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Sustainability assessment of a transportation system under uncertainty: an integrated multicriteria approach

J. Moskolai, Ngossaha*, R. Houé, Ngouna*, B. Archimède*, J. M. Nlong**

* Université Fédérale de Toulouse, ENIT-LGP. 47, avenue d'Azereix, BP 1629, F-65016 Tarbes Cedex, France
(email: {justin.moskolai-ngossaha, raymond.houe-ngouna, bernard.archimede}@enit.fr).

** Université de Ngaoundéré. Faculté des Sciences, BP 454 Ngaoundéré, Cameroun
(email: jmnlng@yahoo.fr).

Abstract: Urban development is a critical issue that many cities are facing, due to the demography growth which results from the economic attractiveness of the urban centers. Based on common standards such as the Urban Development Plans, some projects for transportation systems renewal are progressively launched. In order to allow social cohesion, especially by providing travelers with services which may allow to better organize the transport, it is necessary to structure the transportation system according to sustainability requirements. This paper examines an integrated approach for assessing the sustainability of the current transportation system design, based on a policy making problem, aiming at providing decision makers with a framework allowing them to choose the most eco-responsible policy amongst many alternatives. Since the sustainability indicators may conflict each other, in order to better take into account the requirements of the whole transportation system in its design phase, a system-based approach has been adopted to characterize the complex structure of these indicators. A general methodology for their elicitation is proposed, using a process-object methodology and based on surveys from recent research on sustainable transportation, along with eco-design principles, in order to take into account urban transport priorities, sustainability challenges and the analysis of the whole lifecycle of the transport infrastructure and equipment. To validate this proposal, a multi-criteria decision method, allowing subjectivity, uncertainty, incomplete judgments and group consensus is then performed, based on a case study which shows the flexibility of fuzzy analytical hierarchy process for such assessment.

Keywords: transportation system, sustainability, complexity, system engineering, multi-criteria decision-making, uncertainty, fuzzy analytical hierarchy process.

1. INTRODUCTION

Since a United Nations commission report has formalized the concept of sustainable development, many definitions have been adapted in the context of sustainable transportation, amongst which the one proposed in (Richardson, 2005): "*the ability to meet today's transportation needs without compromising the ability of future generations to meet their transportation needs*". The main aim is to integrate economic, social and environmental requirements of sustainable development at all phases of a transportation system design. In the context of city development, nowadays, it is necessary to take into account these requirements in order for the cities to comply with rules and standards regarding sustainability. Notwithstanding the existence of various methods dealing with sustainability, organizing authorities in cities fail in providing transportation solutions which may fit citizens' needs, along with urban development challenges, mainly due to two major reasons: (1) lack of broad characterization of sustainability which can mitigate conflicted travelers' needs, (2) low availability of flexible decision aid tools allowing to assess transport policy based on human expertise. The present work aims at filling these gaps.

Sustainable transportation has been object of many research, amongst which those dealing with the *impact of land use*,

including social aspects and quality of life (Scheiner, 2006; De la Barra, 1989), *optimization of city logistics and mobility* (Ahmadi-Javid & Hooshangi-Tabrizi, 2015; Anand, Yang, Van Duin, & Tavasszy, 2012; Banister, 2008; Scheiner, 2006), *optimization of infrastructure* (Khadaroo & Seetanah, 2007; Sahely, Kennedy, & Adams, 2005), *economic efficiency* (Litman, 2016), *behavioral factors* influencing voluntary reduction of car use (Bamberg, Fujii, Friman, & Gärling, 2011), etc. These studies tend to focus on specific aspect of transport sustainability, and consequently, according to Goldman & Gorham (2006), they can fail to provide a meaningful and efficient way of facing the sustainability issue that is useful for policy makers, since neither provides a readable idea to which a transportation system might look like. Following Goldman and Gorham, the authors of this paper believe that, in order to keep the whole system in compliance with sustainable requirements over time, a larger picture of the broad system in which a transportation system is embedded should be taken into account, especially when analyzing a transport policy.

