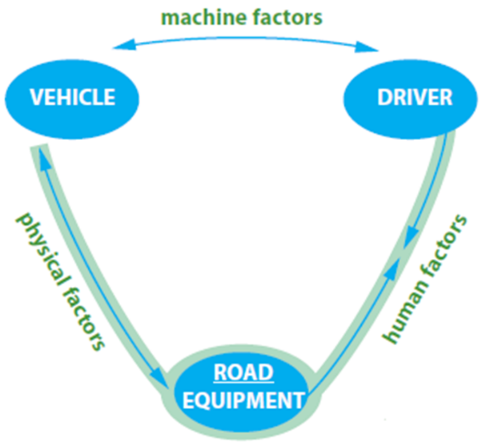
In 2013, the level of safety on the Belgian road network had slightly improved with a global decrease of road deaths by 5.8%. This reduction corresponds to a total of 720 road deaths and it is in accordance with the objectives of the EC of decreasing to 620 road deaths in 2015 and 420 in 2020. However, when comparing with the situation in France (-11%) and Germany (-10%), the decrease is slower in Belgium [58]. Therefore, to accentuate the improvement of road safety in Belgium and to maintain this orientation in the long run, it would be relevant to assess preventively the safety performances of a road project during the design stage.

At first, it is important to define theoretically what road safety is. To do so, we can use the elementary triangle of road safety (Fig. 4.1) which is composed of the dimensions vehicle, driver and road. On the basis of this triangle, we are able to 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). If we want to improve the global level of road safety of an infrastructure, we have to take an interest in one or some of these triangle components. Within the framework of this research, we focused on the road equipment dimension and the human and physical factors. Indeed, according to different studies, from 18% to 28% of the accidents are due to an unsafe road environment or infrastructure [84]. For methodological reasons, we focused in this study on the secondary rural roads of the Belgian network.

4.2.2 An integrated and sustainable approach of road safety

Considering the major environmental, economic and social crisis that the world has experienced, and due to the collective nature of a road infrastructure, it has become crucial to integrate the road sector policies into a more sustainable approach. Indeed, road infrastructures have close links with some sustainable topics such as en-

Fig. 4.1 Elementary triangle of road safety



ergy consumption [42], preservation of environment, economic performance, noise disturbance [82, 7] or even social impact [96]. In practice, it both implies to reconsider current policies by taking into account more precisely 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 previously, several reports have been published during the past years by national and European organizations in order to promote sustainable roads. However, there is still a lack of tools and processes that could assist the actors of the road sector in the practical and integrated evaluation of the sustainable performances of their projects.

In this research project, we aimed to enrich the evaluation of the safety performances of road projects with some fundamental concerns related to the environmental, social and economic dimensions of sustainable development. By doing so, we defined a more complete and integrated assessment model which would meet the needs of the transport and mobility policies in Europe.

4.2.3 A support to innovative projects

During the design stage of a road infrastructure, several alternatives are modeled 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 modeling stage, an alternative is selected among all of those that were modeled (Fig. 4.2). But 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 analyze each alternative and to select the most appropriate to the challenges and the stakes of the project.

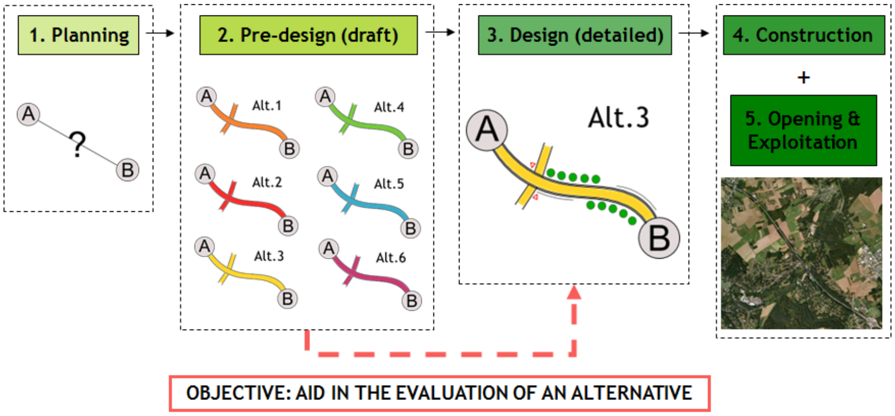


Fig. 4.2 Design stage of an infrastructure and objective of the project

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 and sustainable criteria. This set represents the sustainable road safety.

By using this model, a design engineer would be able to evaluate and to compare several alternatives of a road project based on their technical, economical, environmental and social performances. Therefore, it would be possible to select the best solution according to the characteristics of the project or the demands of the specification. In the long run, the use of integrated assessment during the design stage of road project may promote the development of innovative and sustainable solutions.

4.3 Structuring the multicriteria decision aiding problem

Based on the observations presented in the previous section, this research project had been initiated in 2010 to fulfill two main objectives. At first, the integration of road project evaluations into a sustainable approach by defining the concept of sustainable road safety. And 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.

4.3.1 Definition of sustainable road safety

One of the main findings of this research project is the definition of the concept of sustainable road safety and its representation into quantitative criteria. At first, a large literature review was conducted on the topic of road safety [84, 50]. In particular, we were focusing on the safety issues or characteristics related to the road infrastructure. Then, we have defined from this analysis the seven following topics, spread in the dimensions of Infrastructure (INF) and Services (SRV).

INF1 - Visibility of the infrastructure
INF2 - Protection of the vulnerable roads users (VRU)
INF3 - Quality of the road pavement materials
INF4 - Road design and road safety equipment
INF5 - Intersections
INF6 - Safety on road works
SRV1 - Information and intervention services

These topics constitute the first part of the set of criteria that is used in our multicriteria analysis methodology. They will allow us to quantify the performance of the road infrastructure projects in relation to safety. Then, we defined additional topics to enrich the evaluation of road projects with sustainable concerns. Over the past few years, several studies had been conducted on the topics of sustainable roads; GreenRoads [77], Routes durables [81], Grille RST02 [10]) and sustainable safety (e.g., Vision Zero [104], Sustainable Safety [1]). But regarding the sustainable safety concept, these studies exclusively focused on the social dimension of the sustainable development. As part of this project, we 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 then selected the following five topics.

ENVI1 - Reduction of greenhouse gases emissions
ENVI2 - Limitation of noise pollution
SOC1 - Ensure mobility of all
ECO1 - Limitation of the construction costs
ECO2 - Limitation of the maintenance costs

To our point of view, the association of all these 12 topics illustrates the concept of sustainable road safety. And due to the multidisciplinary nature of the concept of sustainable road safety, we are dealing with a typical multicriteria decision aiding problem wherein the alternatives of the problem are the draft alternatives of the road project at the design stage, and the criteria are the sustainable safety performances.

4.3.2 Modelling of the multicriteria problem

In order to ensure the consistency of the multicriteria evaluation model, it is important to develop a complete set of criteria by identifying the key factors and parameters of each topic. As far as possible, we must try to develop quantitative criteria to limit the subjectivity of the decision maker (DM) during the calculation process. In this study, we have developed the set of criteria by conducting an important literature review on topics related to the legibility of the road infrastructure [84, 85, 44], the protection of vulnerable road users [84, 80, 45], the quality of road pavement materials [20, 22], the impact of road layout and equipment [111], the design of intersections [44], the safety on road works and some others sustainable concerns. Additionally, some meetings were organized with experts from the road sector to review critically and validate the final set of criteria.

To define these criteria, an important stage of modelling and creation of data had been necessary to transform the initial topics - sometimes exclusively qualitative or descriptive - into quantitative criteria which ensure a consistent and meaningful analysis. Given the complexity of some practical phenomena or theoretical concepts associated with these topics, the final criteria are of a different nature (quantitative or qualitative, ordinal or cardinal scales, etc.). In addition, the developments of some criteria have been deliberately limited to a qualitative assessment, mainly due to lack of references in the literature. Nevertheless, if some improvements may still be done in the future, the quantitative nature of these criteria does not undermine the relevance and the overall consistency of the analysis.

The exhaustive definition of the full set of criteria had been done in previous articles (cf. Chapt. 3) and it goes beyond the scope of this paper. However, to ensure the global understanding of the methodology, we briefly introduced the mathematical expression of eight criteria as described below. They are the ones we have used in the illustrative example of this paper.

Visibility (INF1)

The level of visibility of the road C_V is measured by summing the coefficients of visibility α_k of the *m* roadway elements and feature. The coefficient α_k is an integer between 0 (very bad) and 10 (very good) which is attributed to each k roadway element. The values of this coefficient were submitted to the expertise of the members of the Technical Committee for Road Safety of the Belgian Road Research Center.

$$C_V = \frac{1}{m}\sum_{k=1}^{m} \alpha_k \tag{4.1}$$

Protection of the Vulnerable Road Users (INF2)

To assess the global level of safety for vulnerable road users on the road, we calculate the Compatibility of Roads for Cyclists Index CRCI in rural areas [80]. This index measures the global level of safety of bicycle facility on a road by summing the individual scores of several components of the infrastructure, such as the speed limit on the roadway, the dimension of the cycling space, the motorized and heavy truck traffic flows or the roadside condition. It is composed of an index base CRCI_{base} and of an optional part $\text{CRCI}_{options}$.

$$C_{VRU} = CRCI = CRCI_{base} - CRCI_{options} \tag{4.2}$$

Quality of the road pavement materials (INF3)

Based on researches about the development of performance indicators for the selection of road pavements [20, 22], we have defined 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}. The weights were defined in the literature [20].

$$C_{RS} = 0.45 \times (0.7 \times PI_R + 0.3 \times PI_D) + 0.4 \times PI_F + 0.15 \times PI_{WC} \tag{4.3}$$

Road design and road safety equipment (INF4)

We evaluate the performance of the infrastructure C_{SE} regarding to its geometry, the environment and the road 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 [111].

$$C_{SE} = c_0 \times AADT^{c_1} \times c_2^{LW} \times c_3^{PS} \times c_4^{UP} \times c_5^{RS} \times c_6^{TER1} \times c_7^{TER2} \tag{4.4}$$

In (4.4), 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 $\text{TER}_{1,2}$ are variables related to the roadway environment.

Intersections (INF5)

We measure the consistency and the adequacy of the intersections C_{INT} depending on the speed limit on the road infrastructure v, the function of the roads crossing at the intersection F_k and the environment δ_e as shown in (4.5). We identified three levels of performance for the n intersections of the project: consistent, moderately consistent and badly consistent to inconsistent corresponding to the values $\{1,2,3\}$. These levels have been defined for each type of intersection based on the research of Agentschap Wegen en Verkeer on the intersections [3].

$$C_{INT} = \frac{1}{n}\sum_{i=1}^{n} f_i(v, F_k, \delta_e) \tag{4.5}$$

Reduction of the greenhouse gases emissions (ENVI1)

The restriction of the greenhouse gases emissions is one of the most frequently used criteria to represent environmental concerns. The criterion C_{GHG} measures the annual average concentration of PM_{10} (c_{PM}) and NO_2 (c_{NO}) generated by a road project. 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. While we 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 was 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 wherein the weights of the normalized evaluation of concentration $|c_{PM}|$ and $|c_{NO}|$ are respectively the evaluation of $|c_{NO}|$ and $|c_{PM}|$ as shown in (4.6).

$$C_{GHG} = \frac{|c_{PM}|^2 + |c_{NO}|^2}{|c_{PM}| + |c_{NO}|} \tag{4.6}$$

Limitation of noise pollution (ENVI2)

We use a model which calculates the noise pollution generated by a road infrastructure [82]. 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 as shown in (4.7). Then, this value was compared to the limit values for noise pollution (or acceptable values with regards to comfort and health) which have been defined by the noise pollution standards.

$$L = A + 10\log\left[1 + \left(\frac{v}{50}\right)^3 + \left(1 + B \times \eta \times \left(1 - \frac{v}{150}\right)\right)\right] + 10\log(M) + \triangle R \tag{4.7}$$

In (4.7), A is a coefficient depending on the road pavement material, B is an empirical constant, v is the operating speed, M is the traffic flow (vehicles per hour), η is the proportion of heavy trucks and $\triangle R$ 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, this criterion C_{NP} 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 as shown in (4.8).

$$C_{NP} = \frac{|Ln|^2 + |Lden|^2}{|Ln| + |Lden|} \tag{4.8}$$

Limitation of construction costs (ECO1)

We simply measured the global construction costs C_{CC} by summing the costs for each equipment and materials p_k (9). The maintenance costs are evaluated in the same way (ECO2).

$$C_{CC} = \sum_{k=1}^{m} p_k \tag{4.9}$$

4.4 Implementation of the evolutionary algorithm

4.4.1 Nature of the problem

Once a complete set of criteria has been developed, the next step was to identify all efficient solutions of the problem. As introduced previously, the aim of this study was to help engineers in the evaluation step and the selection of road project alternatives at the design stage. Considering that the actions are defined a priori by different combinations of the design parameters of the project, the size of the problem may rapidly become important. As an example, Table 1 illustrates the number of feasible alternatives that could be generated (about 2×10^6) for a very simplified case study with only 12 input parameters (ranging from 2 to 5 values each, except cp_nat). Then, considering the large number of alternatives and criteria, the exhaustive enumerations of all the solutions would imply an important calculation time. As a consequence of this observation and due to the non linear nature of the criteria, we decided to apply a metaheuristic to address this issue.

Table 4.1 Total amount of alternatives for a simplified problem.

Variable	Values	Description (unit)
$w_m ax$	14	Maximum width of the roadway lane (m)
w_l	{2.5;3;3.5}	Width of the roadway lane (m)
n_l	{2;3;4}	Number of lanes
w_{sh}	{0;1;2;3}	Width of the shoulder (m)
b_{sh}	{Y;N}	Physical separation with the shoulders
cp_nat	{1–17}	Type of cycling facility
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}	Operational speed limit (km/h)
alt	**2,350,080**	**Amount of feasible alternatives**

4.4.2 *Implementation of the NSGA-II algorithm*

Structure of the NSGA-II algorithm

In this research project, we decided to use the multi-objective evolutionary algorithm NSGA-II [31]. The model has been completely developed on MATLAB R2014b. The main steps of this algorithm have been described below. From the complete set of alternatives, we randomly select a limited sample of alternatives that constitutes the initial population. Next, we generate the evaluation table of this initial population and then, we identify the non-dominated solutions. Afterwards, 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.

During the genetic process, we select two parents in the current population by using binary tournament selection based on the rank and the crowding distance. When comparing two individuals, we select the one with the smaller rank or with the greater crowding distance. Then, we allow the parents to make a crossover with a probability P_c of 90%. We used *Simulated Binary Crossover* to generate new individuals [30] :

$$\begin{aligned} c_{1,k} &= 0.5 \times \left[(1-\beta_k)\, p_{1,k} + (1+\beta_k)\, p_{2,k}\right] \\ c_{2,k} &= 0.5 \times \left[(1+\beta_k)\, p_{1,k} + (1-\beta_k)\, p_{2,k}\right] \end{aligned} \tag{4.10}$$

where β_k (≥ 0) is a spread factor, $c_{i,k}$ (resp. $p_{i,k}$) is the evaluation of the i^{th} child (resp. parent) on the k^{th} objective.

Then, we allow the individuals of the child population to mutate with a probability P_m of 30%. We use a polynomial mutation to generate the offspring c_i'.

$$c_i' = c_i + \left(c_i^u - c_i^l\right)\delta_i \tag{4.11}$$

where c_i^u (resp. c_i^l) is the upper (resp. lower) bound of the individuals c_i and δ_i is a parameter computed from a polynomial probability distribution [99]. In the following equation, η_m is the distribution index and r_i is a random number between 0 and 1:

$$P(\delta) = 0.5 \times (\eta_m + 1)(1 - |\delta|^{\eta_m}) \tag{4.12}$$

$$\delta_i = \begin{cases} (2r_i)^{\frac{1}{\eta_m+1}} - 1 & \text{if } r_i < 0.5 \\ 1 - (2(1-r_i))^{\frac{1}{\eta_m+1}} & \text{otherwise} \end{cases} \tag{4.13}$$

Results of the simplified problem

Table 4.2 contains the results of the simplified problem introduced previously after using NSGA-II. The initial population was composed of 50 alternatives randomly selected and 50 generations have been conducted in NSGA-II. A limited set of 8 criteria has been considered. The respect of the maximum width available was set as the only constraint of the model. At the end of the process, 186 non-dominated (or Pareto) solutions have been identified. This value corresponds to the average value after 30 runs of the NSGA-II algorithm. On average, the Pareto frontier is computed by the MATLAB model in 25.8 seconds.

Table 4.2 Amount of Pareto solutions obtained after NSGA-II (w_{max} = 14m ; 50 gen ; 30 tests)

Variables	Values	Description (unit)
alt	2350080	Total amount of feasible alternatives
initial_pop	50	Size of the initial population for NSGA-II
gen	50	Number of generations in NSGA-II
time	25.8	Time required to compute the Pareto frontier (s)
pareto_sol	**186**	**Size of the approximate Pareto front**

Figure 4.3 shows a projection view on the objectives *Limitation of the constructions costs* and *Road design and safety equipment* of the successive populations (dots) and the non-dominated solutions of the final population (triangles). In this problem, all the objectives must be minimized. We clearly observe a convergence of

the sets of initial and intermediate solutions towards an improved final population, even if the projection from eight to two dimensions implies a loss of information. At the end of the genetic process, we obtain non-dominated solutions with better evaluations on the criteria of the problem.

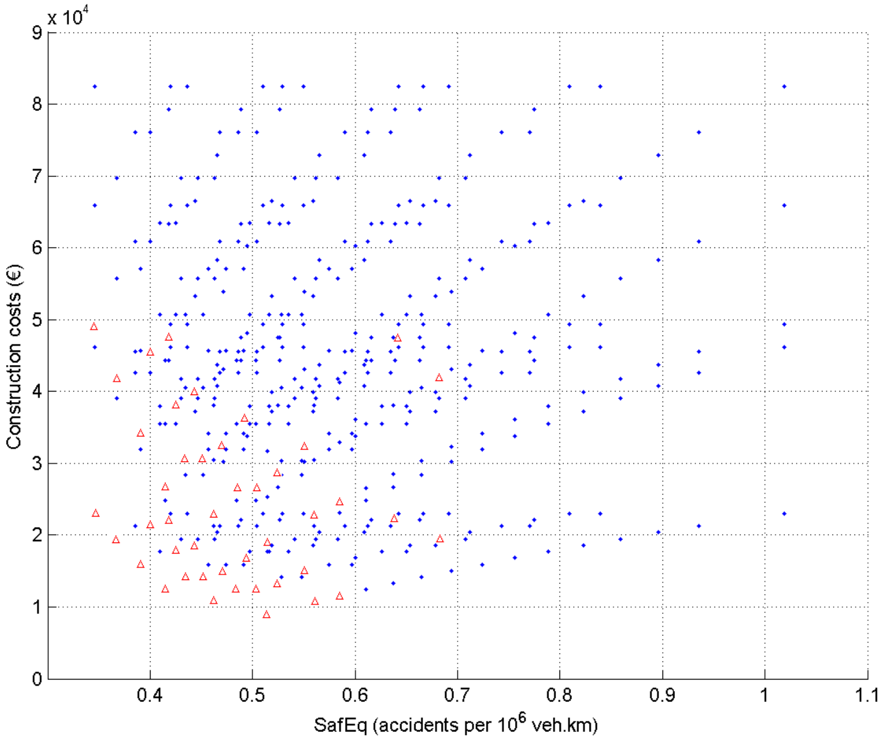


Fig. 4.3 Two-axis projection view of the dominated and non-dominated solutions

These interesting results illustrate the utility of using a multi-objective evolutionary algorithm to describe the problem, given that it proceeds to an efficient and extensive design space exploration. Moreover, it allows us to consider several criteria at the same time and then to give a relevant information to the DM.

4.5 Performance evaluation and Pareto front structure

Once the genetic algorithm was developed, we could take an interest in the study of performance indicators and the analysis of the properties of the design space. These indicators allowed us to quantify the quality of the solution set and the global performance of the NSGA-II algorithm. In the following section, we use some classical indicators from the literature in order to evaluate the convergence of the model (contribution, binary ε-indicator), the diversity of the non-dominated solution set (spread) or both convergence and diversity (binary hypervolume indicator) [99]. The convergence-based and diversity-based indicators were developed in MATLAB R2014b. Concerning the binary hypervolume indicator, we used the algorithm developed in [47] for a set of n non-dominated points in d dimensions.

4.5.1 Convergence-based indicators

According to the literature, the convergence-based indicators allowed us to quantify the effectiveness of a set of non-dominated solutions by evaluating their nearness to the optimal Pareto front.

Dimension and convexity of the Pareto front

The dimension of the Pareto front is a simple metric which evaluates the size of the Pareto frontier and its evolution during the genetic process. Figure 4.4 illustrates the evolution of the dimension of the Pareto frontier towards the final value of 186 non-dominated solutions. Considering the simplified nature of the example, we have measured the exact Pareto front of the full population. For this example, it is composed of 552 unique non-dominated solutions in the objective space (but 952 alternatives in the decision space). For a limited population of 50 alternatives and after 50 generations, the approximated Pareto front was then composed of about 34% of all the non-dominated solutions of the full multicriteria problem (and 44% after 100 generations, 56% after 150 generations). Consequently, due to the loss of information, it is crucial to analyse the convergence and the distribution of the approximated Pareto front in order to determine if it constitutes a good approximation of the exact Pareto front.

In addition, we measured the convexity of the Pareto front by evaluating the position of the non-dominated solutions relatively to a hyperplane. Considering a multicriteria problem with k criteria, this hyperplane is defined from k points randomly selected on the Pareto front. After 30 runs of the algorithm, we obtain an average value of convexity of 82.5%. It indicates that the Pareto front is globally convex, but some non-dominated solutions can be missed due to local concavity.

Finally, solving the exact problem requires a calculation time of about 15 minutes while the solving of the limited problem (50 alternatives and 50 generations) requires a calculation time of 30 seconds. For this simplified example, it corresponds to only 3% of the calculation time of the full problem. Considering more complex problems, this significant win constitutes a very interesting finding. All the tests

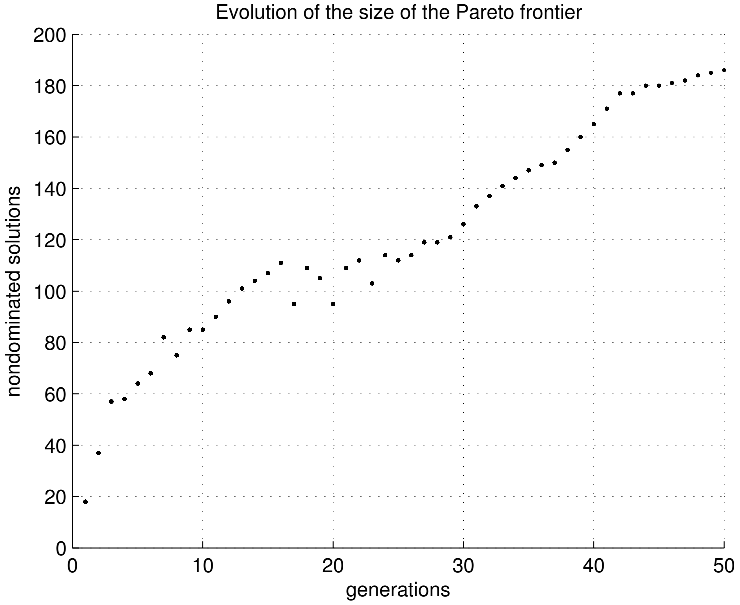


Fig. 4.4 Evolution of the dimension of the Pareto front during the evolutionary algorithm

have been conducted on a computer with Intel Core i5 CPU 2.40 Ghz and 4,00GB of memory.

Contribution

The contribution is a convergence-based binary indicator [99]. During the genetic process, we measured the contribution of an approximation set PO_1 relatively to another approximation set PO_2 by calculating the ratio of non-dominated solutions produced by PO_1 in the merged set of Pareto solutions $PO*$ (or $PO_1 \cup PO_2$). In the following equation, PO is the set of solutions in $PO_1 \cap PO_2$, W_1 the set of solutions in PO_1 that dominate some solutions of PO_2 and N_1 the set of non-comparable solutions of PO_1.

$$Cont\,(PO_1/PO_2) = \frac{\frac{\|PO\|}{2} + \parallel W_1 \parallel + \parallel N_1 \parallel}{\parallel PO^* \parallel} \tag{4.14}$$

At each generation, we generated a merged population ($PO*$) from the union of the new population (PO_1) and the previous population (PO_2). Then, we calculated the contribution of the new set relatively to the previous set at each step of the genetic process. Figure 4.5 illustrates the evolution of the contribution indicator.

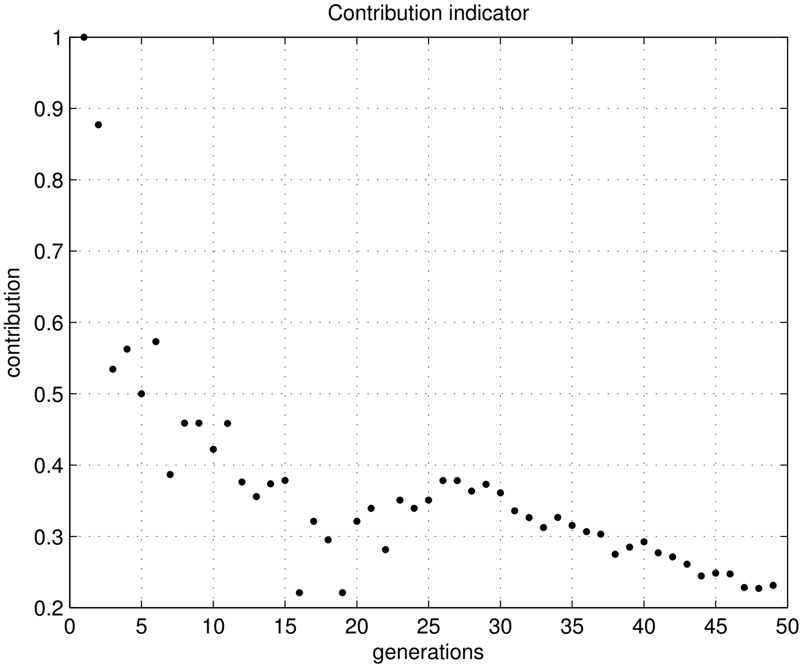


Fig. 4.5 Evolution of the contribution indicator

The contribution metric of PO_1 relatively to PO_2 gives values between 1.0 and 0.3 for the first 20 iterations of the experiment, which means that the genetic algorithm quickly improves the set of non-dominated solutions. Then, we observe a linear decrease of the contribution up to a value of 0.2 in the last iteration of the model, which indicates a convergence of the model.

4.5.2 Diversity-based indicators

A second type of performance indicators is the diversity-based indicators [99]. According to the literature, they measure the uniformity of distribution of the obtained solutions in terms of dispersion and extension. Within the framework of this research, we have studied the diversity of the non-dominated solutions with the assistance of the spread indicator only (mainly because of the high computational cost involved by this type of indicators).

Spread

The spread indicator is noted I_S. It measures the dispersion of the approximation set A over the Pareto front with a neighborhood parameter $\sigma > 0$ and a fitness function F(u) [99].

$$I_S = \frac{\sum_{u \in A} |\{u' \in A : \| F(u) - F(u') \| > \sigma\}|}{|A| - 1} \tag{4.15}$$

The interpretation of the spread indicator is then quite simple: the closer is the measure to 1, the better is the spread of the approximated set A. Figure 4.6 illustrates the result of the spread indicator depending on the value of the neighborhood parameter σ. For values of σ below 1.2, the values of I_S range from 1.0 to 0.95 which corresponds to a very good spread of the non-dominated solutions of the approximated set. For values of σ between 1.2 and 1.6, we observe a decrease of the values of I_S up to 0.8 which indicates that the solutions are still well spread over the Pareto front. Then, the values of I_S drop quickly from 0.8 up to 0 for values of σ between 1.6 and 2.1 and above. We can conclude from this figure that the Pareto-optimal front is globally well spread for values of σ below 1.5.

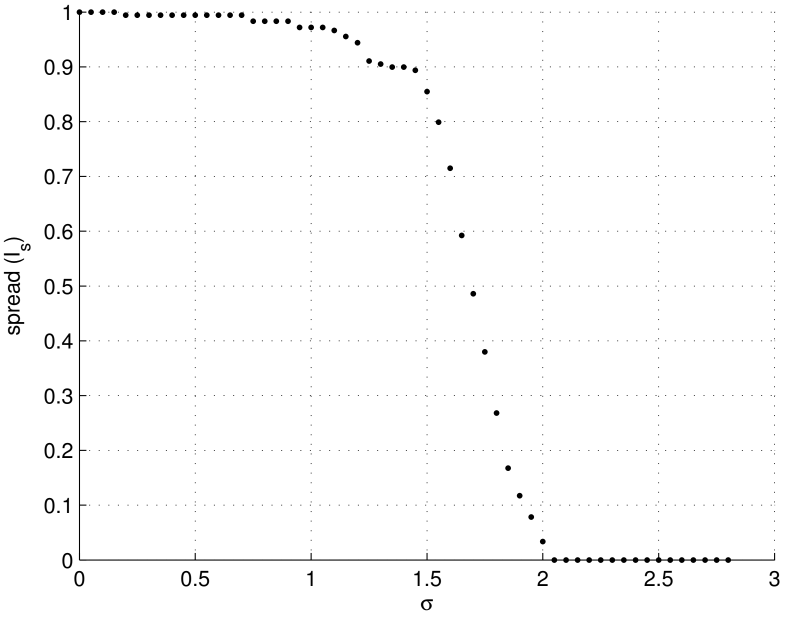


Fig. 4.6 Evolution of the spread indicator with σ

4.5.3 Hybrid indicators

Hypervolume

The hybrid indicators both combine diversity and convergence measures. The hypervolume indicator can be declined into its unary and its binary form. Here, we have only considered the binary hypervolume indicator I_H. According to [114, 113] and [29], considering a reference point Z_{ref}, the binary hypervolume metric measures the volume of the objective space portion which is weakly dominated by the reference set Z_N and not by the approximation set A. The more the value of the hypervolume metric is close to 0, the more the approximation set A is close to Z_N.

In practical, this reference point can be set as the nadir point of the problem, being the vector of the worst objective function values. For this example, the reference point Z_{ref} is the nadir point of the multicriteria problem where all the criteria are simultaneously maximised. Additionally, due to the simplified nature of the example, we have calculated the Pareto front of the exhaustive problem to generate the reference set Z_N.

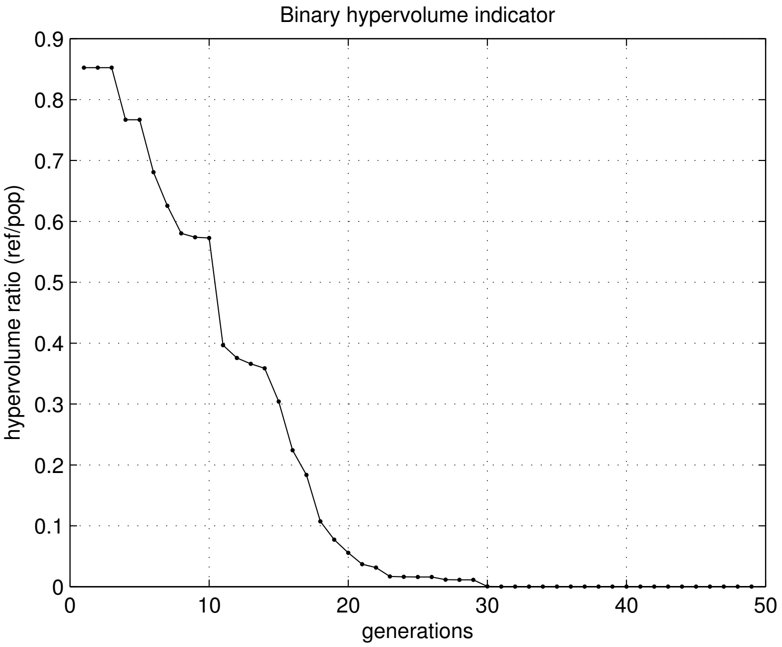


Fig. 4.7 Binary hypervolume indicator during the genetic process

Figure 4.7 shows the evolution of the volume of the objective space portion which is weakly dominated by Z_N but not by A. We clearly observe the convergence of the model after 30 generations. It indicates that the approximation set A is good and well distributed in comparison with the reference set Z_N.

4.6 Discussion

The evaluation of the model with several performance indicators allowed us to characterize the properties of the design space. In particular, the quality of the approximated solution set was underlined. Then, the methodological interest of applying the NSGA-II algorithm to our multicriteria problem was shown. From a practical perspective, using such a genetic algorithm allows the DM to reduce drastically the size of the problem while limiting the loss of information. However, even for a simple problem, the amount of non-dominated solutions in the final approximated set remains important. Consequently, solving the multicriteria decision problem is not trivial.

For the simplified case we have studied, the DM must select the final solution among a set of 186 non-dominated alternatives. Table 4.3 shows the evaluation of a sample of 10 solutions randomly selected from the final approximated set. Table 4.4 contains the values of the decision variables of the corresponding alternatives. Based on the observation of these two tables and considering the full set of non-dominated solutions, it is not obvious for the DM which alternative to choose. The definition of a set of weights could help him in the identification of his most preferred solutions. However, considering the combinatorial nature of the problem when defining the alternatives, several non-dominated solutions are very similar (e.g., id1 and id21, id88 and id104 in the Table 4.4). Then, an interesting approach to solve this multicriteria decision problem could be to generate clusters of similar solutions and to compare ultimately the representative solutions of each cluster.

To solve this clustering problem, we apply the well-known k-means procedure [9, 11, 65] that partition the decision space such that each alternative belongs to the nearest cluster. Each cluster is represented by a centroid (or the *average alternative* of the considered cluster). We set the number of clusters to 10. Table 4.5 shows the cardinality $|K|$ of the 10 clusters and the decision variables values of the non-dominated solutions that are the closest to the centroid of each cluster.

The observation of the Table 4.5 illustrates that several design options are highlighted by the 10 clusters. When focusing on the roadway lanes (width and number), many configurations are represented : 2×2.5, 3×2.5, 2×3.0, 2×3.5, 3×3.5. In addition, five different solutions for the bicyclist equipment are also represented and correspond to a cycle lane on the road ($cp\_nat = 3$), a paved shoulder ($cp\_nat = 4$) and a cycle lane separated from the roadway without physical sep-

Table 4.3 Objective functions values of a sample of solutions from the final approximated set (random selection)

id	C_V	C_{SE}	C_{RS}	C_{VRU}	C_{INT}	C_{GHG}	C_{NP}	C_{CC}
1	**1**	0.18815	**1.8525**	**2**	**1**	4.2686	**2.7667**	2.0774e+06
6	2	0.30146	**1.8525**	64	3	4.2629	2.9173	**76114**
15	**1**	**0.15549**	2.15	9	**1**	4.2607	**2.7667**	5.5196e+05
21	**1**	0.18815	**1.8525**	17	**1**	4.2686	**2.7667**	1.5738e+05
44	2.6667	0.27481	**1.8525**	9	**1**	4.2579	**2.7667**	4.449e+05
59	**1**	0.19583	**1.8525**	4	**1**	4.2607	**2.7667**	2.0394e+06
76	1.6667	0.36177	**1.8525**	39	**1**	4.2607	**2.7667**	81660
88	2	0.44915	**1.8525**	34	**1**	**4.2543**	**2.7667**	4.3216e+05
104	1.3333	0.44915	**1.8525**	39	**1**	**4.2543**	**2.7667**	92892
133	**1**	0.18815	**1.8525**	**2**	3	4.2686	**2.7667**	2.0478e+06

Table 4.4 Decision variables values of a sample of solutions from the final approximated set (random selection)

id	w_l	n_l	w_{sh}	b_{sh}	cp_nat	w_{med}	mat_nat	r^a	m^a	l^a	it^a	v
1	3.5	3	3	1	8	0	6	2	2	3	3	50
6	3.0	2	2	0	1	0	6	1	2	2	2	90
15	2.5	2	3	1	8	0	6	1	1	3	2	50
21	3.5	3	3	0	6	0	6	2	2	3	3	50
44	2.5	2	1	0	7	0	6	1	1	2	3	50
59	3.0	2	2	1	8	0	6	2	2	3	3	50
76	3.5	2	0	0	2	0	6	2	1	3	3	50
88	2.5	2	0	0	10	0	6	1	1	3	3	50
104	2.5	2	0	0	2	0	6	1	2	3	3	50
133	3.5	3	3	1	8	0	6	2	2	3	2	50

[a] r = rsign ; m = marking ; l = lighting ; it = intertype

Table 4.5 Cardinality of the 10 clusters and decision variable values of the non-dominated solutions that are the closest to the 10 centroids (test conducted on a set of 157 solutions)

$\lvert K\rvert$	w_l	n_l	w_{sh}	b_{sh}	cp_nat	w_{med}	mat_nat	r^1	m^1	l^1	it^1	v
6	3.5	2	0	0	4	0	2	2	2	3	3	50
13	3.0	2	3	0	6	0	5	2	2	2	2	50
8	2.5	2	0	0	6	0	6	1	1	3	3	50
27	2.5	3	3	0	7	0	6	2	1	3	3	50
22	3.0	2	0	0	3	0	6	2	1	3	3	50
23	3.5	2	0	0	4	0	6	1	2	3	2	50
16	2.5	3	3	1	8	0	6	1	2	3	2	50
5	3.5	2	0	0	3	0	5	2	2	3	4	50
6	3.5	3	3	1	8	0	6	1	1	0	4	50
31	3.5	3	3	1	8	0	6	2	1	3	3	50

[a] r = rsign ; m = marking ; l = lighting ; it = intertype

aration ($cp\_nat = 6$), with delineators ($cp\_nat = 7$) or with barriers ($cp\_nat = 8$). However, the maximum speed limit is set to 50 km/h for each representative solution.

To conclude, the use of a clustering approach seems fully appropriate to solve this multicriteria decision problem. It should support the DM in the identification of groups of solutions that perform similarly, and ultimately in the selection of the best one according to his preferences. Nevertheless, the *k*-means procedure is only based on the euclidean distance between alternatives and it does not really consider the multicriteria nature of the problem. To tackle this issue, it could be then interesting to develop a clustering approach that partitions the decision space by using the preferential information between alternatives.

4.7 Conclusions and further developments

In this study, we have developed an innovative model to assess both the road safety and the sustainable performance of a project at the design stage. Considering the objectives of the EU 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 preliminary design stage of the process, we generate all the feasible alternatives of the project - by generating parameter combinations and 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. The performance indicators illustrate the quality of the solutions generated by the algorithm in terms of convergence and diversity. In particular, the results obtained from the computation of the binary hypervolume indicator show the quality of the approximation set given by our model. Moreover, the replicability of the results after several runs of the algorithm proves the robustness of the model.

To solve the multicriteria decision problem, the use of a clustering approach seems interesting and appropriate. Especially, it may assist the decision maker in the identification of the representative alternatives of the Pareto frontier. The comparison of these alternatives and the selection of a final solution would then be facilitated. In order to consider the multicriteria nature of the problem and to guarantee the relevancy of the clustering, the development of a clustering model based on the preferential information between alternatives would be very interesting for further research. 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 project safety issues and their quantification.

Chapter 5

Contribution 3: Development of a multicriteria interval clustering model

Sarrazin, R., De Smet, Y. and Rosenfeld, J. (2014). *An extension of PROMETHEE to interval clustering*. Technical Report TR/SMG/2014-009, CoDE-SMG, Université libre de Bruxelles, December 2014.

Note. This paper has been submitted to the European Journal of Operational Research in September 2015 after a major revision.

Abstract Multicriteria clustering techniques aim to detect groups of alternatives evaluated on multiple criteria with similar profiles. The preferential partitioning of the data set allows the decision maker to get a better understanding of the structure of his problem. In this paper, we focus on the particular case of interval clustering. This approach allows us to assign alternatives either in individual or interval clusters. To this purpose, we develop a model based on the PROMETHEE I outranking method and the FlowSort sorting procedure. We evaluate its performances on real-world data sets regarding the convergence, the stability and the quality of the clustering. In particular, we analyse the impact of three update functions and two initialization strategies. This analysis has pointed out some promising results that we underline by comparing the performances of the proposed model with the well-known *k*-means procedure and the P2CLUST model.

Keywords: Multiple Criteria Analysis, PROMETHEE, FlowSort, Multicriteria Interval Clustering

5.1 Introduction

We consider decision problems than can be modelled as a set of alternatives evaluated on several conflicting criteria. Facing such situations, researchers usually consider three main types of so-called problematic [106]. The first one is the choice problem that implies the identification of the best compromise solution (or a subset of interesting solutions). The second one refers to the ranking of the alternatives from the best to the worst one. Finally, the third problem is the sorting problem that corresponds to the allocation of alternatives into pre-defined categories. Since a couple of years, a new kind of problematic has emerged in the multicriteria decision aid community. This is referred as to multicriteria clustering i.e. the detection of groups of alternatives in a multicriteria context.

In data mining, a lot of methods have been proposed to solve the different clustering problems (for instance *k*-means algorithms, hierarchical methods, support vector machines, etc.). Most of them rely on a distance measure that allows to built groups that are as homogeneous as possible but remain highly heterogeneous between themselves.

In multicriteria contexts, the notion of distance between two alternatives is not really appropriate. This is due to the fact that criteria have to be optimized. Most of the time, the comparison between two alternatives will lead to conclude that the first one is better regarding certain criteria while the second is better for the others points of views. This observation has led to build (binary or valued) preferences relations. To our point of view, these asymmetric relations open new doors for clustering; for instance, the detection of complete or partial relations between the groups.