Multi-criteria decision making (MCDM) methods provide various frameworks, allowing decision makers (DM) from different domains to fulfill their judgments, including those dealing with uncertainty and incomplete information,

particularly when a DM is not able to assess a criterion. In nowadays' numerical society, few of these frameworks have been successfully integrated in the architecture of the existing tools: sometimes due to the difficulty of interpreting the theory behind the results, sometimes due to the lack of convenient interaction between experts and the proposed systems. To fill these gaps, the objective of this work is to provide the organizing transportation authorities in a city with a methodology for a new transport system design, and then to assess several transport policies in order to choose the one which can satisfy sustainability requirements, including citizens and other stakeholders needs. To this end, the major part of the work is devoted to the definition of an integrated multi-criteria framework for transport system analysis in order to facilitate its integration in an existing decision support system.

The rest of the paper is structured as follows: section 2 presents the background of this study. In section 3, the methodology for knowledge elicitation regarding the sustainability indicators of a transportation system is described, followed in section 4 by the presentation of a case study. The last section concludes the work and suggests directions for future work.

2. RELATED WORK

Within the current global economy expansion, under the well-known concept of "sustainable development", has emerged the necessity to preserve the ability of the future generations to meet their needs in whatever the society provides. In the context of urban development, the improvement of transportation systems has then become an important part of urban projects renewal. For that purpose, a sustainability indicator system is required in order to guide policies for improving sustainable development. For instance, in (Shiau et al., 2015), the authors have proposed a review of sustainability measurement frameworks for guiding in generation and selection of sustainability indicators, based on principles amongst which: relevance, controllability, availability (including ease of availability, speed of availability), measurability, interpretability, etc. Three categories of frameworks have been outlined: (1) linkage-based framework which emphasizes causality, (2) impact-based framework which focuses on listing impacts for sustainability evaluation (such as "economy, society, environment") and (3) influence-oriented framework which examines the categories of indicators by their level of influence. These studies and others have succeeded in providing qualitative and quantitative frameworks. In a policy making (the context of this work), the authors of the paper believe that a hierarchical-based framework, allowing to characterize complex sustainability indicators structure is necessary.

In a broad sense, a transportation system can be defined as a set of elements and their relationships that produce both the demand for travel within a given period, and the provision of transportation services (Cascetta, 2009); it could be seen as a complex system composed of network of interactions between its components and subsystems (infrastructures, information systems, stakeholders, etc.). Due to the complexity of the structure of sustainability indicators, these latter may conflict each other (for instance, to wish limiting the use of private cars

in favor of public transport, and at the same time, to wish enhancing accessibility in order to promote the city attractiveness). In order to build a robust sustainability indicators' system, we have then adopted a system-based approach, focusing on the analysis of the current design of a transportation system, which combines various points of view (including properties, states, structures and dynamic of the system). Indeed, we think that such approach of characterizing sustainability indicators may help to mitigate their mutual influences if they are defined at the system level, during its design phase. Thus, the sustainability assessment can better comply with the whole transportation system requirements (including sustainable development priorities and challenges) along with the stakeholders needs.

To validate the proposed indicators' system, relatively to urban development, a policy making problem has been considered. To achieve this goal, MCDM-based methods provide an ideal framework of assessment. A dozen methods have been outlined in recent survey (Mardani et al., 2016) amongst which the following: Multi-Attribute Utility Theory, ELECTRE, PROMETHEE, TOPSIS, AHP (Analytic Hierarchy Process). AHP is "*a theory of measurement through pairwise comparisons and relies on the judgments of experts to derive priority scales*" (Saaty, 1980). Due to its ease of use (pair-wise comparisons are indeed familiar process to human reasoning in real-world problem) its development has increased. Due to the pair-wise comparisons, a critical issue is that inconsistent judgments may occur. For that purpose, consistency check methods have been introduced, in order to control such issue and avoid wrong decision. Since it has been successfully used in various real-world applications close to the context of our work (e.g., performance-type problem, resource management, corporate strategy, public policy, political strategy, transport development, etc.) and due to its ease of use, AHP has been finally adopted to validate the proposed sustainability indicators system. Its ability to define hierarchical structure has re-enforced this choice. However, knowledge related to a policy making problem is not given. For that purpose, a methodology for elicitation is described in the following, based on a system engineering approach.