De Smet and Montano are the first who have investigated the multicriteria clustering problem based on binary preferences [26]. Their model relies on the definition of a specific distance that takes into account the multicriteria preferential information induced by the comparison of alternatives. Unfortunately, their algorithm was limited to the detection of nominal clusters. Later, De Smet and Eppe proposed a natural extension of the first work to build relations between the groups (this was further completed by [37] in the context of valued relations) [25]. In this case, no warranty was available regarding the transitivity of the cluster relations or the fact that they were acyclic (even if artificial experiments have shown that such problems were seldom). [27] also developed an exact algorithm to detect a totally ordered clustering. [88] proposed a method for multicriteria clustering in which they distinguish first the clustering approach (which does not integrate the preferences of the decision maker) and then a multicriteria technique to find the relations between the groups. More recently, [73] proposed a formalization of this emerging topic.

In this contribution, we consider a particular multicriteria outranking method called PROMETHEE. It is known for its ease of use, the presence of user-friendly software [53] and a large number of real applications [5]. It is worth noting that a first extension of PROMETHEE for clustering (and sorting) was proposed in 2004 [46]. Unfortunately, this preliminary work suffered from some drawbacks like the non respect of the criterion-depency condition given that clusters could not be compared [16]. An extension of PROMETHEE II was recently presented [24]. By construction, the relations between the clusters respect the transitivity conditions. In this paper, we study the possibility to further extend PROMETHEE I and to address the problem of interval clustering i.e. the allocations of alternatives not only in individual clusters but also to sets of successive clusters. On the one hand, the proposed extension ensures that relations between the clusters will be acyclic (by construction). On the second hand, the detection of possible interval clusters allows to analyse the problem at two levels: individual clusters indicate clear assignments while interval clusters indicate regions where the allocation is less clear. Such information could lead :

1. to build a new cluster if the number of alternatives belonging to the interval cluster is important;
2. to detect alternatives that could be considered as outliers (if only a few of them belong to the interval clusters).

The paper is presented as follows. At first, we introduce the main theoretical concepts of the PROMETHEE and FlowSort methods and we present the multicriteria clustering problem. In particular, the P2CLUST and PROMETHEE CLUSTER methods are briefly described while the notion of interval clustering approach is introduced. Then, we define the proposed model that is based on an extension of the PROMETHEE I method to interval clustering. In the third section, we validate the model on three data sets by evaluating the quality and the stability of the clustering and its convergence. Next, we compare the results obtained with this new approach, the formerly P2CLUST model and the *k*-means procedure.

5.2 State of the art

5.2.1 The PROMETHEE methods

The PROMETHEE outranking methods were initiated in the early 80s by Brans [14, 12, 13, 106]. They offer the Decision Maker (DM) a support to solve multicriteria problems by using a valued outranking relation. This relation is based on pairwise comparisons between alternatives and it defines the preference structure of the PROMETHEE method.

Let us consider a set of alternatives $A = \{a_1 ... a_n\}$ and a set of criteria $F = \{g_1 ... g_q\}$. We suppose in the following that these q criteria have to be maximized. For each criterion g_k, the DM evaluates the preference of an alternative a_i over an alternative a_j by measuring the difference of their evaluation on g_k.

$$d_k(a_i,a_j) = g_k(a_i) - g_k(a_j) \tag{5.1}$$

This pairwise comparison allows the DM to quantify how alternative a_i performs on g_k compared to alternative a_j. Then, we use a preference function P_k to transform this value into a preference degree. Depending on the shape of the preference function, the DM could define the indifference threshold q_k and the preference threshold p_k for each criterion (cf. Fig. 5.1).

$$P_k(a_i,a_j) = P_k[d_k(a_i,a_j)] \tag{5.2}$$

$$0 \leq P_k(a_i,a_j) \leq 1 \tag{5.3}$$

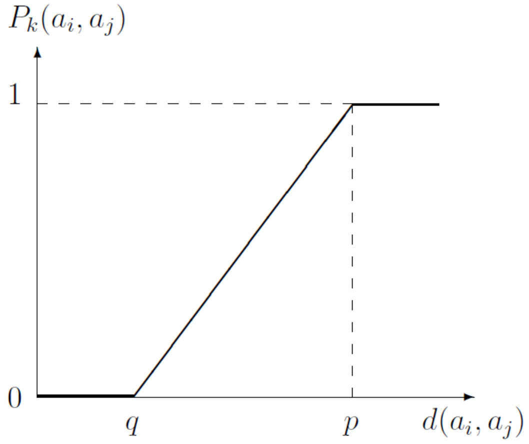


Fig. 5.1 Illustration of a piecewise linear preference function.

To quantify the global preference of a_i over a_j, we define the notion of preference index $\pi(a_i,a_j)$. It allows us to aggregate all the unicriterion preference $P_k(a_i,a_j)$ by considering the weights ω_k associated to each criterion.

$$\pi(a_i,a_j) = \sum_{k=1}^{q} P_k[d_k(a_i,a_j)] \cdot \omega_k \tag{5.4}$$

$$\omega_k \geq 0 \text{ and } \sum_{k=1}^{q} \omega_k = 1 \tag{5.5}$$

The last step of the PROMETHEE methods relies on the calculation of the outranking flows of each action. It allows the DM to quantify simultaneously how an action a_i is preferred to all the remaining actions x of the set A and how these actions x are preferred to a_i. These two notions are respectively represented by the positive flow ϕ^+ and the negative flow ϕ^- in PROMETHEE I.

$$\phi^{+}(a_i) = \frac{1}{n}\sum_{x\in A}\pi(a_i,x) \tag{5.6}$$

$$\phi^{-}(a_i) = \frac{1}{n}\sum_{x\in A}\pi(x,a_i) \tag{5.7}$$

The positive and negative flows could be combined into the outranking net flow ϕ which is used in PROMETHEE II.

$$\phi(a_i) = \phi^{+}(a_i) - \phi^{-}(a_i) \tag{5.8}$$

Based on the positive and negative flow scores, the PROMETHEE I method generates a partial ranking of the alternatives. In PROMETHEE II, a complete order is generated from the net flow scores of the alternatives.

5.2.2 The FlowSort method

The FlowSort method was developed by Nemery and Lamboray [79] for solving multicriteria sorting problems. This method allows the DM to sort the alternatives into categories based on their positive and negative flows. The categories are defined a priori and they remain unchanged during the solving process.

Let us consider a set of categories (or clusters) to which the actions will be assigned $\kappa = \{C_1, C_2 \dots C_K\}$. We assume that the K categories are completely ordered such that C_{j+1} is preferred to C_j. In the FlowSort method, the categories could be defined either by one central profile or two limiting profiles. In the following, we will focus on the categories characterized by central profiles. Figure 5.2 illustrates the central profiles in the FlowSort method for a problem with q criteria and K categories.

Let us denote them $R = \{r_1, r_2 \dots r_K\}$. These reference profiles are representative elements of the category which they belong to and they should respect the dominance principle: r_{j+1} the central profile of C_{j+1} dominates r_j the central profile of C_j (cf. Condition 1) [78].

Condition 1 $\forall r_h, r_l \in R$ such that $h > l$:
$\forall g_k \in F$, $g_k(r_h) \geq g_k(r_l)$ and $\exists g_x \in F \mid g_x(r_h) > g_x(r_l)$

The fundamental principle of the FlowSort method relies in the association of an alternative $a_i \in A$ to a given category using either the net flow scores of PROMETHEE II or the positive and negative flows of PROMETHEE I. Later, the net flow scores will be used to generate a complete clustering while the positive and negative flows are appropriate in the context of an interval clustering. In practice, we generate for each alternative $a_i \in A$ the combined set $R_i = R \cup \{a_i\}$. Then, the

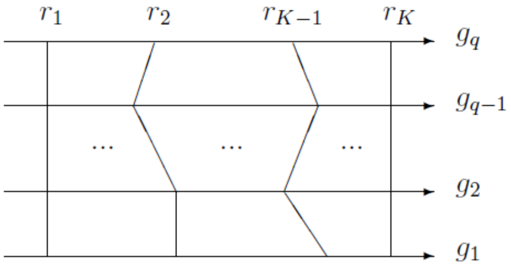


Fig. 5.2 Illustration of central profiles r_j in completely ordered clustering.

assignment of the alternative to a category is done in two steps. First, we compare its flow score to the flow scores of the central profiles. And then, we assign the alternative to the category whose the profile has the closest flow score. With net flow scores, this is formalized by the following condition [78].

Condition 2 $C_\phi(a_i) = C_h$ if: $|\phi_{R_i}(r_h) - \phi_{R_i}(a_i)| = \min_{\forall j} |\phi_{R_i}(r_j) - \phi_{R_i}(a_i)|$

We denote $\delta(A,\kappa)$ the final distribution of the alternatives $a_i \in A$ in the set of categories κ. When the final clustering is of good quality, it produces compact but well-separated categories. Let us stress that the assignment rule based on PROMETHEE will be presented in Sect. 5.3.2.

5.2.3 *Interval Multicriteria Clustering*

Multicriteria clustering relies on the explicit consideration of preference relations between alternatives in order to build clusters. The resulting groups can be (partially or completely) ordered or considered as being incomparable. In the first case, we refer to relational multicriteria clustering. In the second case, we speak about non-relational (or nominal) clustering.

The identification of ordered clusters in a multicriteria context opens new perspectives to structure and understand decision problems. For instance, in sorting problems, categories are assumed to be known beforehand. This assumption is not always satisfied and decision makers may face difficulties to provide this kind of information. In such contexts, multicriteria clustering techniques can be applied to support the DM in the identification of these categories. Other real-world problems often lie at the boundary between sorting and ranking problems. For instance, we can cite the academic rankings of universities. In its current version, the first 100 universities are ranked. Then, other institutions are (arbitrarily) merged by groups of 50. In the later case, threshold effects can appear. Indeed, an improvement of 1 position in the final ranking can lead to pass from the category $151-200$ to $101-150$. In this context, we claim that the identification of ordered clusters could provide an alternative view on the problem. While Harvard would remain (alone) at the first position, we could easily imagine that other (top) institutions could be placed in a same cluster due to their similar evaluations. Finally, homogeneous groups of (lower rank) institutions can be identified based on their multicriteria nature (and not based on a arbitrary parameter).

Recently, the methods PROMETHEE CLUSTER [46] and P2CLUST [24] were developed to address the problematic of multicriteria clustering by using the methodology of PROMETHEE. Both of these two methods are extensions of the *k*-means algorithm adapted to the distinctive features of PROMETHEE. We briefly describe them in the next paragraphs.

PROMETHEE CLUSTER is a non-relational multicriteria clustering technique. Similarly to the *k*-means procedure, it works in four steps. At first, the reference profiles of each category are randomly initialized. Then, the assignment of the alternatives to the categories is done by calculating the deviation of each alternative $a_i \in A$ from the reference profiles $r_j \in R$ based on their the single criterion net flows $\phi_{R_i,k}(a_i)$ and $\phi_{R,k}(r_j)$.

$$\phi_{R_i,k}(a_i) = \frac{1}{|R|-1} \sum_{\substack{r \in R \\ a_i \in R_i}} (P_k(a_i,r) - P_k(r,a_i)) \tag{5.9}$$

$$\phi_{R,k}(r_j) = \frac{1}{|R|-1} \sum_{r \in R} (P_k(r_j,r) - P_k(r_j,r)) \tag{5.10}$$

The deviation $e_1(a_i,r_h)$ between an alternative $a_i \in A$ and a reference profile $r_h \in R$ corresponds to the weighted L_1 distance between the vectors $\phi_{R_i}(a_i)$ and $\phi_R(r_h)$. Then, the alternative a_i is assigned to the category C_h if its deviation is minimum.

$$e_1(a_i,r_h) = \sum_{k=1}^{q} (|\phi_{R_i,k}(a_i) - \phi_{R,k}(r_h)| \cdot \omega_k) \tag{5.11}$$

Next, each reference profile is updated so that it corresponds to the centroid of the corresponding category. Finally, the clustering procedure ends when the cluster membership no longer changes. From a global perspective, this method can be viewed as a direct application of the k-means algorithm in the unicriterion net flow scores space. While this procedure does not provide any information about the potential relations between clusters, it has been criticized [16] because it does not respect the condition of *criteria dependency*.

The model P2CLUST works similarly to PROMETHEE CLUSTER except that the FlowSort procedure is used to assign the alternatives to each category. This assignment rule allows the DM to generate categories that support an ordered structure. Concretely, the complete ranking of the actions of the set $R_i = R \cup \{a_i\}$ is calculated based on the net flow scores. Each alternative a_i is then assigned to a category

C_h if the reference profile r_h satisfies the assignment rule of the FlowSort procedure (cf. Condition 2). Finally, in order to respect the dominance conditions between the reference profiles, their evaluations are sorted after each cycle of the model. The procedure is repeated until the category membership remains unchanged.

PROMETHEE CLUSTER and P2CLUST provide outputs in two extreme contexts. First, all clusters are assumed to be incomparable. Secondly, all clusters can be ranked according to a complete pre-order. Interval Multicriteria Clustering lies between these two extreme situations; clusters are ranked according to a partial pre-order. In other words, it is still possible to identify a cluster that is better than another one. However, if two clusters are too different, the model allows to consider them as being incomparable. By doing so, the outputs are more flexible and the model is likely to better fit the data. The aim of PCLUST is to address this issue.

5.3 Proposed model

Based on the principles of FlowSort and PROMETHEE methods, we have developed the model PCLUST which is an extension of PROMETHEE I for interval clustering. The aim of this model is to solve a multicriteria clustering problem by defining a set of categories κ^* that could be divided in two groups: the principal categories C_i and the interval categories $C_{i,j}$, $\forall i,j \in \{1 \dots K\}$ and $i \neq j$. The principal categories are ordered and respect the dominance principle. While the interval categories $C_{i,j}$ are located "between" the principal categories C_i and C_j. Considering the preference relation of PROMETHEE, it means that the profile $r_{i,j}$ is incomparable with r_i and r_j. In this paper, we assume that the number of categories is defined a priori by the DM. The clustering procedure of the PCLUST method is composed of the following steps:

1. Initialization of the central profiles (2 strategies)
    a. Random initialization
    b. Equidistributed initialization
2. Assignment of the alternatives to the categories
3. Update of the central profiles (3 functions)
4. Repeat the procedure from step 2 until stop condition
    a. Distribution remains unchanged during 10 cycles
    b. Maximum 100 cycles

In the following, we describe each step of the clustering procedure. The reader who is familiar with the *k*-means procedure directly see that our approach follows the same mains steps. Nevertheless, as in P2CLUST, two distinctive features have to be highlighted. At first, the allocation is based on a multicriteria sorting method. Secondly, the update of the reference profiles have to respect the multicriteria nature of the problem (i.e. the dominance condition).

5.3.1 Initialization of the central profiles

At first, we determine the central profiles either randomly (Rdm) or by equidistributing (Eqd) the evaluations on every criterion. When initializing the reference profiles randomly, we need to sort the evaluations on every criteria in order to respect the dominance principle between clusters (cf. Condition 1).

5.3.2 Assignment of the alternatives to the categories

Next, the assignment of the alternatives to the categories is done with respect to an assignment rule. Let consider an alternative $a_i \in A$ and the set of reference profiles $R = \{r_1 \dots r_K\}$. As in FlowSort, we define the set $R_i = R \cup \{a_i\}$. We compute the preference degrees between the actions of R_i and we calculate the positive and negative flows. Finally, we assign an alternative to a category by following these two conditions:

Condition 3.1 $C_{\phi^+}(a_i) = C_h$ if: $|\phi^+_{R_i}(r_h) - \phi^+_{R_i}(a_i)| = \min\limits_{\forall j} |\phi^+_{R_i}(r_j) - \phi^+_{R_i}(a_i)|$

Condition 3.2 $C_{\phi^-}(a_i) = C_l$ if: $|\phi^-_{R_i}(r_l) - \phi^-_{R_i}(a_i)| = \min\limits_{\forall j} |\phi^-_{R_i}(r_j) - \phi^-_{R_i}(a_i)|$

Based on these conditions, two different categories C_h and C_l could be obtained. In order to assign each alternative to one category, we define the following assignment rule:

Assignment rule $\forall a_i \in A, \forall h,l \in \{1 \dots K\}$:

$$\begin{cases} a_i \in C_h & \text{if } C_{\phi^+}(a_i) = C_{\phi^-}(a_i) = C_h \\ a_i \in C_{h,l} & \text{else} \end{cases}$$

We denote the categories C_h as the principal categories while $C_{h,l}$ are the interval categories $(h \neq l)$.

5.3.3 Update of the central profiles

At the end of each iteration, all the alternatives of the set A are assigned to categories. So, we need to update the reference profile of each category in order to take into consideration this new distribution. In totally ordered clustering, the updated value of the reference profile r_h corresponds to the average value of the evaluations of the alternatives in C_h. However, in interval clustering, the alternatives of the problem could be assigned either in principal or interval categories. Consequently, we could imagine that the updated value of the reference profile r_h would also consider the alternatives in the interval categories $C_{h,j}$ which are related to C_h, $\forall j = \{1 \dots K\}, j \neq h$.

In this paper, we present three functions to update the reference profiles and their respective performances. Considering the principal category C_h, we denote $C_{h,l}$ the interval category that is related to C_h and C_l. The categories $C_{h,l}$ and $C_{l,h}$ are similar in the sense of interval clustering, such that we only consider the notation $C_{h,l}$ $(h < l)$ for simplicity reasons. We denote $\{C_{h,j}\}$ the set of all the interval categories that are related to C_h.

First update function $Upd1$

At first, to describe the structure of the first function, we need to distinguish the principal categories that contain at least one alternative and the principal categories that are empty.

(1.NE) Non-empty principal categories.

If the principal category C_h is not empty, the updated value of its reference profile r_h is simply equal to the average value of the evaluations of the alternatives a_i that belong to this category (5.12). If $|C_h| \neq 0$ $(\forall k \in \{1 \dots q\}, \forall h \in \{1 \dots K\})$:

$$g_k(r_h) = \frac{1}{|C_h|} \sum_{a_i \in C_h} g_k(a_i) \tag{5.12}$$

(1.E) Empty principal categories.

If the principal category C_h is empty, we update the reference profiles differently if the category is extreme (i.e., $h = \{1, K\}$) or not.

(1.E.e) Extreme principal categories.

If the principal category C_h is extreme, the updated value of its reference profile r_h is equal to the average value of the alternatives a_i that belong to the set of interval categories $\{C_{h,j}\}$ (5.13). If $|C_h| = 0$ and $|\{C_{h,j}\}| \neq 0$ $(h \in \{1, K\}, \forall k \in \{1 \dots q\}, \forall j \in \{1 \dots K\})$:

$$g_k(r_h) = \frac{1}{|\{C_{h,j}\}|} \sum_{a_i \in \{C_{h,j}\}} g_k(a_i) \tag{5.13}$$

If this set $\{C_{h,j}\}$ is empty, the updated value of r_h is equal to a random value comprised in an interval with an upper bound (respectively lower bound) that corresponds to the evaluations of the next (respectively previous) reference profile (5.14). If $|C_h| = 0$ and $|\{C_{h,j}\}| = 0$ $(\forall k \in \{1 \dots q\})$:

$$\begin{aligned} g_k(r_1) &= rand \in [0, g_k(r_2)] \\ g_k(r_K) &= rand \in [g_k(r_{K-1}), \max_{\forall a_i}(g_k(a_i))] \end{aligned}$$

(1.E.ne) Non-extreme principal categories.

If the principal category C_h is not extreme, the updated value of its reference profile r_h is equal to a random value comprised between the reference profiles of the closest upper category C_{up} and the closest lower category C_{low} that are non-empty (5.14). If $|C_h| = 0$ $(\forall h \in \{2 \dots K-1\}, \forall k \in \{1 \dots q\})$:

$$g_k(r_h) = rand \in [g_k(r_{low}), g_k(r_{up})] \tag{5.14}$$

Second update function $Upd2$

The second update function is very similar to the first one, except for the update of the principal categories that are empty and extreme (2.E.e).

(2.E.e) Extreme principal categories.

In this configuration, if the principal category C_h is empty while the set of interval categories $\{C_{h,j}\}$ contains at least one alternative, the updated value of the reference profile r_h is calculated only by considering the alternatives from the set of interval categories $\{C_{h,j}\}$ that are closer to C_h than to C_j, $\forall j \in \{1 \dots K\}, j \neq h$. For simplicity reasons, we denote this set of alternatives $\{C_{h,j}\}^h$. We use the notion of closeness within the meaning of PROMETHEE II that is defined by the Condition 2. Then, we calculate the update value of the reference profile r_h with the following Eq. (5.15). If $|C_h| = 0$ and $|\{C_{h,j}\}| \neq 0$ $(h \in \{1, K\}, \forall k \in \{1 \dots q\}, \forall j \in \{1 \dots K\})$:

$$g_k(r_h) = \frac{1}{|\{C_{h,j}\}^h|} \sum_{a_i \in \{C_{h,j}\}^h} g_k(a_i) \tag{5.15}$$

The update procedure for all the others configurations remains the same than for the first function.