3. ELICITATION OF KNOWLEDGE FOR THE SUSTAINABILITY ASSESSMENT

Since knowledge on sustainability assessment is generally based on various principles, depending on the point of view used, in order to provide a robust evaluation framework which may be useful in a long-term period, we have adopted a system engineering approach, based on a holistic view of a transportation system. The associated theoretical framework is described in the following, based on the process-object methodology.

3.1 System-based approach for transportation system design

Object-Process Methodology (OPM) is "*a holistic approach to the study and development of systems, which integrates the object-oriented and process-oriented paradigms into a single frame of reference*" (Dori, 2002). Hence, this methodology allows to design a system, allowing to define both its structure and its behavior. And besides, another interesting feature is the

bi-modal expression of the model via intuitive formal graphics and equivalent natural language, which may be of great interest to allow a non-specialist in modeling to understand or

even validate a provided model. OPM building blocks are, mainly, two classes of entities: **objects** and **processes** which are connected by **procedural links** and **structural** ones.

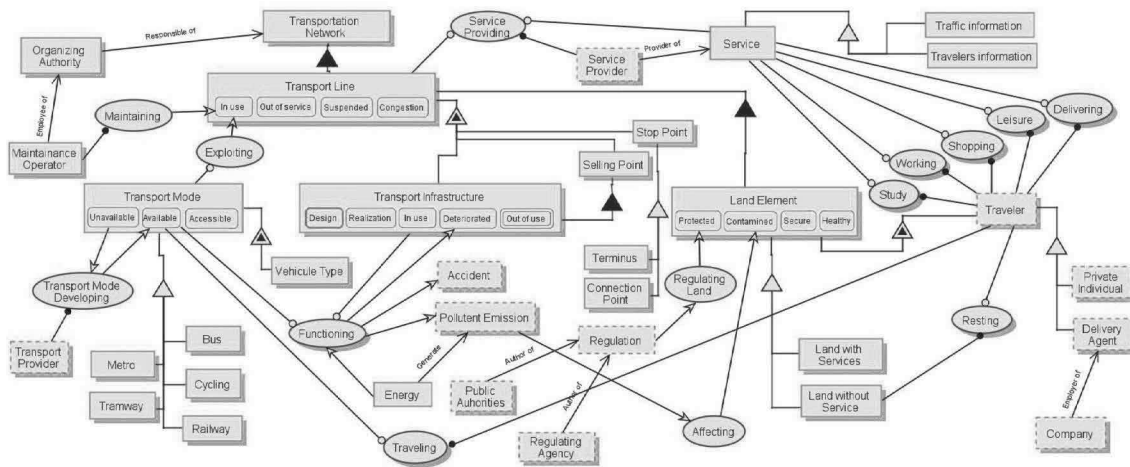


Fig. 1: Macro view of a transportation system based on Object-Process Language.

Objects are things that exist for some time. They are graphically represented by rectangles (e.g., the object "service" as depicted at the top right side of Fig. 1); they can be physical or non-physical, environmental (i.e., extern to the system) or systemic. An environmental object is depicted with a dotted line, while continuous line is used for a systemic object. This can be useful for highlighting the stakeholders of the transportation system that can be considered as external to the system (e.g. a "service provider" as depicted at the top middle of Fig. 1). An object can be characterized by its **states**, which illustrate various situations at which an object can be; states are graphically represented by rounded rectangles (e.g., the state "available" in which a transport mode can be, as depicted at the top middle of Fig. 1). *Processes* are things that transform objects and are graphically represented by ellipses (e.g., the process "regulating land" at the middle right of Fig. 1, which transforms the object "regulation" into a "protected" land element of the transportation system).

Structural links are those which denote persistent relations between objects and may be useful to define the structure of the different parts of a transportation system: aggregation/participation denotes a structural link between a part and its sub-parts (e.g., the part "transportation network" which is composed of "transport line" as depicted at the top left of Fig. 1); exhibition/characterization is a structural link between a thing and its features (e.g., the part "transportation line" is characterized by "stop point", "selling point", "transport infrastructure" defined as its features); generalization/specialization is a structural link similar to the well-known "is-a" relation and denotes a relation between a thing and its specializations (e.g., the thing "bus" is a specialization of the thing "transport mode" as depicted at the bottom left of Fig. 1). A general tagged link is a structural relation between two things of which semantic is expressed through its tags (e.g. the link "provider of" as depicted at the top middle of Fig. 1). A *procedural link* is a link between a process and the object it transforms, or the state of that object. It is of various types: consumption/result or input/output links

(e.g., the thing "pollutant emission" is consumed by or is an input of the process "affecting", while the state "contaminated" of a land element is its output/result, as depicted at the middle of Fig. 1); agent/instrument links (e.g., the thing "transport provider" is an agent of the process "transport mode developing", as depicted at the bottom left of Fig. 1), etc. The rest of the model is self-explanatory.

3.2 Methodology for the conceptualization of the sustainability indicators

Based on the above notations, the proposed methodology for sustainability indicators elicitation is summarized as follows: (1) characterize the main part of a transportation system, relatively to its parts and sub-parts and their features and states, (2) identify the stakeholders of the concerned system and specify their needs according to their use of transport, (3) define the sustainability indicators relatively to the transportation system parts which need to comply with a sustainability requirement, (4) structure the resulting indicators in a hierarchy in order to control the complexity, (5) assess a transport policy in order to validate the ability of the proposed model to evaluate the transport sustainability.

As stated earlier, such methodology for characterizing sustainability indicators, using a system-based approach, allows to define a transportation system, taking into account both the needs of all the stakeholders and the requirements of the concerned system, which is a robust approach for assessing the sustainability. The whole system of the transportation at hand (designed as previously described), in order to identify the main stakeholders, we have analyzed technical reports on urban mobility plans and various standards proposed, while the critical indicators for sustainability assessment have been carried out from surveys of specific studies on sustainable transport (Litman, 2016; WBCSD, 2016; Buzási & Csete, 2015; Miller et al., 2013; Castillo & Pitfield, 2010; Cascetta, 2009; Richardson, 2005). We have identified these indicators as factors that may affect the sustainability of "objects" or "processes" of the proposed transportation model (see Fig. 1).

From these surveys, it appeared that no common agreement on the evaluation of sustainability indicators have been established, while few studies are dealing with recyclability issues, which are of great interest for any sustainability analysis; this re-enforced the need for a holistic view, including the analysis of the whole lifecycle of all the equipment concerned with a transportation system, as suggested in (Brezet & Van Hemel, 1997) and applied in the context of product design (Houé & Grabot, 2009). The suggested methodology for recyclability analysis includes three main levels of analysis: (i) *equipment level* according to selection of low-impact material, reduction of materials usage, etc.; (ii) *equipment structure level* according to optimization of production techniques and reduction of impact during use through cleaner and lower energy consumption, etc.; (iii) *equipment system level* according to the optimization of end-of-life system through recycling material used, and optimization of initial lifetime, by promoting the use of modular structures, etc. Some thirty indicators have finally been identified: in order to control the complexity induced, a structuration in a hierarchy has been performed. The resulting indicators system is close to the parameters of the ontology proposed in (Anand et al., 2012), enriched with considerations regarding factors related to the methodology for recyclability analysis.