Third update function $Upd3$

Finally, the third update function is similar to the second one, except for the update of the principal categories that are empty and not extreme (3.E.ne).

(3.E.ne) Non-extreme principal categories.

In this configuration, we distinguish the cases where the set of interval categories $\{C_{h,j}\}$ is empty or not. If this set is empty, we apply the same update rule than the first function (1.E.ne). If this set is not empty, we apply the same update rule than for the principal categories that are empty and extreme in the second function (2.E.e) as expressed in Eq. (5.16). If $|C_h| = 0$ and $|\{C_{h,j}\}| \neq 0$ ($\forall k \in \{1 \ldots q\}$, $\forall h, j \in \{1 \ldots K\}$, $j \neq h$) :

$$g_k(r_h) = \frac{1}{|\{C_{h,j}\}^h|} \sum_{a_i \in \{C_{h,j}\}^h} g_k(a_i) \tag{5.16}$$

The update procedure for all the others configurations remains the same than for the second function.

For each function, the update procedure is concluded by the verification of the order of the reference profiles. In practice, the evaluations of the profiles on every criteria are sorted such that the condition 1 is verified. This correction mechanism is applied to respect the ordering principle of our approach.

By defining these different functions, we aim to compare the performances of the model during the update procedure. In particular, it will allow us to identify to what extent the use of the preference information from the interval categories would impact the convergence of the model and the quality of the final clustering.

5.3.4 *Repetition of the procedure until convergence of the model*

Given that the clustering procedure is iterative, we have to introduce conditions to stop the model. At first, we define a convergence condition that stops the clustering procedure when the distribution $\delta(A, \kappa)$ remains unchanged during 10 successive iterations. This value was measured experimentally from tests specifically modelled to provoke a situation of local convergence (e.g. 10 alternatives to cluster in 10 categories). In addition, we define a stopping condition that interrupts the model after 100 iterations without converging.

5.4 Validation

In this section, we apply the model on two structured data sets from the literature. The use of structured data sets would allow us to underline the good performance of the model while assuring the impartiality of the validation stage. The first data set concerns the Environmental Performance Index 2014 (EPI). It is composed of 178 alternatives and 2 criteria [54]. The second one is a standard benchmark data set about CPU evaluation from the UCI repository that had been preprocessed by A.F. Tehrani et al. [101]. It contains 209 alternatives and 6 criteria. For both of these data sets, linear preference functions have been selected for each criterion. Due to the nature of the evaluations, the same indifference and preference thresholds were used for each criterion (cf. Table 5.1). In PROMETHEE, we assume that the preference functions P_k and the thresholds q_k and p_k are inputs of the problem. Consequently, we did not study the impact of these values on the final results.

Table 5.1 Parameters of the EPI and CPU datasets

Parameters	Values (EPI)	Values (CPU)
n	178	209
q	2	6
w_k	$\{0.4, 0.6\}$	0.167
P_k	$\{q_k = 10, p_k = 50\}$	$\{q_k = 0.1, p_k = 0.5\}$

The aim of the validation process is to compare the three update functions and two initialization strategies of the model. In particular, we would identify if the use of the preferential information from the interval categories improves the performance of the model. We will evaluate the performances of the PCLUST procedure regarding the quality and the stability of the clustering and the convergence of the model. Each test was computed with MATLAB R2013b on a Intel Core i5 CPU 2.40GHz with 4.00GB of RAM.

5.4.1 *Quality of the clustering*

At the end of the procedure, we measure the quality of the obtained partition. We assume that a high quality clustering sort the alternatives in the categories such that the inter-distance between the categories is the highest and the intra-distance within each category is the lowest. In the ideal case, the interval categories are at equal distance from the associated principal categories. In addition, we suppose that two clustering distributions with k and $k+1$ clusters would share some similarities. We use a contingency table to illustrate this point.

Quality indicator

In order to represent the relative quality of the clustering distributions from the computation of each update functions, we have defined a quality indicator based on a penalty system that uses the preference information between the alternatives. For a given distribution $\delta(A, \kappa)$ of the alternatives in the categories and a set of reference profiles $R = \{r_1 \dots r_K\}$, we calculate the penalties based on the preference index $\pi(a_i, r_h)$ of each alternative $a_i \in A$ with the reference profile $r_h \in R$. In the following, we denote $\pi(a_i, r_h)$ as π_{ih} for simplicity reasons.

Three cases are then considered to measure the penalties. First, if we measure the intra-distance within each principal category, the preference between an alternative a_i with the corresponding centroid r_h must be minimized so that the homogeneity of each principal category is maximized. In that case, the penalty corresponds to the sum of π_{ih} and π_{hi}. Secondly, we consider an alternative a_i and a reference profile r_l so that $a_i \in C_h$ and $h > l$. If we measure the inter-distance between the principal categories, it is necessary to maximize the preference between a_i and r_h so that the heterogeneity of the population of principal categories is maximized. The corresponding penalty is equal to 1 minus the difference between π_{ih} and π_{hi}. Finally, if an alternative a_i belongs to an interval category $C_{h,l}$ with $h > l$, the penalty system considers that a_i would be as much preferred by the reference profile r_h of C_h that it prefers the reference profile r_l of C_l. Consequently, the penalty corresponds to the difference between the sum of π_{ih} and π_{hi} and the sum of π_{il} and π_{li}.

Moreover, the aim of the quality indicator is not to compare the interval categories but to evaluate their position regarding the associated principal categories. So the penalty system does not consider the case of alternatives that belong to an interval categories with the reference profiles of others interval categories. Then, considering the three cases described previously, we evaluate the quality index QI_{ij} of the alternative $a_i \in A$ and the reference profile $r_j \in R$ as follows:

$$QI_{ij} = \begin{cases} \pi_{ij} + \pi_{ji} \quad \text{if} \begin{cases} a_i \in C_h \\ r_j \in C_h \\ h \in \{1 \ldots K\} \end{cases} \\ \\ 1 - \alpha \cdot (\pi_{ij} - \pi_{ji}) \quad \text{if} \begin{cases} a_i \in C_h \\ r_j \in C_l \\ h,l \in \{1 \ldots K\},\ h \neq l \\ \alpha = \begin{cases} 1 \text{ if } h > l \\ -1 \text{ if } h < l \end{cases} \end{cases} \\ \\ |(\pi_{ij} + \pi_{ji}) - (\pi_{ik} + \pi_{ki})| \quad \text{if} \begin{cases} a_i \in C_{h,l} \\ r_j \in C_h,\ r_k \in C_l \\ h,l \in \{1 \ldots K\},\ h > l \end{cases} \end{cases} \tag{5.17}$$

Finally, we calculate the global quality index QI of the final clustering by summing the quality indexes QI_{ij}. In order to obtain a normalized value of QI, we divide this sum by the total number of pairwise comparisons that we consider when measuring the quality index. We denote this number N. Equation 5.18 expresses that the highest is QI, the better is the clustering distribution.

$$QI = 1 - \frac{1}{N} \sum_{\substack{\forall a_i \in A \\ \forall r_j \in R}} QI_{ij} \tag{5.18}$$

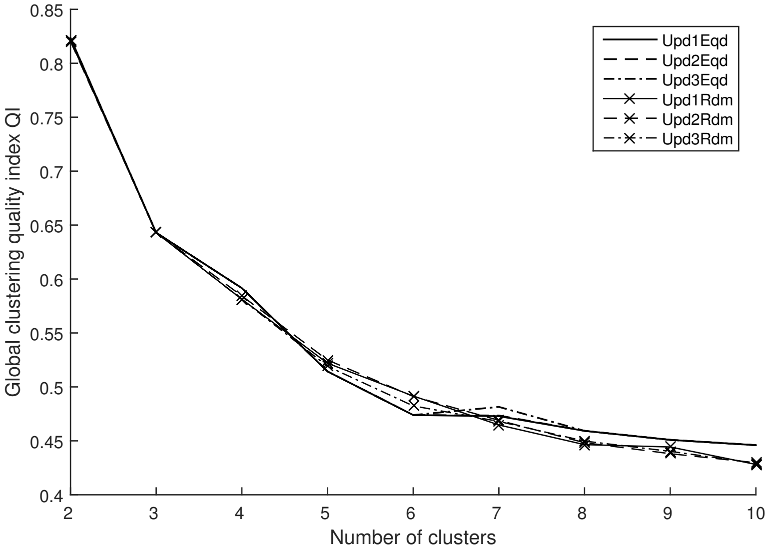


Fig. 5.3 Evolution of the clustering quality with the number of clusters, 30 tests, EPI data set.

When comparing the results of different clustering processes, the best distribution of alternatives in the categories would then obtain the highest global quality index QI. Figures 5.3 and 5.4 illustrate the evolution of the clustering quality with the number of categories respectively for the EPI and CPU data sets. The global clustering quality index QI is calculated for the three update functions and the two initialization strategies (i.e., *Rdm* and *Eqd* as introduced previously). Each test has been computed 30 times and the average values have been calculated. Note that both for the EPI and CPU data sets, the number of categories originally referenced is $k = 4$.

We observe on the Fig. 5.3 that the same clustering quality QI is obtained for the three update functions with an equidistributed or random initialization of the reference profiles. Consequently, it is very difficult to differentiate the update functions or initialization strategies at this point regarding the global clustering quality index QI. However, we note that the lower is the number of categories, the better is the quality of the final clustering. For $k < 6$, we observe values of QI higher than 0.5 which indicates a quite good quality of clustering. Note that the standard deviation of the values of QI is very limited for each update procedure. The highest deviation is 0.023 and it is obtained by $Upd1Rdm$ with $k = 5$.

The analysis of the Fig. 5.4 leads to slightly different observation. In particular, we observe better results for the global clustering quality index QI for $k < 5$ when updating the reference profiles with the third function $Upd3$. On the contrary, the

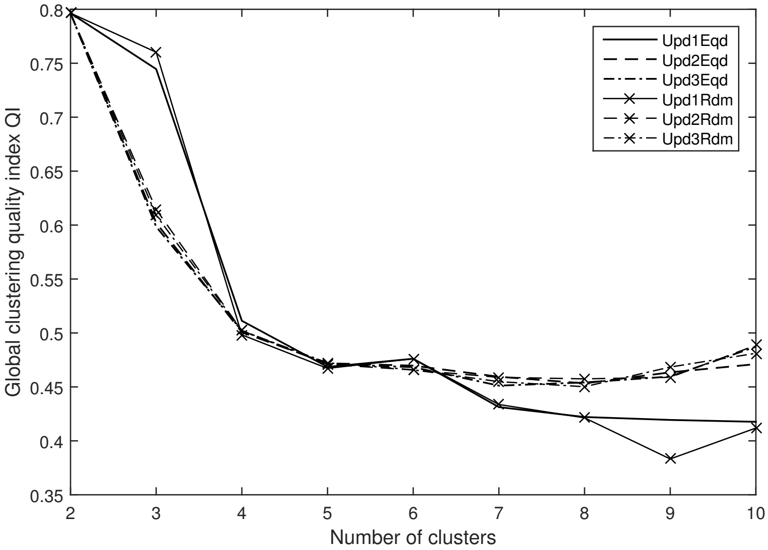


Fig. 5.4 Evolution of the clustering quality with the number of clusters, 30 tests, CPU data set.

others functions are most efficient for $k > 6$. Concerning the initialization of the central profiles, the two strategies generate similar results. Finally, we observe good values of QI overall. Similarly to the EPI data set, we observe low values of standard deviation on the CPU data set. The highest deviation is 0.034 and it is obtained by $Upd2Eqd$ with $k = 9$.

Contingency table

Obviously, the quality of a clustering distribution does depend on the number of clusters. However, if the model performs well, we assume that adding an extra category should not affect the previous distribution too much. Then, we could imagine that the distribution of the alternatives between a clustering with k categories and a clustering with $k+1$ categories would share common features. In other words, when comparing the two distributions, we expect that the majority of the alternatives would belong either to the same category C_h or to a category adjoining C_h (i.e. C_{h+1}, C_{h-1} or an interval category associated to C_h).

To verify this assumption, we generate the contingency table of the clustering distributions with respectively 2 and 3 categories for the EPI data set (cf. Table 5.2). This table allows us to compare the distribution of alternatives in the categories for the first update function and a random initialization of the central profiles. The use of the second and third update functions during the clustering procedure leads to the same type of results. In the same way, we obtained a similar contigency table with the CPU data set.

Table 5.2 Contingency table of two clustering distributions with $k = 2$ and $k = 3$ categories, $Upd1Rdm$, EPI data set

	$\|C_1\|$	$\|C_{12}\|$	$\|C_2\|$	$\|C_{23}\|$	$\|C_3\|$	$\|C_{13}\|$	Σ
$\|C_1\|$	56	7	7	0	0	0	70
$\|C_{12}\|$	0	2	50	6	0	0	58
$\|C_2\|$	0	0	0	13	37	0	50
Σ	56	9	57	19	37	0	**178**

We clearly observe in the Table 5.2 that the alternatives assigned to the categories C_1, C_{12} and C_2 of the distribution $\kappa_{k=2}$ are mainly located in the principal categories C_1, C_2 and C_3 of the distribution $\kappa_{k=3}$. In addition, the spread of the alternatives is limited to maximum two principal categories and one interval category. Consequently, when adding a principal category to the clustering procedure, the new distribution of the alternatives seems consistent compared to the previous one. This observation is also illustrated on the visual representation of the distributions $\kappa_{k=2}$ and $\kappa_{k=3}$ on the Fig. 5.5. It shows the consistency of the clustering aside from the number of categories, the type of update procedure or the initialization conditions.

5.4.2 Convergence

The analysis of the convergence of the model is a good indicator to measure the performance of each update function and the influence of the initialization strategies. We have run the model 100 times for each update function (Upd) and each initialization strategy (Eqd and Rdm). Table 5.3 indicates the average number of iterations that are required to observe a convergence of the model and the standard deviation. We consider that the model converges when it reaches the first iteration of a cycle of 10 successive unchanged distributions.

For the EPI data set, we clearly see that the influence of the update functions on the convergence is not significant. For the CPU data set, the first update function is the fastest while the third one requires more iterations to converge. Concerning the initialization strategy, it seems that the use of random or equidistributed initialization has a stronger influence on the convergence. Both for the EPI and CPU data sets, the random initialization of the reference profiles leads to a fastest convergence compared to the equidistribution of the evaluations when initializing the clustering procedure. However, the standard deviation of the results is larger when initializating the central profiles randomly. Note that for the CPU data set, two situations of non-convergence were observed during the 100 runs of $Upd3Rdm$ (none for the oth-

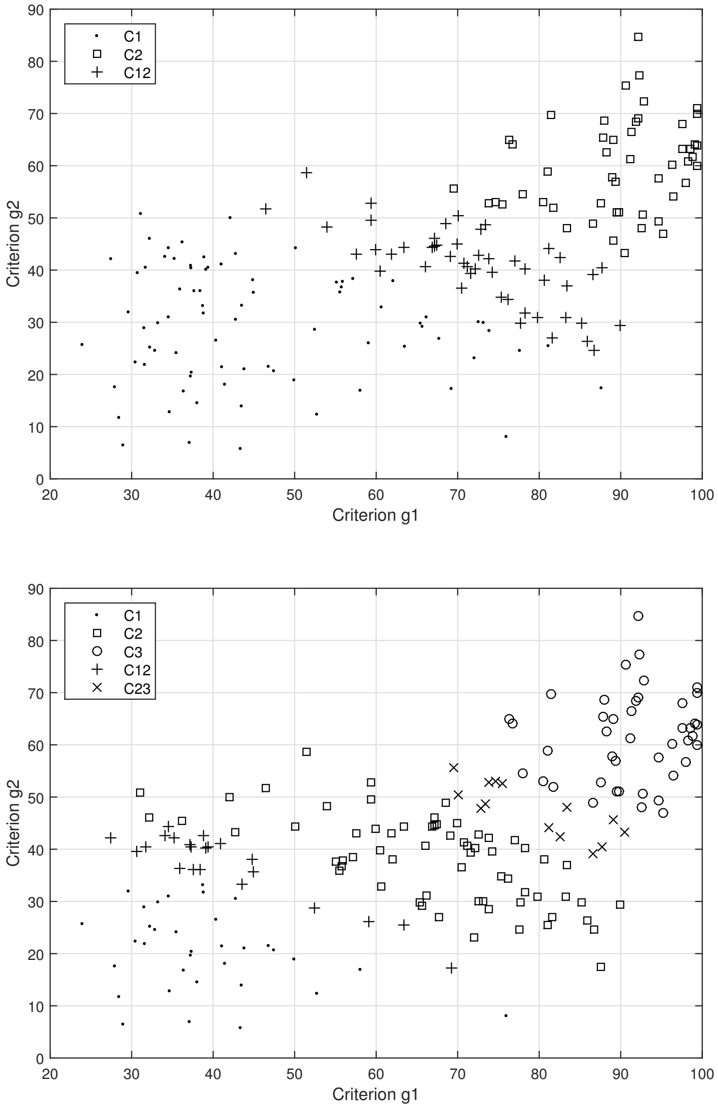


Fig. 5.5 Visual representation of the clustering for $k = 2$ and $k = 3$ ($Upd1Rdm$), EPI data set.

Table 5.3 Average number of iterations to converge (i_{tot}), standard deviation (std) and total calculation time in seconds (t_{100}), 100 runs, EPI ($k = 4$) and CPU ($k = 4$) datasets.

	EPI			CPU		
	i_{tot}	std	t_{100} (s)	i_{tot}	std	t_{100} (s)
Upd1Eqd	17	0	95.52	16.28	4.57	217.83
Upd2Eqd	17	0	96.98	20.46	6.51	282.52
Upd3Eqd	17	0	96.03	25.33	0.49	328.29
Upd1Rdm	10.04	4.51	72.88	14.89	4.90	204.92
Upd2Rdm	9.70	4.61	69.85	16.38	5.77	217.79
Upd3Rdm	10.39	5.43	73.99	18.81	12.83	253.47

ers procedures). It explains the high value of the standard deviation for $Upd3Rdm$ (12.83) in comparison with $Upd1Rdm$ and $Upd2Rdm$.

Figure 5.6 illustrates the evolution of the distribution during the clustering procedure for all the update functions and initialization strategies. At each iteration, we measure the amount of alternatives that have changed category as compared to the previous iteration. Each test has been computed 100 times such that the difference of distribution between two successive iterations corresponds to an average value. We observe almost no difference between the three update functions, while the influence of the initialization strategy is slightly more important especially for the CPU data set. Nevertheless, the convergence of the model is good for every clustering procedure.

5.4.3 Stability

We assume that a clustering procedure is stable when the final distribution of the alternatives in the categories does not vary much from one run of the model to another. In other words, the stability of the algorithm is represented by its ability to generate the same clustering structure for a given data set.

Then, to measure the stability of the model on the EPI and CPU data sets, we run the model 100 times and we identify which distribution $\delta(A,\kappa)$ is the most represented at the end of each clustering procedure for each update function and initial condition. We define the stability $\mathscr{S}$ as the occurrence of the most represented distribution after 100 runs of the model. The results of these measures of stability are presented in the Table 5.4.

We clearly notice that the stability of the clustering is very high when the reference profiles are initiated from an equidistribution of the evaluations on every criteria. On the contrary, the stability drops below 50% for the EPI data set when

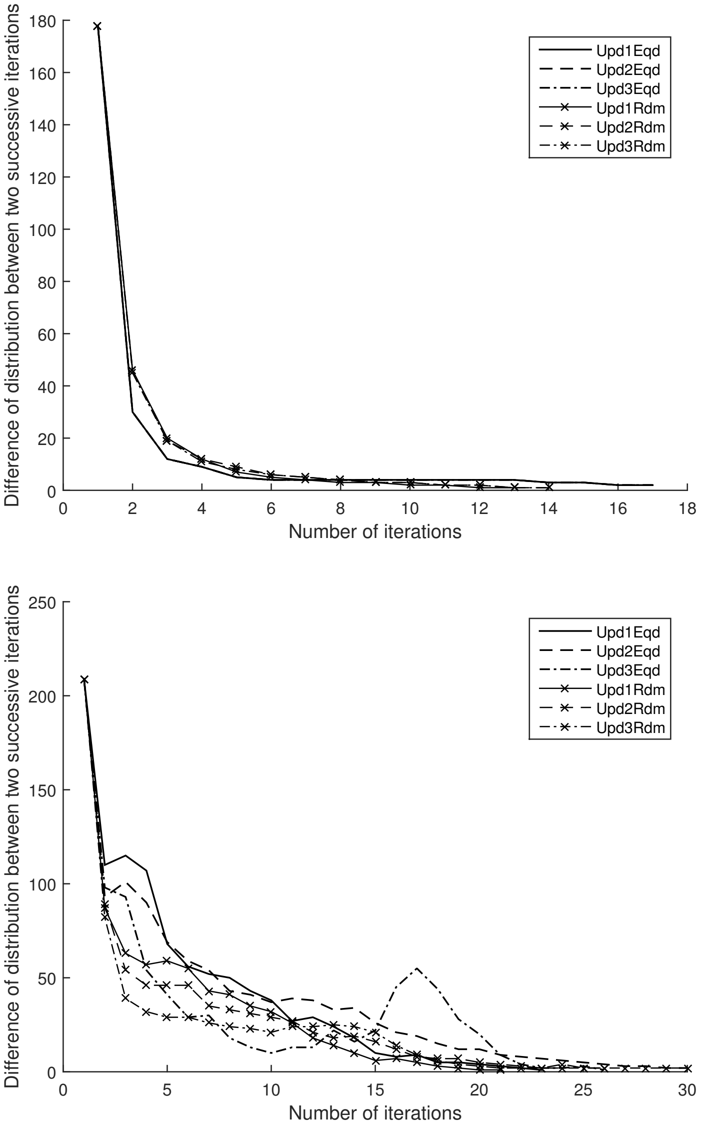


Fig. 5.6 Difference between two successive distribution during the clustering procedure, 100 tests, EPI (top) and CPU (bottom) data sets.