4. CASE STUDY AND DISCUSSION

In order to validate the proposed model and to analyze the feasibility of its application in a real-world problem, a case study has been performed, which is briefly described in the following.

4.1 Context of the study

The case study is a real-world problem regarding urbanization development. The council of a city in a developing country was about to launch new urban projects, and the main issue was to determine the target policy amongst five alternatives which are intended to enhance the transport in the city and around: policy 1 (development of an administrative area), policy 2 (development of a commercial area), policy 3 (development of an industrial zone), policy 4 (construction of a leisure area), policy 5 (construction of a cycle path in a shopping center). It is worth notice that these policies have been defined according to the needs of this city's citizens in various services, and that transport issues, in term of infrastructure and equipment development, are induced. This justifies the choice for a system-based approach to model the transportation system, highlighting the needs of the stakeholders and the requirements of the system.

Due to the low availability of the higher positions' members, the DM panel consisted in four employees from different administrative fields of the council. The aim of the work was to provide the council with a decision aid allowing to choose the best policy, according to sustainability requirements. A survey (of which the associated form is not described here for brevity) has been submitted to the DM, made of questions related to the identified transportation criteria. The theoretical framework of the concerned assessment is described in the following.

4.2 Theoretical framework of the sustainability assessment

The assessment framework is based on a AHP-approach, of which the main steps are described in the following.

Problem structuring. A general AHP model is a hierarchy of criteria with the goal of the study at the highest level; criteria and sub-criteria used to choose amongst alternatives are in intermediate levels, while the lowest level lists the alternatives to be evaluated. The AHP model of this work (see Fig. 2) is based on the sustainability indicators identified. The final tree structure has four levels: the top level (i.e. the goal) is the choice of the most sustainable transportation policy, whereas the second one represents the sustainability indicators with respect to this goal, which are "social", "environmental" and "economic" indicators. These latter are in turn characterized by sub-elements, e.g. "social" is composed of "mobility", "technology acceptability", necessity of "information system", "accessibility" and "affordability", which in turn are each composed of other indicators (which are omitted in the Fig. 2 for brevity).

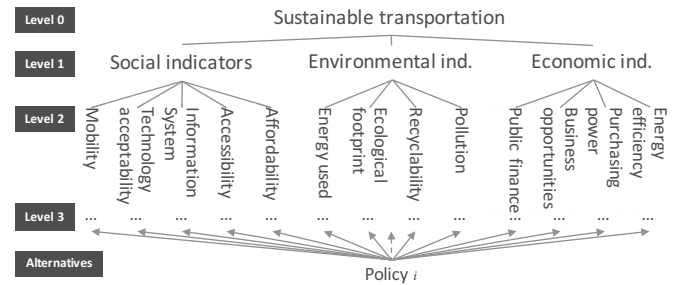


Fig. 2: Partial view of the sustainability indicators hierarchy.

Elicitation of pairwise comparisons. With the hierarchy structure at hand, pairwise comparisons of criteria in a given level are performed, with respect to the criteria of the immediate higher level (following a top down procedure). This results in comparisons' matrices in the form of (1) where each element \tilde{a}_{ij} represents an estimated ratio scale regarding the respective weights criteria i and j and estimates how strong criterion i is more important than criterion j , based on the Saaty (1980) nine-point scale and their reciprocals: $\{\frac{1}{9}, \frac{1}{8}, \dots, \frac{1}{2}, 1, 2, \dots, 8, 9\}$. In order to take into account the uncertainty with which a judgment is made, triangular fuzzy number has been used to estimate each \tilde{a}_{ij} , a choice which fits human reasoning and may help a DM to fulfill uncertain judgments.

$$\tilde{A} = \begin{bmatrix} (1,1,1) & \tilde{a}_{12} & \dots & \tilde{a}_{1n} \\ \tilde{a}_{21} & (1,1,1) & \dots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \dots & (1,1,1) \end{bmatrix} \quad (1)$$

According to the extent analysis proposed in (Chang, 1996), $\tilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij})$, where l_{ij}, u_{ij} are respectively the lower and upper bound of each judgment, while m_{ij} represents the (middle) value of which the membership function is equal to 1. Based on the extension principle of the fuzzy theory, $\tilde{a}_{ji} = (\tilde{a}_{ij})^{-1} = (\frac{1}{u_{ij}}, \frac{1}{m_{ij}}, \frac{1}{l_{ij}})$ for $i, j = 1 \dots n, i \neq j$.