Table 5.4 Stability of the clustering $\mathscr{S}$ (%).

Procedure	Value (EPI)	Value (CPU)
Upd1Eqd	100	89
Upd2Eqd	100	96
Upd3Eqd	100	100
Upd1Rdm	36	94
Upd2Rdm	38	93
Upd3Rdm	35	95

initializing the reference profiles randomly. It remains between 93% and 95% for the CPU data set. The analysis of the results for the EPI data set has pointed out that 11 different distributions were generated when applying the random initialization and the first update function (9 with $Upd2Rdm$, 11 with $Upd3Rdm$). Table 5.5 shows their percentage $\%_{\delta_i}$ of representation in the set of distributions after 100 runs of the model, as well as the percentage of dissimilarity $\%_D$ with the reference distribution $\delta_1(A,\kappa)$.

Table 5.5 Proportion of distribution $\delta_i(A,\kappa)$ after 100 runs and percentage of dissimilarity, procedure $Upd1Rdm$, EPI dataset.

Distributions	Proportion (%)	Dissimilarity (%)
$\delta_1(A,\kappa)$	36.00	0.00
$\delta_2(A,\kappa)$	30.00	1.12
$\delta_3(A,\kappa)$	10.00	64.61
$\delta_4(A,\kappa)$	5.00	64.61
$\delta_5(A,\kappa)$	5.00	64.61
$\delta_6(A,\kappa)$	4.00	3.93
$\delta_7(A,\kappa)$	4.00	55.62
$\delta_8(A,\kappa)$	3.00	57.86
$\delta_9(A,\kappa)$	1.00	48.88
$\delta_{10}(A,\kappa)$	1.00	64.61
$\delta_{11}(A,\kappa)$	1.00	69.66

Then, we can see on Table 5.5 that 2 of these 8 distributions represent 66% of then entire set. When focusing on all the distributions with a percentage of dissimilarity lower than 4%, it represents 70% of the set (i.e. δ_1, δ_2 and δ_6). Consequently, it is obvious that this stability metric is strongly penalizing given than a neglecting difference between two distributions affects the final value of $\mathscr{S}$ as much as two distributions totally different. For example, a comparative analysis of the distributions $\delta_1(A,\kappa)$ and $\delta_2(A,\kappa)$ shows that only 1.12% of alternatives are allocated to a different category (i.e. 2 alternatives among 178). It indicates that if these distributions are not strictly equivalent, they are highly similar. From that perspective, we can conclude that the stability of the model on the EPI data set remains generally acceptable with a random initialization of the reference profiles.

5.5 Comparison with existing procedures

Once the PCLUST model has been defined and tested on several indicators, we could compare its performance with the well known *k*-means procedure [9, 11, 65] and the P2CLUST model. In the following, we analyse the results of the models on the EPI and CPU data sets introduced previously.

At first, let us compare the clustering distribution of each model with the PROMETHEE II ranking. Indeed, PCLUST and P2CLUST are both methods based on the PROMETHEE methodology and they generate respectively partially and totally ordered clustering distributions. Consequently, we assume that the final category membership obtained with these methods should be highly comparable to the PROMETHEE II ranking. For simplicity reasons, we only consider the $Upd1Eqd$ procedure for the PCLUST model and the equidistributed initialization strategy for the P2CLUST model, but similar results are observed with different update functions and initialization strategies. The analysis is done on the CPU data set. We observe on Table 5.6 that the first alternative of the PROMETHEE II ranking is assigned to the best cluster C_4 with the PCLUST and P2CLUST models, while it is located in the category C_3 with the *k*-means procedure. Overall, the structure of the *k*-means distribution weakly respects the PROMETHEE ranking. This observation comes as no surprise given that the *k*-means model is not suitable for ordered clustering. It shows that even if the clustering process of the PCLUST model seems to share some similarities with the *k*-means procedure, these two methods generate highly different clustering distributions. In addition, when focusing on the principal categories in the Table 5.6, we observe that the PCLUST distribution strictly respect the PROMETHEE II ranking. More precisely, there is no overlap in the PROMETHEE II ranking between alternatives assigned to different principal categories. With the P2CLUST model, we detect some ranking issues (e.g. alternatives ranked at position 77 and 78, 121 and 122). When analyzing the complete PROMETHEE II ranking, we report 26 ranking issues over the 209 alternatives (12%) with the P2CLUST model and 0 with PCLUST. Consequently, the use of interval clustering approach allows the DM to generate a clustering distribution that is closer to the PROMETHEE II ranking than when using a totally ordered clustering model.

The comparison of the global clustering quality index scores on the CPU data set also underlines the better performances of the PCLUST model in comparison to P2CLUST. Figure 5.7 shows that the values of QI are always higher than 0.45 for PCLUST. In comparison, the P2CLUST model obtains values that are always lower from 0.1 to 0.2 points (when comparing similar initialization procedures). Concerning the *k*-means procedure, it is not surprising to observe very bad quality values given that the quality index is based on the relational nature of the clustering distribution. Finally, note that the comparison of the global clustering quality index scores on the EPI data set showed quite similar results for both the PCLUST and P2CLUST models. This is due to the structure of the data set and the limited interest of using interval categories in that case.

Table 5.6 Comparison of the clustering distribution of the PCLUST, P2CLUST and *k*-means models with the PROMETHEE II ranking, 100 runs, CPU dataset ($k = 4$).

PROMETHEE II		Clustering distribution (category)		
Rank	Net flow	PCLUST	P2CLUST	k-means
1	0,664	4	4	3
2	0,495	4	4	4
3	0,491	4	4	4
4	0,486	4	4	4
5	0,446	4	4	4
6	0,421	4	4	3
7	0,397	4	4	3
8	0,368	4	4	3
9	0,359	4	4	3
10	0,326	4	4	4
11	0,300	3-4	4	3
12	0,300	3-4	4	3
13	0,289	3-4	4	3
14	0,255	3-4	4	2
15	0,237	3	4	3
16	0,193	3	4	2
	...	...	...	...
71	-0,001	3	4	2
72	-0,001	3	4	2
73	-0,001	2-3	4	1
74	-0,002	2-3	4	2
75	-0,005	2-3	4	2
76	-0,005	2-3	4	2
77	-0,006	2	3	2
78	-0,009	2-3	4	2
79	-0,012	1-3	3	1
	...	...	...	...
120	-0,066	1-2	1	1
121	-0,068	1-2	1	1
122	-0,069	2	2	1
123	-0,069	1	2	1
124	-0,069	1-2	1	1
	...	...	...	...
204	-0,102	1	1	1
205	-0,103	1	1	1
206	-0,106	1	1	1
207	-0,106	1	1	1
208	-0,107	1	1	1
209	-0,109	1	1	1

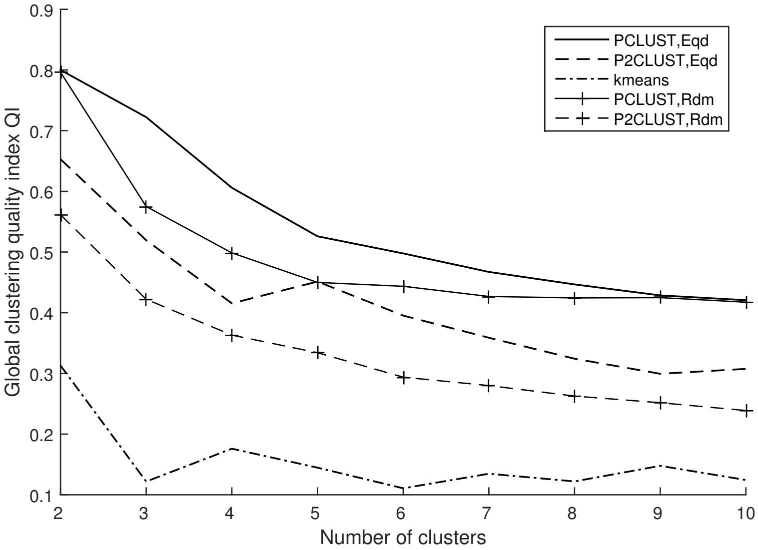


Fig. 5.7 Evolution of the clustering quality with the number of clusters, 30 tests, CPU data set. Comparison of the models PCLUST, P2CLUST and *k*-means.

Concerning the convergence of PCLUST and P2CLUST, Table 5.7 shows the performance of the two models on both data sets. We observe that the P2CLUST model converges significantly faster than PCLUST when comparing the number of iterations. However, the gain remains low to moderate when focusing on the total calculation time. On the EPI data set, the PCLUST model requires about 70 to 95 seconds to compute 100 runs while the P2CLUST method takes only 50 to 65 seconds. When focusing on the number of iterations, it corresponds to a gain between 34% and 57% for the P2CLUST model. Concerning the CPU data set, the gain in total calculation time varies between 0% ($Upd1Eqd$) and 41% ($Upd3Rdm$) in favor of the P2CLUST model. In addition, P2CLUST is 18% to 55% quicker when focusing on the average number of iterations to converge.

Finally, concerning the stability of the clustering, the Table 5.8 shows that the P2CLUST model performs very well on the EPI and CPU data sets with equidistributed initialization strategy while it obtains bad to average results when generating the initial reference profiles randomly. Concerning the PCLUST model, it obtains also good results in equidistributed initialization but it performs better than P2CLUST in random initialization (especially on the CPU data set). When considering all the distributions with a percentage of dissimilarity lower than 4%, the stability $\mathscr{S}_{\%_D<4}$ of PCLUST on the EPI data set increases up to 67% in the worst case while it remains around 30% for P2CLUST. On the CPU data set, the stability remains unchanged and strongly in favor of PCLUST.

Table 5.7 Average number of iterations to converge (i_{tot}), standard deviation (std) and total calculation time (t_{100} in seconds), methods PCLUST and P2CLUST, 100 runs, EPI ($k = 4$) and CPU ($k = 4$) datasets.

	EPI			CPU		
	i_{tot}	std	t_{100} (s)	i_{tot}	std	t_{100} (s)
PCLUST						
$Upd1Eqd$	17	0	95.52	16.28	4.57	217.83
$Upd2Eqd$	17	0	96.98	20.46	6.51	282.52
$Upd3Eqd$	17	0	96.03	25.33	0.49	328.29
$Upd1Rdm$	10.04	4.51	72.88	14.89	4.90	204.92
$Upd2Rdm$	9.70	4.61	69.85	16.38	5.77	217.79
$Upd3Rdm$	10.39	5.43	73.99	18.81	12.83	253.47
P2CLUST						
Eqd	8.00	0.00	64.26	13.33	0.84	217.07
Rdm	6.40	2.59	52.14	8.48	2.80	149.99

Table 5.8 Stability of the clustering $\mathscr{S}$ and $\mathscr{S}_{\%_D<4}$, methods PCLUST and P2CLUST, 100 runs, EPI ($k = 4$) and CPU ($k = 4$) datasets.

	S		$S_{\%_D<4}$	
	(EPI)	(CPU)	(EPI)	(CPU)
PCLUST				
$Upd1Eqd$	100	89	100	89
$Upd2Eqd$	100	96	100	96
$Upd3Eqd$	100	100	100	100
$Upd1Rdm$	36	94	70	94
$Upd2Rdm$	38	93	67	93
$Upd3Rdm$	35	95	68	96
P2CLUST				
Eqd	100	100	100	100
Rdm	25	61	30	68

Consequently, the comparison of the PCLUST model with the k-means procedure and the P2CLUST method has shown interesting results. At first, when comparing the clustering distributions with the PROMETHEE II ranking, we observed that PCLUST was more efficient to generate distributions that respect the preferential relations among alternatives. In addition, the PCLUST model obtains great performance regarding the stability and the quality of the final clustering. Nevertheless, the performance results on the convergence indicator are weakly in favor of P2CLUST.

Thus, the interval clustering which has been proposed brings something new in the field of decision aid. In fact, the interval categories give a different information compared to the principal categories. The alternatives belonging to an interval category do not have a relation between them, unlike the alternatives belonging to a principal category which should be similar. In many data sets, the data distribution promote the use of the interval clustering, which refines the ordering clustering of P2CLUST.

5.6 Conclusions

In this paper, we developed an extension of PROMETHEE I to interval clustering and we tested the performance of the proposed model on several indicators. The originality of this approach relies on the use of the preferential information among alternatives given by the PROMETHEE I method to solve the multicriteria problem of interval clustering. The proposed model uses the PROMETHEE positive and negative flow scores to assign the alternatives to the corresponding categories. We solve the problem by strictly using the preferential information among alternatives on every criteria. Thus, it limits the loss of information during the solving process and it allows the DM to generate clustering with higher quality.

Moreover, the performance analysis of the model on the EPI and CPU data sets has shown interesting results. In particular, the stability and the quality of the final clustering are particularly good with the PCLUST model. Concerning the clustering quality, the comparison of the PCLUST model with the P2CLUST approach (and more clearly with the *k*-means procedure) pointed out that the proposed model improves the quality index score from 20% with 5 categories up to 75% with 10 categories on the CPU data set. Moreover, the PCLUST model obtains on average a better stability than the P2CLUST approach. As regards the convergence of the model, PCLUST obtains acceptable results even if it requires slightly higher calculation time in comparison with the P2CLUST model.

Furthermore, the analysis of three different update procedures for the PCLUST model pointed out the limited interest of using the preferential information from the interval categories. In addition, we studied the impact of the equidistributed and random initialization strategies on the performance of the model. It emerges from this analysis that the equidistributed initialization of the reference profiles led to more stable clustering while the random initialization allows the model to converge faster.

To conclude, the PCLUST model developed in this paper had led to promising results. The use of the PROMETHEE I flow scores in the context of interval clustering constitute an added-value in the field of research of multicriteria clustering. Moreover, the analysis of the performance of the model on real-world data sets are encouraging. The comparison of the proposed model with the well-known *k*-means procedure and the formerly developed P2CLUST method has underlined a strong interest in using such an approach to characterize complex multicriteria clustering problems.

Chapter 6
Contribution 4: Practical application to a case study

Sarrazin, R. and De Smet, Y. (2015). “Solving a multicriteria road design problem: a practical example”. In: *Technical Report TR/SMG/2015-00X*, CoDE-SMG, Université libre de Bruxelles, September 2015.

Note. This paper has been accepted as a Chapter of the book *Multiple Criteria Decision Making: Applications in Management and Engineering* (Springer) in November 2015.

Abstract Improving the safety performances of road infrastructures had been a major issue in recent transport policies 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, few methodologies have been developed to support actively the road sector in the design of safer and greener roads: road designing remains mainly a single-criterion decision problem based on the global costs. This study seeks to develop a multicriteria methodology to carry out an integrated and preventive assessment of road projects at the design stage by considering both their safety performances and some economic and environmental aspects. It would support design engineers in the analysis of their projects and the identification of innovative, consistent and performing solutions. To this intent, we consider road designing as a combinatorial optimisation problem to be solved in a multicriteria context. For a given road project, we use an evolutionary approach to identify efficient solutions. Then, we apply a multicriteria clustering technique based on PROMETHEE to detect groups of similar alternatives that support a partially ordered structure. We illustrate the methodology on a real design project of a rural road infrastructure in Belgium.

6.1 Introduction

Designing a road project is not an easy task. It requires a strong technical expertise to develop efficient and performing solutions that would respect the design standards. Simultaneously, many external aspects should be taken into consideration in order to develop the most appropriate solutions according to the characteristics of the project and the demands of the specification. Among these aspects, we may cite the economic performances and the social values of the project, the environmental impacts of the road infrastructure, the travel safety and comfort, the preservation of the landscape, or even some societal and political aspects.

Over the past few decades, designing safer and greener roads has became a major concerns of mobility and transport policies in Europe. Since 2001, several reports and directives were published by the European Commission (EC) about the improvement of the safety level on the European road network. In the European White Paper on Transport Policy [38], an objective of halving the overall number of road deaths in the European Union by 2010 had been targeted. Then, this challenging objective has been updated and reinforced in the Road Safety Programme 2011-2020. It has been completed with several strategic objectives and principles such as the development of an integrated approach to road safety [41]. In 2003, the European Road Safety Charter had been 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 2008, the European Commission had published the Greening Transport Package about strategies to apply in order to strive for a transport system more respectful of the environment [40].

In Belgium, the Federal Commission for the Road Safety had been formed in 2002 with intent to fulfill the EC objectives. In 2011, the initiative ”Go For Zero” has been launched by the State Secretary for Mobility and the Belgian Institute for Road Safety. It conducts several actions to make the road users sensitive to road safety issues (e.g., speed, seatbelt, alcohol and driving, etc.) [57]. In Wallonia, the government reaffirmed its willingness to promote sustainable mobility for every road user in its declaration of regional policy for the period 2009-2014 [107].

However, this increasing political support is not followed by practical and effective actions while they would be essential to meet the objectives of the EC. In particular, an effort should be made to develop preventive and innovative tools which may be used during the design stage to assess the technical and sustainable performances of a road project. In the long run, these tools would allow us to design innovative road infrastructure projects and to promote solutions that are more consistent with sustainable transport policies.

To date, the assessment of the road safety performances of an infrastructure is essentially based on reactive approaches such as the evaluation of databases containing accident statistics. These offer the administration a support in the identification of the areas or routes with high accident concentration - also called black spots. These methods consist of curative analysis and handling of the high accident concentration areas. Moreover, the selection of project alternatives at the design stage is still mainly motivated by the economic aspect while the environmental and the social aspects are often neglected. Based on these observations, we have initiated the development of a preventive analysis of the sustainable and safety performances of a road project at the design stage.

In the field of operational research, only a few studies were conducted to address the problems of infrastructure management, road design and road safety assessment from a multicriteria perspective. Concerning the evaluation of road safety, we could cite studies that were related to the development of safety performance indicators [20] or aggregated indices based on ex-post evaluation of road projects or features [4]. Recently, multicriteria decision making techniques were applied to specific safety assessment problems such as prioritizing the accident hot spots based on geometric characteristics of the road infrastructure and traffic conditions of the road network [86] or evaluating the safety performances of pedestrian crosswalks [112]. 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 [89]. 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 [63]. 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 design, 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 [34]. 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 [67]. 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 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 [15]. Road safety performances were not considered.

Based on these observations, this study was initiated with the aim of developing a multicriteria analysis method to assess the performances of road project alternatives at the design stage. This assessment both consider the road safety performances from a preventive perspective and some environmental and economic concerns related to the sustainable character of road infrastructures. In practice, our approach is composed of two main models. At first, we use a multiobjective evolutionary approach that allow us to consider road design as a combinatorial optimisation problem and to extend the analysis to all feasible solutions of a given road project. The approximated set of the best solutions is then identified. Secondly, we use an multicriteria ordered clustering technique that regroup the solutions according to their similarity and separate those that are not. The groups of solutions finally obtained support an ordered structure so that it is possible to rank them from the best to the worst one (while allowing incomparability between some pairs).

The structure of this paper is as follows. First we provide a description of the research motivation where we briefly discuss the evaluation of road safety and the integration of sustainability assessment in the design process. Next, the methodology is presented. We introduce briefly the state of the art of our approach and we describe the multiobjective evolutionary approach and the multicriteria clustering technique. Thereafter, the method is applied on a practical case study to underline the results that could be obtained. Finally, some conclusions are provided.

6.2 Research Motivation

During the design process of a road infrastructure project, a limited set of alternatives is defined. Different design choices are made by varying parameters that represent the main characteristics of the project, such as the number of lanes, their width, the nature of the pavement materials, the type of intersections, etc. At the end of this modeling stage, an alternative is selected among the limited set of proposed solutions. But 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 analyze the performances of each alternative on multiple criteria. As a consequence, the selected solution might not be the most appropriate regarding all the characteristics, challenges and constraints of the project.

In this paper, we propose an approach that aims to support design engineers in the evaluation of their project alternatives on the one hand, and the identification of the best possible solutions on the other hand. This assessment is done in a multicriteria context so that it would be possible to select the best solution according to the characteristics of the project or the demands of the specification. Each alternative is evaluated on a set of criteria which is composed of road safety performances and some sustainable aspects related to environmental, social and economic issues. In the long run, we assume that the use of integrated assessment during the design stage of road project may promote the development of innovative and sustainable solutions. In addition, the preventive evaluation of the road safety performances may support engineers in designing safer projects in accordance with the EC policies.

6.2.1 An Innovative Approach of Road design

6.2.1.1 For a Preventive Assessment of Road Safety

In 2013, the level of safety on the Belgian road network had slightly improved with a global decrease of road deaths by 5.8%. This reduction corresponds to a total of 720 road deaths and it is in accordance with the objectives of the EC of decreasing to 620 road deaths in 2015 and 420 in 2020. However, when comparing with the situation in France (-11%) and Germany (-10%), the decrease is slower in Belgium [59]. Therefore, to reinforce the improvement of road safety in Belgium and to maintain this orientation in the long run, it would be relevant to assess the safety performances of a road project during the design stage. We assume that this preventive evaluation of road projects would allow design engineers to identify and avoid potential safety issues.

From a theoretical point of view, we may define road safety as a complex concept resulting from the association of the dimensions vehicle, driver and road equipment. On the basis of this so-called *triangle of road safety*, we are able to classify all the causes of an accident in at least one dimension of the triangle, or even a combination of them (cf. Fig. 6.1). To improve the global level of safety of a road infrastructure, it is then relevant to take an interest in the dimensions of this triangle. According to different studies, from 18% to 28% of the accidents are due to an unsafe road environment or infrastructure [84]. These safety issues might occur either due to the misapplication of the guidelines or because of the local characteristics of the project. In our approach, we then focus on the analysis of safety issues related both to the road equipment dimension and the interactions road-driver and road-vehicle. Regarding the nature of the roads concerned by our analysis, we concentrate specifically on the evaluation of secondary rural roads. Indeed, the Belgian road network is composed of roads with different functions[1] and roadside environment[2] so that their characteristics may differ significantly with regard to traffic volume and composition, density of the road network, travel patterns, roadside obstacles, etc. Then, the safety issues that may occur on these different roads are related to different causes. Consequently, the methodology that we would use to assess the performances of these roads should also differ in order to consider their distinctive features.

A large literature review was conducted on the topic of road safety [84, 50]. In particular, we analyzed the safety issues or characteristics related to the legibil-

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[1] Highway, primary, secondary or local

[2] Urban, peri-urban or rural

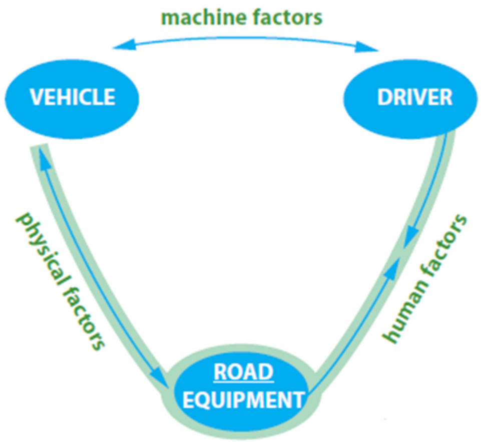

Fig. 6.1 Elementary triangle of road safety

ity of the road infrastructure [84, 85, 44], the protection of vulnerable road users [84, 80, 45], the quality of road pavement materials [20, 22], the impact of road layout and equipment [111], the design of intersections [44] and the safety on road works [109]. The seven following criteria were identified and sorted in the categories Infrastructure (INF) and Services (SRV).

INF1 - Visibility of the infrastructure
INF2 - Road design and road safety equipment
INF3 - Quality of the road pavement materials
INF4 - Protection of the vulnerable roads users (VRU)
INF5 - Intersections
INF6 - Safety on road works
SRV1 - Information and intervention services

They constitute the first part of the set of criteria that is used in our multicriteria analysis methodology. They will allow us to quantify the performance of road infrastructure projects in relation to safety. As mentioned previously, our approach is based on a preventive assessment of road project at the design stage. Consequently, we need to develop criteria exclusively from design parameters and data that are available at this stage (e.g. operational traffic volumes either from predictive models or preliminary collect sessions in case of an existing road infrastructure). Due to this constraint, the definition of the criteria was a strong methodological challenge that required an important stage of modelling and creation of data. Additionally, a few meetings were organized with experts from the road sector to review critically and validate the selected criteria.

6.2.1.2 A Support to Sustainable Road Projects

Considering the major environmental, economic and social crisis that the world has experienced, and due to the collective nature of a road infrastructure, it has become crucial to integrate the road sector policies into a more sustainable approach. Indeed, road infrastructures have close links with some sustainable topics such as energy consumption [42], preservation of environment, economic performance, noise disturbance [82, 7] or even social impact [96]. In practice, it both implies to reconsider current policies by taking into account more precisely 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 previously, several reports have been published during the past years by national and European organizations in order to promote sustainable roads. However, there is still a lack of tools and processes that could assist the actors of the road sector in the practical and integrated evaluation of the sustainable performances of their projects.

In this study, we aim to enrich the evaluation of the safety performances of road projects with some fundamental concerns related to the environmental, social and economic dimensions of sustainable development. 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. Over the past few years, several studies have been conducted on the topics of sustainable roads [77, 81, 10] and sustainable safety (e.g., Vision Zero [104], Sustainable Safety [1]). But regarding the sustainable safety concept, these studies exclusively focused on the social dimension of the sustainable development. As part of our approach, we broadened the sustainability notion to the three pillars of sustainable development - economic (ECO), social (SOC) and environmental (ENVI). The five following criteria were selected.

ENVI1 - Reduction of greenhouse gases emissions
ENVI2 - Limitation of noise pollution
SOC1 - Ensure mobility of all
ECO1 - Limitation of the construction costs
ECO2 - Limitation of the maintenance costs

The association of these criteria with the ones introduced in the previous section illustrates the concept of sustainable road safety. They constitute the set of criteria of our multicriteria decision aiding problem. The exhaustive definition of the full set of criteria goes beyond the scope of this paper but we refer to [94] for further information. Obviously, the importance of each criterion might vary depending on the characteristics of the road project, the specifications or the preferences of the decision maker. For instance, we may consider a rural road project in a non-developed area that would exclusively support motorized traffic. In that case, the criteria about noise pollution (ENVI2), mobility (SOC1), or even protection of the VRU (INF2) would be of low importance.

6.2.2 Towards a Multicriteria Analysis of the Design Process

Once a complete set of criteria has been developed, we could imagine to evaluate the alternatives that were defined at the design stage on every criteria. By doing so, it would be possible to identify which would be the set of best solutions among the ones defined by the design engineers. However, the actual design process only consider a limited set of alternatives (generally from 5 to 15 alternatives) while it would be very interesting to consider the exhaustive set of all the feasible solutions. It would allow the decision maker to analyse more precisely his problem and to finally select the most performing and consistent solution considering his own preferences and the characteristics of the project.

In this study, we assume that the design process of a road infrastructure could be considered as a combinatorial optimisation problem. Each alternative of a road project is composed of a list of variables, such as the number of lanes, their width, the type of road surface materials, the nature of the road signs, lighting equipments or vehicle restraint systems, the nature of the pedestrians and cyclists facilities, the speed limit on the roadway or even the type of intersections. Each of these variables could take a finite number of values so that a complete set of alternatives could be generated by simply combining them. As an example, if we consider a simple combinatorial optimisation problem with 10 parameters that can take 4 different values each, the number of feasible alternatives that could be generated is already quite important (about 10^6 possible combinations). In Sect. 6.4, we will see that even for a design problem that involves 12 variables ranging from 2 to 5 values, the size of the problem is significantly large. Efficient solutions are then identified by using a metaheuristic approach. Finally, a multicriteria clustering model is used to structure the multicriteria problem and identify groups of similar solutions that are partially ordered.

6.3 Methodology

The methodology we present in this paper is composed of two successive approaches. First, we use a multiobjective evolutionary approach to identify a set of performing solutions. Then, a multicriteria ordered clustering approach is applied to group similar solutions, rank them according to their performances and solve the multicriteria problem by selecting the best ones. In the following section, we briefly define the proposed model by introducing the main theoretical concepts that are related to the proposed method.

6.3.1 Multiobjective Evolutionary Algorithm

Optimization techniques are applied with the aim to find a global optimal solution (or a set of global optimal solutions). When a model is always able to identify the global optimal solution of a problem in a reasonnable amount of time, it is classified in the family of exact optimization algorithms. However, computing optimal solutions could be sometimes difficult, or even impossible, when dealing with very large and complex decision problems. In many situations, decision makers are then satisfied with a set of performing and acceptable solutions, so called a *good approximated set of solutions* that can be computed quickly. To obtain this approximated set, we may use approximate algorithms such as metaheuristics. Due to their efficiency and applicability, metaheuristics are then used in many real-world optimization problems in the fields of engineering, system modeling or data mining [48].

When solving multiobjective optimization problem with a metaheuristic, a good approximated set is obtained when the solutions are both well-performing and diversified. It corresponds to an approximation of the Pareto front that is as close as possible to the optimal Pareto front and with solutions that are well-spread. These characteristics refer respectively to the exploitation of the best solutions that are found (i.e. intensification) and to the examination of nonexplored areas of the search space (i.e. diversification) [99]. In this paper, we use the popular non-dominated sorting-based genetic algorithm called NSGA-II[3][31].

The main steps of the multiobjective evolutionary algorithm NSGA-II are described below. From the complete set of alternatives, we randomly select a limited subset that constitutes the initial population. Next, we generate the evaluation table of this initial population and then, we identify the non-dominated solutions. Afterwards, 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 are identified.

During the genetic process, we select two parents in the current population by using binary tournament selection based on the non-dominated rank of the alternatives and the crowding distance. When comparing two individuals, we select the one with the smaller rank (i.e. the *most performing*) or with the greater crowding distance (i.e. the *most diversified*). Then, we allow the parents to make a crossover with a probability P_c of 90%. We use *Simulated Binary Crossover* to generate new individuals [30] :

$$\begin{aligned} c_{1,k} &= 0.5 \times \left[(1-\beta_k)\, p_{1,k} + (1+\beta_k)\, p_{2,k}\right] \\ c_{2,k} &= 0.5 \times \left[(1+\beta_k)\, p_{1,k} + (1-\beta_k)\, p_{2,k}\right] \end{aligned} \tag{6.1}$$

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[3] Nondominated Sorting Genetic Algorithm II

where β_k (≥ 0) is a spread factor, $c_{i,k}$ (resp. $p_{i,k}$) is the evaluation of the i^{th} child (resp. parent) on the k^{th} objective.

Then, we allow the individuals of the child population to mutate with a probability P_m of 30%. We use a polynomial mutation to generate the offspring c_i'.

$$c_i' = c_i + \left(c_i^u - c_i^l\right)\delta_i \tag{6.2}$$

where c_i^u (resp. c_i^l) is the upper (resp. lower) bound of the individuals c_i and δ_i is a parameter computed from a polynomial probability distribution [99]. In the following equation, η_m is the distribution index and r_i is a random number between 0 and 1:

$$\begin{aligned} P(\delta) &= 0.5 \times (\eta_m + 1)(1 - |\delta|^{\eta_m}) \\ \delta_i &= \begin{cases} (2r_i)^{\frac{1}{\eta_m+1}} - 1 & \text{if } r_i < 0.5 \\ 1 - (2(1-r_i))^{\frac{1}{\eta_m+1}} & \text{otherwise} \end{cases} \end{aligned} \tag{6.3}$$

6.3.2 Multicriteria Ordered Clustering Model

After applying the multiobjective evolutionary algorithm to the combinatorial road design problem, we obtain an approximated set of good solutions. However, the size of this set of solutions may remain quite important so that it may not be trivial to make decisions. To this end, we propose to use a multicriteria clustering approach to simplify the multicriteria problem. Multicriteria clustering refers to the detection of groups of alternatives in a multicriteria context. It relies on the explicit consideration of preference relations between alternatives in order to build clusters. The resulting groups can be (partially or completely) ordered or considered as being incomparable. Instead of considering all Pareto optimal solutions, we can focus ourselves on representative elements of the different class in order to guide the DM.

In this study, we apply the PCLUST model which is an extension of the outranking method PROMETHEE I for interval (or partially ordered) clustering. The aim of this model is to structure a multicriteria clustering problem by defining a set of categories that supports a partially ordered structure. In other words, it groups the alternatives that are similar and separate those that are not. As a consequence, it partitions the decision space (i.e. the alternatives of the approximated set) into a set of partially ordered clusters. Then, we consider two different types of clusters in the PCLUST model: the principal clusters that are completely ordered from the best one to the worst one, and the interval clusters that are located *between* two principal clusters and then induce a partial order. We assume that the use of principal and interval clusters allows the decision maker to generate a clustering structure that reflects better the preferential information in a complex multicriteria problem.

In the following, we briefly introduce the PROMETHEE and FlowSort methods. Then, we describe our PCLUST model.

6.3.2.1 The PROMETHEE methods

The PROMETHEE outranking methods were initiated in the early 80s by J.P. Brans [12, 13, 14, 106]. They offer the decision maker a support to solve multicriteria problems by using a valued outranking relation. This relation is based on pairwise comparisons between alternatives and it defines the preference structure of the PROMETHEE method.

Let us consider a set of alternatives $A = \{a_1 \ldots a_n\}$ and a set of criteria $F = \{g_1 \ldots g_q\}$. We suppose in the following that these q criteria have to be maximized. For each criterion g_k, the DM evaluates the preference of an alternative a_i over an alternative a_j by measuring the difference of their evaluation on g_k.

$$d_k(a_i,a_j) = g_k(a_i) - g_k(a_j) \tag{6.4}$$

This pairwise comparison allows the DM to quantify how alternative a_i performs on g_k compared to alternative a_j. Then, we use a preference function P_k to transform this value into a preference degree. Depending on the shape of the preference function, the DM could define the indifference threshold q_k and the preference threshold p_k for each criterion.

$$P_k(a_i,a_j) = P_k[d_k(a_i,a_j)] \tag{6.5}$$

$$0 \leq P_k(a_i,a_j) \leq 1 \tag{6.6}$$

To quantify the global preference of a_i over a_j, we define the notion of preference index $\pi(a_i,a_j)$. It allows us to aggregate all the unicriterion preference $P_k(a_i,a_j)$ by considering the weights ω_k associated to each criterion.

$$\pi(a_i,a_j) = \sum_{k=1}^{q} P_k[d_k(a_i,a_j)] \cdot \omega_k \tag{6.7}$$

$$\omega_k \geq 0 \quad \text{and} \quad \sum_{k=1}^{q} \omega_k = 1 \tag{6.8}$$

The last step of the PROMETHEE methods relies on the calculation of the outranking flows of each action. It allows the DM to quantify on average how an action a_i is prefered to all the remaining actions x of the set A and how these actions x are prefered to a_i. These two notions are respectively represented by the positive flow ϕ^+ and the negative flow ϕ^- in PROMETHEE I.

$$\phi^+(a_i) = \frac{1}{n}\sum_{x\in A}\pi(a_i,x) \tag{6.9}$$

$$\phi^-(a_i) = \frac{1}{n}\sum_{x\in A}\pi(x,a_i) \tag{6.10}$$

The positive and negative flows could be combined into the outranking net flow ϕ which is used in PROMETHEE II.

$$\phi(a_i) = \phi^+(a_i) - \phi^-(a_i) \tag{6.11}$$

Based on the positive and negative flow scores, the PROMETHEE I method generates a partial ranking of the alternatives. In PROMETHEE II, a complete order is generated from the net flow scores of the alternatives.

6.3.2.2 The FlowSort method

The FlowSort method was developed by Nemery and Lamboray [79] for solving multicriteria sorting problems. This method allows the DM to sort the alternatives into categories based on their positive and negative flows. The categories are assumed to be defined a priori and to remain unchanged during the sorting process.

Let us consider a set of categories (or clusters) to which the actions will be assigned $\kappa = \{C_1, C_2 \dots C_K\}$. We assume that the K categories are completely ordered such that C_j is preferred to C_{j+1}. In the FlowSort method, the categories could be defined either by one central profile or two limiting profiles. In the following, we will focus on the categories characterized by central profiles [78]. Let us denote them by $R = \{r_1, r_2 \dots r_K\}$. These reference profiles are representative elements of the category which they belong to. In order to be consistent with the categories definition, they should respect the dominance principle as mentioned in Definition 6.1.

Definition 6.1. $\forall r_h, r_l \in R$ such that $h < l : \forall g_k \in F$, $g_k(r_h) \geq g_k(r_l)$ and $\exists g_x \in F \mid g_x(r_h) > g_x(r_l)$

The fundamental principle of the FlowSort method relies in the association of an alternative $a_i \in A$ to a given category using either the net flow scores of PROMETHEE II or the positive and negative flows of PROMETHEE I. Later, the net flow scores will be used to generate a complete clustering while the positive and negative flows are appropriate in the context of an interval clustering. In practice, we generate for each alternative $a_i \in A$ the combined set $R_i = R \cup \{a_i\}$. Then, the assignment of a given alternative to a category is done in two steps. First, we compare its score to the scores of central profiles. And then, we assign the alternative to the category whose the profile has the closest flow score. With net flow scores, this is formalized by the following condition [78].

Definition 6.2. $C_\phi(a_i) = C_h$ if: $|\phi_{R_i}(r_h) - \phi_{R_i}(a_i)| = \min\limits_{\forall j} |\phi_{R_i}(r_j) - \phi_{R_i}(a_i)|$

We denote $\delta(A,\kappa)$ the final distribution of the alternatives $a_i \in A$ in the set of categories κ. When the final clustering is of good quality, it produces compact but well-separated categories.

6.3.2.3 The PCLUST Model

Based on the principles of FlowSort and PROMETHEE methods, we have developed the PCLUST model which is an extension of PROMETHEE I for interval clustering [95]. The aim of this model is to solve a multicriteria clustering problem by defining a set of categories κ^* that could be divided in two groups: the principal categories C_i and the interval categories $C_{i,j}$, $\forall i, j \in \{1 \ldots K\}$ and $i \neq j$. The principal categories are ordered and respect the dominance principle. While the interval categories $C_{i,j}$ are located ”between” the principal categories C_i and C_j. Considering the preference relation of PROMETHEE, it means that the profile $r_{i,j}$ is incomparable with r_i and r_j. In this paper, we assume that the number of categories is defined a priori by the DM. The clustering procedure of the PCLUST method is composed of the following steps:

1. Initialization of the central profiles
2. Assignment of the alternatives to the categories
3. Update of the central profiles
4. Repeat the procedure from step 2 until stop condition

In the following, we describe each step of the clustering procedure. The reader who is familiar with the *k*-means procedure directly see that the proposed approach works similarly. Nevertheless, two distinctive features have to be highlighted. At first, the allocation is based on a multicriteria sorting method. Secondly, the update of the reference profiles has to respect the multicriteria nature of the problem (i.e. the dominance condition).

Initialization of the central profiles

At first, we determine the central profiles either randomly (*Rdm*) or by equidistributing (*Eqd*) the evaluations on every criterion. When initializing the reference profiles randomly, we need to sort the evaluations on every criteria in order to respect the dominance principle between clusters.

Assignment of the alternatives to the categories

Let us consider an alternative $a_i \in A$ and the set of reference profiles $R = \{r_1 \ldots r_K\}$. As in FlowSort, we define the set $R_i = R \cup \{a_i\}$. We compute the preference degrees between the actions of R_i and we calculate the positive and negative flows. Finally, we assign an alternative to a category by refering to these two definitions:

Definition 6.3. $C_{\phi^+}(a_i) = C_h$ if: $|\phi^+_{R_i}(r_h) - \phi^+_{R_i}(a_i)| = \min_{\forall j} |\phi^+_{R_i}(r_j) - \phi^+_{R_i}(a_i)|$

Definition 6.4. $C_{\phi^-}(a_i) = C_l$ if: $|\phi^-_{R_i}(r_l) - \phi^-_{R_i}(a_i)| = \min_{\forall j} |\phi^-_{R_i}(r_j) - \phi^-_{R_i}(a_i)|$

Based on these conditions, two different categories C_h and C_l could be obtained. In order to assign each alternative to one category, we apply the following assignment rule:

Definition 6.5. $\forall a_i \in A, \forall h,l \in \{1 \ldots K\}$

$$\begin{cases} \text{if } C_{\phi^+}(a_i) = C_{\phi^-}(a_i) = C_h, & a_i \in C_h \\ \text{else,} & a_i \in C_{h,l} \end{cases}$$

We denote the categories C_h as the principal categories while $C_{h,l}$ are the interval categories $(h \neq l)$.