Consistency check. Since a "rational" DM should not contradict himself, for the quality of the assessments,

consistency indexes of the judgments have been proposed in the literature. For this study, the Saaty (1980) consistency check have been used, based on (2):

$$CR = \frac{CI}{RI_n} \quad (2)$$

where $CI = \frac{\lambda_{max} - n}{n - 1}$, λ_{max} is the highest eigenvalue, and RI_n is a real number estimating the average CI obtained from a large enough set of randomly generated matrices of size n ; random index values for each n is provided in the literature. In practice, according to Saaty (1980), judgments' matrix with $CR \leq 0.1$ are accepted as being consistent. For simplicity, in our study, we have used the crisp value m_{ij} to compute the consistency check of each DM judgments.

Aggregation of judgments in group decision. In real-world applications, Groups Decision (GD) are established through committees, or any other team of stakeholders/experts for pairwise comparisons elicitation. In such contexts, many aggregation methods are provided, several ways of aggregating as well. For the present study, we used the Aggregation of Individual Judgments (AIJ) approach, and for robustness purpose, the geometric mean method to aggregate single judgments, which is computed as follows:

$$l_{ij} = \left(\prod_{k=1}^p (l_{ij})_k \right)^{1/p}, m_{ij} = \left(\prod_{k=1}^p (m_{ij})_k \right)^{1/p}, u_{ij} = \left(\prod_{k=1}^p (u_{ij})_k \right)^{1/p} \quad (3)$$

given p DM, where $(l_{ij})_k$, $(m_{ij})_k$, and $(u_{ij})_k$ characterize the judgment of the k -th DM.

Calculation of the priority vectors. The associated process is based on the extent analysis method on fuzzy AHP (Chang, 1996). This latter is valid only for consistent evaluations: in our case study, all the inconsistent judgments have been removed from the evaluation process, based on the consistency check indicator in (2). In order to determine an estimate of vectors of weights under each criterion, based on the representation of the DM judgments, comparisons of fuzzy numbers are necessary:

$$V(\tilde{M}_i \succcurlyeq \tilde{M}_j) = hgt(\tilde{M}_i \cap \tilde{M}_j) = \begin{cases} 1, & \text{if } m_i \geq m_j \\ 0, & \text{if } l_j \geq u_i \\ \frac{l_j - u_i}{(m_i - u_i) - (m_j - l_j)}, & \text{otherwise} \end{cases} \quad (4)$$

where \tilde{M}_i and \tilde{M}_j (for $i, j = 1 \dots n, j \neq i$) are two fuzzy numbers, and $hgt(\tilde{M}_i \cap \tilde{M}_j)$ represents the highest intersection between the possibility distribution of the two fuzzy numbers. The comparisons of the judgments are then computed using "fuzzy synthetic extent" values defined as follows, based on the extent analysis method (Chang, 1992):

$$\tilde{S}_i = \sum_{j=1}^n \tilde{a}_{ij} \otimes \left[\sum_{i=1}^n \sum_{j=1}^n \tilde{a}_{ij} \right]^{-1} \quad (5)$$

where \tilde{a}_{ij} are the triangular fuzzy numbers of the decision matrices representing the DM judgments at any level of the decision tree. The calculations are based on the operation laws deduced from the extension principle of fuzzy theory. The approximation of the weights is estimated using the values:

$$\omega'_i = \min_{j \in \{1 \dots n\}, j \neq i} V(\tilde{S}_i \geq \tilde{S}_j) \text{ for } i = 1 \dots n \quad (6)$$

which give a vector $\omega' = (\omega'_1, \dots, \omega'_n)^T$ through which the priorities vector is calculated, after normalization.