Update of the central profiles

At the end of each iteration, all the alternatives of the set A are assigned to categories. So, we need to update the reference profile of each category in order to take into consideration this new distribution. In completely ordered clustering, the updated value of the reference profile r_h corresponds to the average value of the evaluations of the alternatives in C_h. However, in interval clustering, the alternatives of the problem could be assigned either in principal or interval categories. So, we could imagine that the updated value of the reference profile r_h would also consider the alternatives in the interval categories $C_{h,j}$ which are related to C_h, $\forall j = \{1 \ldots K\}, j \neq h$.

The description of the update procedure goes beyond the scope of this contribution but we refer to Chapter 5 for further information.

Repetition of the procedure until convergence of the model

Given that the clustering procedure is iterative, we have to specify stopping conditions. At first, we define a convergence condition that stops the clustering procedure when the distribution $\delta(A, \kappa)$ remains unchanged during 10 successive iterations. This value was measured experimentally from tests specifically modelled to provoke a situation of local convergence (e.g. 10 alternatives to cluster in 10 categories). In addition, we define a stopping condition that interrupts the model after 100 iterations without converging.

6.4 Case Study: a Rural Road Project in Belgium

In order to illustrate the interest of using multicriteria decision aiding tools during the design process of a road project, we propose to apply the proposed approach to a real case study. It concerns the reconstruction of the national road N243a in the rural area of Walhain in Belgium. This road section connects the highway E411/A4[4] and the national road N243[5], so that important motorized traffic volumes are observed including numerous commuters and a local heavy traffic of trucks and agricultural vehicles.

The N243a is 2 kilometers long and it presents 4 at-grade intersections with rural roads. It was previously a small rural road with a speed limit of 50 km/h and some strong horizontal and vertical curves. Due to the growing traffic it supports, the N243a was under standard (i.e. narrow width, lack of marking and safety equipments, etc.) and the pavement was deteriorating on some sections of the road. On the basis of these observation, a reconstruction project was initiated to improve both the level of safety and the mobility on the infrastructure. In particular, the installation of safety equipments and the creation of a cycling facility were identified as priorities.

6.4.1 Definition of the problem

At first, we structure the road design problem of the N243a in our model by defining the local parameters of the project and the considered variables of the road. The local parameters refer to the characteristics and the constraints of the project such as the geometrical parameters (e.g. maximum road width, road length, etc.), the environmental parameters (e.g. roadside environment, presence of eventual obstacles along the roadway, number of intersections, number of retails, industrial or residential entrances, etc.) and operational parameters (e.g. function of the road, traffic volume, fraction to traffic congestion, proportion of heavy vehicles, etc.). These local parameters are available in the Table 6.1. Note that the maximum road width is also used as the feasible constraint of the combinatorial design problem.

The variables of the combinatorial optimisation problem refer to the parameters that are used to build the different alternatives of the problem. Each alternative may be defined as a vector of variables (see the Table 6.2). Depending on the value of the feasible constraint and the range of values take the variables, the size of the problem varies. For the case study of the N243a, we must handle about 2×10^6 alternatives. Obviously, this practical example is used as a proof of concept so that 10^6 solutions constitutes a lower bound. It is clear that bigger problems would involve many more alternatives. Consequently, given that computing the exhaustive multicriteria analysis would be intractable regarding the calculation time, we use the multiobjective evolutionary algorithm NSGA-II to identify an approximated set of performing solutions.

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[4] 2x3 lanes motorway section between Namur and Brussels

[5] 2x1 lanes carriageway connecting the city of Wavre with the village of Perwez (and numerous local connections with smaller villages)

Table 6.1 Local parameters of the N243a rural road

Parameter	Values	Description (unit)
w_{max}	14	Maximum width of the road reserve (m)
L_{tot}	2400	Total length of the road (m)
$rdfct$	secondary	Function of the road
$AADT$	3246	Annual average daily traffic (veh/day)
$AADThv$	13.7	Proportion of heavy vehicles in the AADT[a] (%)
FS	5.0	Fraction of the traffic congestion (%)
$typeroad$	1	Roadside environment coefficient[b]
$typespeed$	2	Roadway average speed type[b]
d_{obs}	6	Average distance obstacles–road (m)
obs_{1m}	10	Obstacles at less than 1 m of the road lanes (%)
$entr$	0	Number of entrances per kilometer[c]
cr	3	Number of crossroads along the road
$n_{l,cr}$	{1;2;2;2}	Number of lanes of each crossing road
$rdfct_{cr}$	local	Function of each crossing road
$AADT_{cr}$	{20;120;450;250}	AADT on each crossing road (veh/day)

[a] AADT = Annual Average Daily Traffic.
[b] These parameters are defined in the CAR model [62].
[c] Residential, retail and industrial entrances are considered.

Table 6.2 Variables of the design combinatorial optimisation problem of the road N243a

Variable	Values	Description (unit)
w_l	{2.5;3;3.5}	Width of the roadway lane (m)
n_l	{2;3;4}	Number of lanes
w_{sh}	{0;1;2;3}	Width of the shoulder (m)
b_{sh}	{Y;N}	Physical separation with the shoulders
cp_nat	{1–17}	Type of cycling facility
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}	Operational speed limit (km/h)

6.4.2 Identifying the approximated set of performing solutions

The application of the NSGA-II to the studied problem allows us to identify an approximated set of performing solutions. The initial population was composed of 50 alternatives randomly selected and 50 generations have been conducted in NSGA-II. A limited set of 8 criteria has been considered for methodological reasons[6]. At the end of the process, 169 non-dominated (or Pareto) solutions have been identified

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[6] The criteria INF6, SRV1, SOC1 and ECO2 were not considered.

Table 6.3 Parameters and results of the NSGA-II algorithm applied to our problem.

Data	Value	Description (unit)
alt	2350080	Total amount of feasible alternatives
initial_pop	50	Size of the initial population for NSGA-II
gen	50	Number of generations in NSGA-II
time	25.8	Average time to compute the Pareto front (s)
pareto_sol	**169**	**Size of the approximated Pareto front**

as illustrated in Table 6.3. Concerning the computational time, the Pareto frontier is computed in 25.8 seconds on MATLAB R2014b with Intel Core i5 CPU 2.40 Ghz and 4,00GB of memory. This value is determined on an average basis after 30 runs of the NSGA-II algorithm.

These interesting results illustrate the utility of using a multiobjective evolutionary algorithm to describe the problem, given that it proceeds to an efficient and extensive design space exploration. Moreover, it allows us to consider several criteria at the same time and then to give a relevant information to the DM. However, it is crucial to analyse the quality of the approximated set at the end of the genetic process. In particular, we must verify that the convergence of the model and the diversity of the final solutions on the Pareto front. To this end, we use the unary hypervolume indicator.

According to Zitzler et al. [114, 113] and Deb [29], when considering a reference point Z_{ref}, the unary hypervolume metric quantifies the volume of the multiobjective space portion which is weakly dominated by the approximation set A. The more the value of the hypervolume metric is close to 1, the more the quality of the approximation set A increases. We set the reference point Z_{ref} as the nadir point of the problem, being the vector of the worst objective function values. Fig. 6.2 shows the evolution of the unary hypervolume indicator during the genetic process. We clearly observe the convergence of the model after 20-25 generations. It indicates that the approximation set A is good and well distributed. The methodological interest of applying the NSGA-II algorithm to our design combinatorial optimisation problem is also underlined.

From a decision perspective, using such a metaheuristic allows the decision maker to reduce significantly the size of his problem - from 2.35×10^6 to 169 solutions, while preserving the quality of the final solutions. However, the selection of the most preferred solution from the approximated set remains a non-trivial task. In order to structure the set of efficient solutions, we decide to apply the PCLUST algorithm. This allows to identify the set of best solutions but also to point out different groups of profiles within road projects. To our point of view, this qualitative information will help the DM in the selection of the most interesting solution.

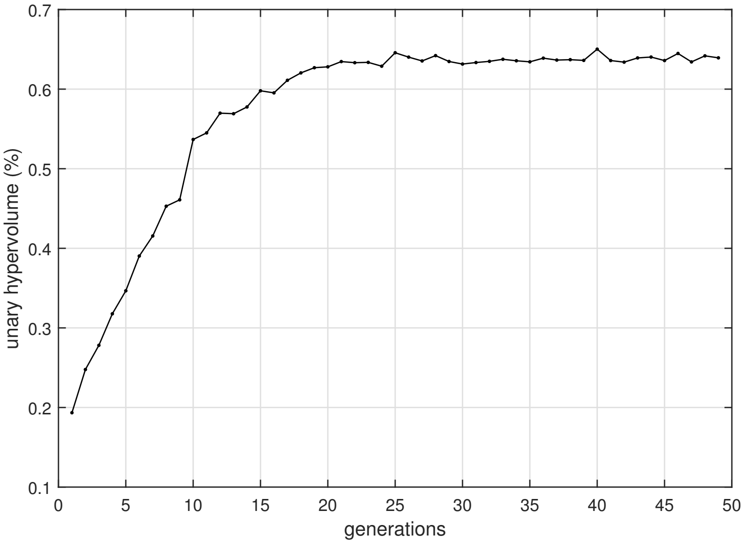

Fig. 6.2 Evolution of the unary hypervolume indicator during the genetic process (N243a)

6.4.3 Solving the multicriteria decision problem

In the design problem of the N243a rural road, the decision maker must select the best compromise alternative from a set of 169 non-dominated solutions. To support him in the identification of the solutions that would be the most performing and adapted to the design problem of the N243a rural road, we propose to use the PCLUST model. We set the number of clusters to $k = 10$. We use the equidistributed strategy to initialize the reference profiles.

Concerning the PROMETHEE parameters instantiation, we consider usual preference functions for the criteria ENVI1 and ENVI5 because of their few evaluation levels. We select the linear preference function for the remaining criteria and we set the preference threshold p_k to the third quartile of the difference between all the evaluations on each criterion. Besides, equal weights are considered given that the preferences of the DM were not defined a priori. This allows to study the problem neutrally by considering that each criterion has the same importance.

Table 6.4 shows the distribution of the 169 solutions of the approximated set among the principal and interval categories of the clustering structure. For the purposes of clarity, Table 6.4 is a double-entry table with the clustering distributions $\delta_{\phi^+}(A,\kappa)$ and $\delta_{\phi^-}(A,\kappa)$ respectively obtained with the positive and negative flows of PROMETHEE I. The distribution $\delta_{\phi^+}(A,\kappa)$ is readable vertically while the distribution $\delta_{\phi^-}(A,\kappa)$ is readable horizontally. The final distribution corresponds to

Table 6.4 Clustering distribution for the N243a design problem (169 alternatives, $k = 10$)

		δ_{ϕ^+}									
		$\lvert C_1\rvert$	$\lvert C_2\rvert$	$\lvert C_3\rvert$	$\lvert C_4\rvert$	$\lvert C_5\rvert$	$\lvert C_6\rvert$	$\lvert C_7\rvert$	$\lvert C_8\rvert$	$\lvert C_9\rvert$	$\lvert C_{10}\rvert$
δ_{ϕ^-}	$\lvert C_1\rvert$	0	0	0	0	0	0	0	0	0	0
	$\lvert C_2\rvert$	-	1	4	0	0	0	0	0	0	0
	$\lvert C_3\rvert$	-	-	5	9	0	0	0	0	0	0
	$\lvert C_4\rvert$	-	-	-	26	11	5	0	1	0	0
	$\lvert C_5\rvert$	-	-	-	-	19	29	3	1	0	0
	$\lvert C_6\rvert$	-	-	-	-	-	12	11	6	0	0
	$\lvert C_7\rvert$	-	-	-	-	-	-	4	13	0	0
	$\lvert C_8\rvert$	-	-	-	-	-	-	-	8	1	0
	$\lvert C_9\rvert$	-	-	-	-	-	-	-	-	0	0
	$\lvert C_{10}\rvert$	-	-	-	-	-	-	-	-	-	0

Table 6.5 Objective functions values of the references profiles r_i ($k = 10$)

	INF1	INF2	INF3	INF4	INF5	ENVI1	ENVI2	ECO1
r_1	1.000	0.162	1.852	5.627	1.000	4.2552	2.6957	$7,14\times10^{4}$
r_2	1.000	0.173	1.852	5.671	1.000	4.2582	2.6957	$9,99\times10^{4}$
r_3	1.000	0.176	1.852	7.000	1.000	4.2653	2.6957	$1,36\times10^{5}$
r_4	1.109	0.211	1.852	11.000	1.066	4.2659	2.6957	$1,67\times10^{5}$
r_5	1.205	0.256	1.852	23.538	1.154	4.2670	2.6957	$1,99\times10^{5}$
r_6	1.421	0.282	1.852	28.667	1.316	4.2685	2.6957	$2,17\times10^{5}$
r_7	1.556	0.341	1.852	33.579	1.833	4.2696	2.6957	$3,25\times10^{5}$
r_8	1.667	0.343	1.859	40.125	2.000	4.2697	2.6957	$4,62\times10^{5}$
r_9	2.000	0.388	1.880	40.750	2.000	4.2703	2.6998	$4,91\times10^{5}$
r_{10}	2.152	0.491	2.083	45.112	2.000	4.2710	2.7098	$1,27\times10^{6}$

the combination of the assignment in the rows and columns. For instance, the alternatives that are assigned to C_4 in the both direction are in the principal cluster C_4, while the alternatives that are assigned to C_4 horizontally and C_6 vertically belong to the interval category C_{4-6}. Table 6.5 shows the objective functions values of the reference profiles of each principal category of the clustering structure.

On the basis of these two tables, we clearly observe that the distribution of the solutions within the different clusters is quite well-spread. However, the best and worst clusters are empty. It may indicate that the two extreme reference profiles are too exclusive or that any alternatives of the set maximise (resp. minimize) their evaluations on every criteria. In addition, we see that 1 alternative is assigned to the best non-empty principal category C_2 while 4 alternatives belong to the interval category C_{2-3} and 5 alternatives are assigned to C_3. To select the best alternative of the multicriteria problem, the DM should then focus on these solutions. In order to define the composition of each category, we may analyse the values of the decision variables of each representative solution.

The analysis of the Table 6.6 indicates that several design options are represented. For simplification reasons, we only considered the non-empty principal categories and the best non-empty interval category C_{2-3}. At first, when focusing on the roadway lanes (width and number), many configurations are represented : 2×2.5, 2×3.0, 2×3.5. In addition, four different solutions for the cycling equipment are also represented and correspond to a mixed traffic on the roadway ($cp\_nat = 1$), a marked lane on the roadway ($cp\_nat = 2$) and a cycle lane separated from the roadway without physical separation ($cp\_nat = 6$) or delineators ($cp\_nat = 7$). Similarly, the nature of the equipments for the road signs and the marking differs from a category to another. However, the maximum speed limit is set to 50 km/h for each representative solution, essentially because we did not considered the mobility criterion (SOC1).

Table 6.6 Decision variables values of a the non-dominated solutions that are the closest to the reference profiles of each category of the clustering structure

C_i	id	w_l	n_l	w_{sh}	b_{sh}	cp_nat	w_{med}	mat_nat	r^a	m^a	l^a	it^a	v
C_2	130	2.5	2	3	0	7	0	6	2	2	3	3	50
C_{2-3}	131	2.5	2	3	0	6	0	6	2	2	3	3	50
C_3	19	3.5	2	3	0	6	0	6	2	2	3	3	50
C_4	67	2.5	2	3	0	7	0	6	2	1	3	3	50
C_5	158	2.5	2	3	0	6	0	6	1	2	3	1	50
C_6	114	3.0	2	3	0	7	0	6	2	1	3	1	50
C_7	107	2.5	2	1	0	1	0	6	2	1	3	1	50
C_8	163	3.5	2	1	0	2	0	6	1	1	3	1	50

[a] r = rsign ; m = marking ; l = lighting ; it = intertype

Consequently, based on the results of the multicriteria clustering problem, a performing solution for the reconstruction of the N243a should consider an efficient and safe cycling facility (with a physical separation from the roadway). In addition, the better are the road signs, marking and lighting equipments, the better is the global performance of the designed solution. These two observations constitutes an interesting output while they were the main requirements in the specifications for the reconstruction of the N243a. Moreover, we observe that the construction of wide shoulders is strongly recommended. However, it seems that increasing the operational speed limit is not necessary.

These first conclusions provide the basis for a strategic discussion between the DM and the others actors of the project at the end of the pre-design stage. In particular, they convey preliminary information and guidelines to refine the search of a performing and consistent solution (e.g. by eliciting the weights associated to each criterion more precisely). The design of a road project may then be considered as an iterative process that would involve the different actors of the project at the end of each stage. This would support the development of performing compromise solutions.

6.5 Conclusions

Considering the objectives of the EU to reduce the number of fatalities on the road network by 2020, it is crucial to take practical and effective actions in favor of road safety. In this study, the development of an innovative model to assess both the road safety and the sustainable performance of a project at the design stage had led to interesting results. In addition, we underlined the interest of applying successively a multiobjective optimisation approach and a multicriteria clustering technique to assist the engineers during the design process of an infrastructure. In particular, the consideration of the road design process as a combinatorial optimisation problem and the use of an ordered clustering approach seem fully appropriate to solve this multicriteria decision problem. Moreover, we do think that the proposed methodology is scalable to more complex problems.

About the use of a multiobjective evolutionary approach to characterize the design problem, the main added-value lies in the consideration of the design process as a combinatorial optimisation problem. By doing so, we enrich the preliminary stage of the road design process by considering all the feasible solutions of a specific project. Then, it may support the engineers in the identification of new challenging solutions and the comparison of several design options. From a methodological point of view, performance indicators illustrate the quality of the solutions generated by the algorithm in terms of convergence and diversity. In particular, the results obtained from the computation of the unary hypervolume indicator show the quality of the approximation set given by our model. Let us point out that a quantified study of this approach has been provided in [93].

To structure the multicriteria decision problem, the use of a multicriteria clustering approach seems also interesting and appropriate. Especially, it may assist the decision maker in the identification of the representative alternatives of the Pareto frontier. The comparison of these alternatives and the selection of a final solution would then be facilitated. In order to consider the multicriteria nature of the problem and to guarantee the relevancy of the clustering, the development of a clustering model based on the preferential information between alternatives is particularly interesting. This approach allows the decision maker to partition the set of performing solutions by taking into account the preferential relations between them. In the end, the definition of a partially ordered clustering structure constitutes a strong information in a decision aiding context, while it indicates which are the best and worst categories or even the categories of alternatives with singular profiles (i.e. interval categories).

Additionally, some improvement could be done in the proposed approach to give an even more relevant, precise and useful output to the decision maker. In particular, the improvement of the set of criteria may help to have a better understanding of the road project safety issues and their quantification. Concerning the methodology, it may be interesting to integrate the weights elicitation procedure in the multiobjective evolutionary algorithm in order to identify efficient solutions that illustrate the preferences of the DM. To help structuring the multicriteria decision problem, we may also imagine to consider the number of categories as a variable of the multicriteria clustering model. By doing so, we may suggest to the DM the clustering structure that partitions the set of alternatives by maximising the quality of the distribution.

In the long run, the use of this model may lead to the definition of innovative and integrated solutions. It may also help design engineers in the promotion of their solutions by the others actors of the project and to set off constructive discussions.

Appendix A
Appendix: Additional contribution

Sarrazin, R. and De Smet, Y. (2011). *A preliminary study about the application of multicriteria decision aid to the evaluation of the road projects performance on sustainable safety*. In: Proceedings of 2011 IEEE International Conference on Industrial Engineering and Engineering Management, pp. 727-732.

Abstract Since 2002, improving road safety has been a main issue in policies for transport and mobility in Europe. In Belgium, the Federal Commission for the Road Safety had defined an objective of reducing the number of deaths on Belgian roads to 500 by 2015. Then, this research aims to improve road safety on Belgian roads by developing a multicriteria decision aid model for the evaluation of sustainable road safety on secondary rural roads. In this preliminary study, we describe the approach which led us to the development of the first elements of our methodology. At first, we define the set of criteria that structures the problem, and then, we apply them to a specific case study the redevelopment of the N243a. Finally, we analyze the results to prove the complexity of this type of problems and to point out the usefulness of a multicriteria decision aid methodology to resolve them.