4.3 Results and discussion

The fuzzy AHP model of this work is based on the proposed indicators system described previously (see Fig. 2).

The assessment process follows the top-bottom line: the goal of the first step is defined by the top level of the tree ("sustainable transportation system") of which each DM has to provide a decision matrix, based on the comparisons of the criteria "environmental", "social" and "economic". The aim here is then, for each DM, to set how strong each criterion (amongst these three) is more important than the two others, resulting in a 3x3 matrix (see Table 1).

Table 1. Aggregated judgments for the group decisions according to the goal.

	Env	Eco	Soc
Env	(1,1,1)	(0.8736,1.1259,1.6510)	(0.4368,0.5429,0.6786)
Eco		(1,1,1)	(0.3150,0.5228,0.7211)
Soc			(1,1,1)

For brevity, in this table, the triangular fuzzy numbers representing the judgments of all the respondents (DM) to the questionnaire have already been aggregated, according to the geometric mean method. But for the quality of the analysis, all the inconsistent single judgments (according to the consistency check indicator described previously) have beforehand been removed. By applying formula (5) on the triangular fuzzy numbers of Table 1, we obtain the synthetic value for each criterion, for instance:

$$\begin{aligned} \tilde{S}_{env} &= (2.3114, 2.8028, 3.3296) \otimes \left(\frac{1}{12.6596}, \frac{1}{9.8742}, \frac{1}{8.0914} \right) \\ &= (0.1826, 0.2839, 0.4115) \end{aligned}$$

And then, by applying (4), the degree of possibility that each criterion is better than another is computed, for instance:

$$\begin{aligned} V(\tilde{S}_{env} \geq \tilde{S}_{eco}) &= 1, \\ V(\tilde{S}_{env} \geq \tilde{S}_{soc}) &= \frac{(0.3049 - 0.4115)}{(0.2839 - 0.4115) - (0.4816 - 0.3049)} = 0.3502 \end{aligned}$$

After normalization of the vector $\omega'_G = (0.35, 0.17, 1.00)^T$, we can then obtain the priorities vector of the criteria "environmental", "economic" and "social", "social" with respect to the goal: $\omega_G = (0.23, 0.11, 0.66)^T$. The priorities vector of the criteria "affordability", "accessibility", etc., with respect to "social", is computed following the same procedure, and so on up to the last level. Next, all the five policies are pair-wise evaluated with respect to each criterion of the last level and the associated priorities vector is obtained similar to the previous procedure. Finally, this last priorities' vector is combined to the weights of the upper levels in order to calculate the priorities vector of the policies with respect to goal: $W_G = (0.27, 0.41, 0.19, 0.05, 0.10)^T$. This result states that policy 2 is the best. The concerned result is then submitted to the DM who are allowed to revise their judgments until a consensus is found; which provides a readable and convenient

interaction between the DM and also between these latter and the decision aid tool.

5. CONCLUSION

In this paper, a model for a sustainable transportation system has been proposed, which takes into account the needs of the transport stakeholders along with the requirements of the concerned system, whereas the sustainability indicators have been identified through a process-object methodology. We have shown that mutual conflict between indicators which may occur could be mitigated using such model which is based on a holistic view of the transportation system. And besides, the policy making problem considered to validate the proposed model has also highlighted the flexibility of the fuzzy AHP. The provided results on the sustainably analysis may then allow consensus within the decision group, which permits the DM to revise to their judgments, through an interactive process.

For future work, a deep analysis of the complexity of the transportation system, based on an extension of the proposed model, will be studied, along with a simulation of an example of deployment of a target policy, in order to identify where problems can occur, and help the organizing authorities of transport to improve their strategic decisions.

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