Keywords: Multiple Criteria Analysis, Decision Aiding, Road Infrastructure, Sustainable Road Safety

A preliminary study about the application of multicriteria decision aid to the evaluation of the road projects' performance on sustainable safety

R. Sarrazin[1 2], Y. De Smet[1]
[1] CoDE-SMG laboratory, Engineering Faculty, Université Libre de Bruxelles, Brussels, Belgium
[2] Division of Safety and Road Management, Belgian Road Research Centre, Brussels, Belgium
(r.sarrazin@brrc.be ; yves.de.smet@ulb.ac.be)

Abstract – **Since 2002, improving road safety has been a main issue in policies for transport and mobility in Europe. In Belgium, the Federal Commission for the Road Safety had defined an objective of reducing the number of deaths on Belgian roads to 500 by 2015. Then, this research aims to improve road safety on Belgian roads by developing a multicriteria decision aid model for the evaluation of sustainable road safety on secondary rural roads. In this preliminary study, we describe the approach which led us to the development of the first elements of our methodology. At first, we define the set of criteria that structures the problem, and then, we apply them to a specific case study – the redevelopment of the N243a. Finally, we analyze the results to prove the complexity of this type of problems and to point out the usefulness of a multicriteria decision aid methodology to resolve them.**

Keywords – **multicriteria analysis, decision aiding, road infrastructure, sustainable road safety**

I. INTRODUCTION

For many years, both improving road safety and recognizing sustainable development have been central issues in policies for transport and mobility in Europe. In 2001, the European Commission had published the European White Paper on Transport Policy [1] in which an objective of halving the number of road deaths in the European Union had been targeted. According to this report, the Federal Commission for the Road Safety in Belgium had supported this decision by defining an objective of reducing the number of deaths on Belgian roads to 500 by 2015 [2]. The road safety can be defined in theory by use of the elementary triangle of road safety (Fig. 1) – driver, vehicle and the road environment [3].

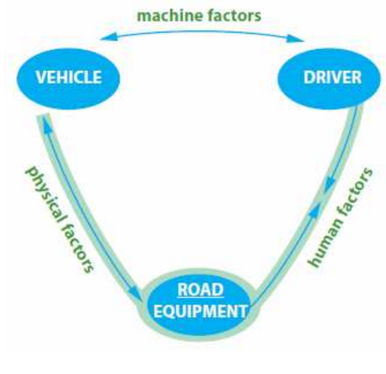

Fig. 1 Triangle of road safety [4]

On the basis of this triangle, we are able to classify all of the causes of an accident in one of the three main elements (i.e. apexes of the triangle) or their interactions (i.e. sides of the triangle). Then, according to different studies, from 18% to 28% of the accidents are due to an unsafe road environment or infrastructure [4]. Then, improving the safety of a road and its environment appears to be an important part of all the measures which should be taken in order to achieve the national and European objectives of reducing the number of fatalities.

Otherwise, the Belgian road network is composed of three main types of roads – the highways (1.1% of the whole road network), the primary roads (9.2%) and the secondary roads (89.7%) [5] – and it is divided into the urban network and the rural network. Moreover, there are fewer of accidents on rural roads (35.3%) than on urban roads (56.9%) but the rural road accidents are far more severe (50.2% of all the road deaths; 45.4% of all the severe injuries) [6]. Therefore, within the framework of this research, we are focusing on the potential improvement of road safety on secondary rural roads.

To achieve this goal, we have to evaluate the performance of the road project during the design process (i.e. *a priori* approach). However, the actual evaluation methods are based on an *a posteriori* approach. It means that the road safety of the Belgian roads is evaluated on the basis of some accident statistics and improvements are planed according to the level of road safety which has been measured by these statistics. Consequently, using an *a priori* evaluation method would lead to the application of some preventive actions (in contrast with the actual reactionary policies) and to provide decision makers with a better understanding of the infrastructure-related parameters which could influence the global road safety level of a road infrastructure. To be relevant, this evaluation should be global and exhaustive with regards to road safety and to some additional concerns related to sustainable development (environmental, economic and social concerns). To do so, the use of multicriteria decision aid appears to be appropriate and consistent considering the multidisciplinary nature of this topic. In addition, by using a MCDA method, we would be able to evaluate and rank the different alternatives defining a given road project after the *draft design* stage. Then, it would be possible to support the design engineer in the selection of an alternative (for the continuation of the design process) in accordance with the preferences of the decision maker and the *sustainable road safety* performances of the alternative.

II. METHODOLOGY

In practical terms, we would like to rank the different draft alternatives of a road project with the assistance of a multicriteria decision aiding method. Then, each alternative would be evaluated on a set of criteria which would describe the *sustainable road safety*. This represents a typical MCDA problem wherein the alternatives of the problem are the draft alternatives of the road project and the criteria illustrate the sustainable road safety performances of this project. A major added value of this paper mainly relies on the proposition of a set of criteria that correctly represent this main objective.

A. Global methodology

The methodology used to obtain a ranking of the draft alternatives of a road project is composed of two main stages. In the first place, we have to build the evaluation table Alternatives x Criteria. This part of the methodology is crucial and could be very complex. Indeed, the definition of the criteria implies an important stage of modeling and creation of data. This constitutes a main part of the preliminary study this will be explained in details in what follows. In the second place, we have to resolve and analyze the MCDA problem. In practical terms, this means that we have to build an aggregation and evaluation procedure by defining notably the characteristics of the criteria and the preferences of the decision maker. For now, we have chosen to use a multicriteria decision aid software – *D-Sight* – implementing the PROMETHEE and GAIA method [7]. The PROMETHEE rankings are used as prescriptive tools while GAIA is a visual interactive module which supply the decision maker some additional information about the results and the data of the problem Finally, a sensitivity analysis can be realized to observe the robustness of the problem. A description of this methodology is, of course, beyond the scope of this paper. We refer the interested reader to [8] for a good introduction to this topic.

B. Definition of a set of criteria

In order to structure the problem, we have to define a set of criteria which represent the sustainable road safety performances of a road project. These criteria should describe the factors contributing to rural road accidents and the factors which promote sustainability. Then, according to the results of the project SafetyNet about the development of road safety performance indicators [9] and to some personal assumptions, we can define five families of criteria which completely describe the problem: *Infrastructure*, *Services*, *Environmental*, *Economic* and *Social*. The *Infrastructure* and *Services* families of criteria describe the performances of the road infrastructure and road environment with regards to road safety whereas the *Environmental*, *Economic* and *Social* families of criteria are the expression of the sustainable concerns of the road project.

B.1 Infrastructure

This group of criteria enables the decision maker to evaluate the road safety performance of a road project by analyzing the infrastructure-related factors which contribute to road safety on secondary rural roads.

B.1.1 Road legibility and consistency

When a driver is traveling on a road, he generates a mental representation of the road which will condition his behaviour on it (e.g. safe operating speed). 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 [3]. 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 PIARC [10], 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 (e.g. to turn left at intersections). In order to guarantee the legibility of the road, these sight distances must never be greater than the theoretical sight distance which corresponds to the minimum sight distance to ensure safety on the road. This theoretical sight distance is defined by the standards [11].
According to these parameters, the criteria “*Road legibility and consistency*” evaluates the level of legibility and consistency of the road from the measure of the ratio between the operating and the theoretical stopping sight distance *DVA* on the *n* sections of the road (1).

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

In the previous formula, $DVA_{i,op}$ is the operating sight distance (i.e. measured with the operating speed V_{85}) and $DVA_{i,th}$ is the theoretical sight distance. The measure of sight distance as a criterion to evaluate the legibility of a road has been introduced in many studies [3;12;13]. Obviously, this criterion has to be minimized.

B.1.2 Visibility

The visibility of the road refers to the roadway elements and equipments which convey visual information to the road drivers (e.g. road signs, geometric design elements, road lighting, etc.). These elements could affect (positively or negatively) the global understanding of the infrastructure and its environment by the road user.
Then, the aim of the criteria “*Visibility*” is to evaluate the influence of roadway equipments on the visual recognition of the road by the road users. Unfortunately, for now, there is lack of information about this topic. Then, the level of visibility of the road C_V is measured by

summing the coefficients of visibility α_k of the m roadway elements and equipments. α_k is an integer between 0 (very bad) and 10 (very good) which is attributed by the DM to each k roadway element. For the moment, this scale is temporary but it will be submitted to experts for consideration. This criterion has to be maximized.

$$C_V = \frac{1}{m}\sum_{k=1}^{m}\alpha_k \tag{2}$$

B.1.3 Safety equipments (roadside obstacles)

On Belgian rural roads, run-off accidents represent around 32% of all fatal rural accidents [3]. Then, if we cannot totally avoid this type of road accidents, we can reduce them severity by installing some safety equipments along the infrastructure. Thus, the criterion "*Safety equipments*" measures the influence of these equipments on the reduction of accident severity. Furthermore, the evaluation of the equipments at the intersections of the road is done separately because of the singular approach which is required for these road sections. The performance of the safety equipments is expressed on each section of the road through a scale from 0 (very bad) to 10 (very good). Similarly to the previous criteria, this scale is temporary and it will be submitted to experts for consideration.

B.1.4 Road surface quality

A poor road surface quality can result in a loss of control of the drivers' vehicle (e.g. skidding). Combined with the high speeds on rural roads, these structural defects can lead to highly severe accidents. Consequently, it is very important to preserve the quality of the road surface.

On the basis on some researches about the development of performance indicators for road pavements evaluation [14;15], we can define a safety index for the road surface (C_{RS}). This index is calculated with a weighted sum of 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}.

$$C_{RS} = 0.45\cdot\left(0.7\cdot PI_R + 0.3\cdot PI_D\right) + 0.4\cdot PI_F + 0.15\cdot PI_{WC} \tag{3}$$

The actual weighting has been defined on the basis of some research from COST [15] or BRRC [14] but the selected values will be submitted to experts for consideration in the next couple of months. The performance indicators are common values stored in a database (for several road pavement materials). This criterion must be minimized.

B.1.5 Protection of Vulnerable Road Users

One of the main characteristics of the secondary rural roads is their 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 equipments 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 studies of Davis and Epperson [16;17] about the Bicycle Safety Index Rating (BSIR), we have defined a criterion C_{BSI} which expresses the global level of safety of a bicycle equipment on a road:

$$C_{BSI} = 0.5\cdot C_{BSI,segment} + 0.5\cdot C_{BSI,inters} \tag{4}$$

wherein $C_{BSI,segment}$ is the Bicycle Safety Index on straight segments of the road and $C_{BSI,inters}$ is the Bicycle Safety Index at intersections. 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 defining 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 [3]. On the basis of these observations, we have defined the index C_{MSI} about the safety of motorcyclists.

Then, we define the criterion C_{VRU} which expresses the global level of safety for vulnerable road users on the road:

$$C_{VRU} = 0.4\cdot C_{BSI} + 0.2\cdot C_{PSI} + 0.4\cdot C_{MSI} \tag{5}$$

The actual weights have been defined on the basis of the statistics of accidents on rural roads [6] but they will be submitted to experts for consideration.

B.1.6 Work zones

This last criterion of the group "*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. But, due to the complexity of this topic and to lack of information about it, this criterion has not been developed yet. This will constitutes one of our further researches in the next couple of months.

TABLE I

Project N243a – Evaluation of alternatives on each criterion

Alternatives	Criteria										
	C_{V}	C_{LC}	C_{SE}	C_{RS}	C_{VRU}	C_{WZ}	C_{CC}	C_{MC}	C_{EmS}	C_{GHG}	C_{NP}
Alt1	7,04	8,75	6,33	3,58	3,04	7,55	650000	25000	4	3,57	3
Alt2	7,04	8,75	6,33	2,63	3,04	7,55	695000	25000	4	3,37	2
Alt3	7,04	8,75	6,33	3,58	3,52	7,55	475000	15000	4	3,57	3
Alt4	7,04	8,75	6,33	2,63	3,52	7,55	520000	15000	4	3,37	2
Alt5	7,04	8,75	6,33	3,58	2,98	7,55	725000	30000	4	3,57	3
Alt6	2,4	5,35	1,67	3,58	3,62	7,55	216000	5750	4	1,57	3
Alt7	6,4	8,75	8,6	3,58	3,52	7,55	650000	11500	4	3,32	3

B.2 Services

This group of criteria enables the decision maker to evaluate the performance of emergency and trauma care services. There is no criterion about the information services because the latter are already measured in the criterion "*Visibility*" (and "*Work zones*" concerning the information services during maintenance and reconstruction activities). However, no criteria have yet been developed to evaluate the performance of services. Both emergency services and trauma care services are evaluated by the decision maker with a subjective scale (from very good to very bad). The definition of relevant criteria "*Services*" will constitutes one of the main objectives of our further research in the next few month.

B.3 Environmental

This group of criteria concerns the evaluation of the environmental performance of a road project.

B.3.1 Greenhouse gases emissions

The restriction of the greenhouse gases emissions is one of the most frequently used criteria to represent environmental concerns. The criterion C_{GHG} measures the global emissions generated by a road project by summing the emissions of all of the *n* construction and maintenance activities ($Em_{GHG,i}$). The emissions generated by the traffic are not considered for the moment. This criterion must be minimized.

$$C_{GHG} = \sum_{i=1}^{n} Em_{GHG,i} \tag{6}$$

B.3.2 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. But, the evaluation of noise pollution is very complex and requires the development of computer models. As a consequence, we had decided to limit – for the time being, our evaluation of the noise pollution to the characteristics of the road surface. Then, depending on the nature of the road surface material of the project *mat*, the criterion C_{NP} measures its noise sensitivity γ_{ns}. The parameter γ_{ns} is available in the literature for several materials [14]. This criterion must be minimized.

$$C_{NP}(mat) = \gamma_{ns}(mat) \tag{7}$$

B.4 Economic

This group of criteria enables the decision maker to evaluate the economic performance of a road project by analyzing the construction and maintenance costs. The evaluation of the operating costs will be implemented soon. These criteria are expressed in euros (€) and must be minimized.

B.5 Social

B.5.1 Mobility and accessibility

To guarantee a good mobility and accessibility on the road infrastructure is an important element with regard to the social performance of a road project. Indeed, JM. Huriot defines the accessibility as a measure of the ease of reaching a particular location [18]. The SETRA adds that accessibility can be used to quantify the efficiency of a road or network [19]. Then, in order to measure the efficiency of a road, we can use the Speed Efficiency Coefficient *SEC* which measures the extent of a road that performs at least as well as the target or threshold speed (i.e. theoretical operating speed $v_{i,th}$).

$$SEC = \frac{\sum_{i} l_i\left(v_{i,op} \geq v_{i,th}\right)}{l_{tot}} \tag{8}$$

To calculate this parameter, we sum the length of the sections of the road $l_i(v_{i,op} \geq v_{i,th})$ on which the operating speed $v_{i,op}$ is equal or higher than the theoretical speed $v_{i,th}$ and we divide this sum by the total length of the road l_{tot}. This criterion must be maximized.

C. Application to a case study

In order to validate this first model, we adopt a particular approach by studying a specific project: the redevelopment of the N243a, a Belgian secondary road in a rural area near Wavre. The main characteristics of this project are the following:

- Length: 2.4 km
- Number of lanes: 2
- Available width (road platform): 13.70 m
- Intersections: 5
- Cycle lane: Yes
- Average daily traffic: 3250 vpd

Seven alternatives had been designed for this project with different solutions about the road surface material, some geometric design parameters, the type of cycle paths, some roadside equipments (lighting, signalization and safety barriers) and maintenance activities.

III. RESULTS

As mentioned in section II.A, a preliminary computation was conducted in order to evaluate the different alternatives according to the selected criteria. The evaluation matrix is presented in table 1. Then, the D-SIGHT software was used in order to assess the quality of these alternatives. Preference parameters are presented in table 2 (second column “Weights”).

A detailed discussion about the values of these parameters goes beyond the scope of this paper. They have been assessed on the basis of subjective judgments and then presented to a road research specialist who judged them as not too arbitrary – given that this evaluation process is innovative and not comparable to current methods.

The first analysis leads us to the ranking presented in Fig. 2 (PROMETHEE II net flow scores of the seven alternatives).We can conclude from this ranking that the alternatives 3, 4, 7 seem to be the best according to the DM’s preferences. Indeed, if we refer to the Table 1, we observe that these alternatives obtain some good – or even average – results on every criterion. In addition, the analysis of the GAIA plane (Fig. 3) illustrates that these alternatives are quite similar because they are located in the same area. Moreover, this tool allows us to conclude that both maintenance and construction costs are highly correlated.

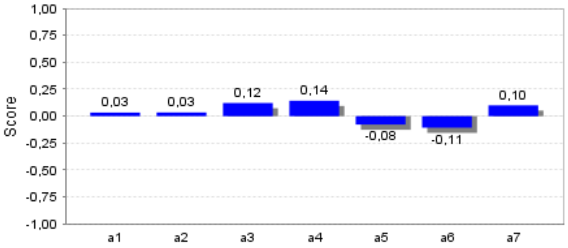

Fig. 2 Final ranking of the draft alternatives (project N243a)

TABLE II

N243a – Analysis of sensitivity: stability level for the 1st position

	Min weights	Weights	Max weights
C_V	0%	10%	100%
C_{LC}	0%	10%	100%
C_{SE}	0%	13%	20%
C_{RS}	5%	10%	100%
C_{VRU}	0%	16%	47%
C_{WZ}	0%	7%	100%
C_{CC}	4%	12%	17%
C_{MC}	0%	3%	11%
C_{EmS}	0%	5%	100%
C_{GHG}	0%	11%	34%
C_{NP}	0%	4%	100%

Additionally, one may determine that two groups of criteria are in opposition. On one hand, we have: work zones, legibility and consistency, safety equipments and visibility. On the other hand, we have: GHG emissions, noise pollution and emergency, protection of VRU and road surface quality. Obviously, the strong conflict between these two families makes the problem hard to solve. In addition, the red area on the GAIA plane represents the so-called *Decision Maker Brain*. This is the area including all the extreme points of the PROMETHEE decision axis (red axis with a big red point to its end) for a set of allowable weights [8]. Then, for this problem, we can observe that the *DM Brain* is including the origin of the graph but being principally in the left area of the GAIA plane. That means that the problem is quite hard to resolve and that compromise solutions can be in all directions of the graph – but preferentially in its top-left area. Finally, if we carry out a sensitivity analysis by modifying the weights, we can verify the robustness of our problem. On Table 2, we can observe the stability level for the first ranking position. Then, if the weights of the criteria C_{MC}, C_{CC} and C_{SE} cannot be modified on a large interval, the rank of the first alternative will not be affected by an important modification of the weights on the others criteria. Then, the selection of alternative 4 is quite robust.

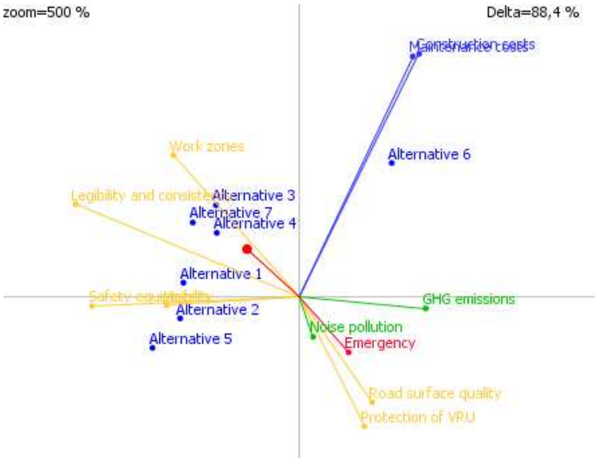

Fig. 3 Project N243a - GAIA plane

IV. DISCUSSION

Considering the complexity of the theory about road safety on rural roads, the set of criteria which has been defined within the framework of this preliminary study is not completely consistent. However, given this complexity, one of the main interests of this research is based on the development of a relevant set of criteria which could define sustainable road safety. Then, further research will be necessary to improve the criteria and to better understand some complex phenomenon about road safety. For example, road lighting generates positive effects on visibility during night-time but it could lead to an increase of the operating speeds and then to the accident risk (due to the inconsistency of the road, for example).

Moreover, about the quantification of the *real* level of performance of some equipments (or combination of equipments), there is uncertainty due to the unpredictable behaviour of road users. As a consequence, uncertainty should be taken into account in the evaluation of criteria.

Finally, as regards the complexity of the road safety theory, the study of a specific road project seems to be relevant so as to develop a multicriteria decision aid tool. But it will be crucial not to *particularize* the evaluation of road safety. Indeed, as regards the uniqueness of every road project, one of the main challenges of this research will be to develop a global and macroscopic evaluation that would be suitable for every secondary rural road project, and a more specific evaluation that would analyze the singular characteristics of each of them.

V. CONCLUSION

This preliminary study about the application of a MCDA methodology to the evaluation of the sustainable road safety performance of road projects had led to encouraging results. Indeed, despite the preliminary nature of the problem, the first observations that have been made about the analysis of the case study seem relevant and consistent with respect to road safety. However, many improvements should be done on the definition and the evaluation of criteria (e.g. definition of C_V, C_{SE}, C_{WZ}, C_{NP} and evaluation of C_{RS} and CV_{RU}). Moreover, the current evaluation of the alternatives does not take into account the life span of the equipments and materials while it is an important parameter. Consequently, some improvements would be done in the next couple of months in order to integrate this parameter in the different criteria or to define a new criterion to evaluate the global life span of the project.

The main goal of this project was to suggest the application of multicriteria decision aid for the road project's performance on sustainable safety. This is a new research project and we are aware that a lot of issues remain to be addressed. Nevertheless, we do think that this contribution already bring some added value in this application field. At least, it illustrates the complexity of such a process.

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