Location of global logistic hubs within Africa based on a fuzzy multi-criteria approach

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ABSTRACT

Choosing the location of a global logistic hub for reaching a new market can be considered as a “facility location problem” addressed through optimization based on quantitative criteria, or as a multi-criteria decision making problem using both quantitative and qualitative criteria. The second approach has been chosen for considering the real case of a logistic provider in Africa. The first originality of this article is to suggest a global framework positioning the different types of criteria that may be used, based on an analysis of the relationships between the concept defining the decision making context. For assessing the various decision criteria, an important requirement of the company was to reuse when possible assessments coming from trustable external sources, mainly international organization indexes (World Bank, World Economic Forum, etc.), and to complete them with knowledge coming from internal experts. This knowledge being often imprecise and uncertain, Fuzzy TOPSIS, often used for Multi Criteria Decision Making, is chosen as a global methodology. The standard method has been modified on two important points: (1) a new fuzzy distance is suggested to measure the difference between two solutions, allowing to postpone the defuzzification process until the end of the reasoning, (ii) a measure of confidence has been added to each elementary assessment, allowing the experts to clearly distinguish the fuzziness of an evaluation (“around 10”) and the possibility that this evaluation is wrong. We show in an illustrative example how taking into account this new distance and the suggested confidence level may yield richer results than the standard method.

1. Introduction

Logistic hubs enable to consolidate material flows coming from different origins, to sort them by their next destination and to prepare their shipment using unimodal or multimodal transportation resources (Farahani, Hekmatfar, Arabani, & Nikbakhsh, 2013). Logistic hubs should allow decreasing logistic costs (transportations, handling, customs…) while meeting high customer’s service levels (Alumur & Kara, 2008). Different types of logistic hub have been identified in the literature depending on their geographical coverage and/or their usage and activities (Essaadi, Grabot, & Fénies, 2016; Essaadi, Grabot, & Giard, 2016; Rimienė & Grundey, 2007; Skowron-Grabowska, 2008). Rimienė and Grundey (2007) distinguish four types of logistic hub. An *international distribution centre, or Global Logistic Hub (GLH)* is the point of entry into a specific continental region by linking national suppliers or producers to overseas markets and vice-versa. It manages important flows of various types of goods at an international level and provides a place for industrial firms to perform functional activities among which transhipment, multimodal transportation, storage, consolidation, assembly, labelling, packing/co-packing, finance, R&D services and post-manufacturing (Lee, Huang, & Teng, 2009). A ***National Distribution Centre (NDC)*** manages and consolidate flows coming from GLH to distribute them to the whole country or to supply a network of regional distribution centres, to achieve national coverage. In general, inbound and outbound goods are transported on a trunk haul journey. A ***Regional distribution centre*** consolidates flows coming from GLH or NDC to serve a region within a network of similar facilities to achieve national coverage. It is often served by a trunk haul from a port, manufacturing site or national distribution centre (Oum & Park, 2004). A ***Local Distribution Centre (LDC)*** is located downstream a distribution network, i.e. close to customer locations, insuring the consolidation of flows coming from (RDC), for distributing them to their final users at the last-kilometre (Awasthi, Chauhan, & Goyal, 2011). Among these hubs, GLHs have become increasingly important for logistic providers and industrial

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firms, in particular for those aiming to expand their supply chain network toward overseas emerging markets. Thus, their location is of a critical importance, and depends not only on the effectiveness and the efficiency of the distribution network but also on the attractiveness of the country. The location of logistic hubs is a specific case of the «facility location problem» (Current, Daskin, & Schilling, 2001; Melo, Nickel, & Saldanha-Da-Gama, 2009). It consists in selecting at least one new facility from several possible locations, while satisfying at least one objective function expressing the decision maker's preferences (Farahani, SteadieSeifi, & Asgari, 2010; Żak & Węgliński, 2014). The alternative that best satisfies the compromise between all decision criteria is selected (Awasthi et al., 2011).

Many previous studies (Contreras, Cordeau, & Laporte, 2012; Gelareh & Nickel, 2011; Melo et al., 2009; Sadeghi, Tavakkoli-Moghaddam, & Babazadeh, 2018; Vahdani, Behzadi, Mousavi, & Shahriari, 2016) only consider a quantitative objective function and solve the model using analytical exact methods, like mathematical programming (Contreras et al., 2012; Gelareh & Nickel, 2011; Klose & Drexl, 2005) or meta-heuristics (Sadeghi et al., 2018; Vahdani et al., 2016). Extensive surveys on this domain are for instance presented in Alumur and Kara (2008) and Farahani et al. (2013), showing that location models based on operational research often ignore criteria that can only be qualitatively assessed, such as country stability, life quality, and infrastructure quality (Long & Grasman, 2012). In order to get a holistic view, Murthy and Mohle (2001) claim that good performance criteria for evaluating potential locations should include both quantitative and qualitative assessments and suggest that a decision regarding a location could be efficiently addressed using analytical Multi-Criteria Decision Methods (MCDM) (Long & Grasman, 2012; Zavadskas & Turskis, 2011). Following this perspective, a significant number of articles have applied MCDM to this class of problems. An in-depth analysis of this literature shows that in many cases, the authors choose their criteria in a very empirical way and often abruptly translate the subjective evaluation of a criterion into a precise mark, failing to consider that imprecision is an inherent characteristic of human judgment.

In this context, a study has been conducted with a Moroccan logistic service provider, with the objective to support decision makers for the location of RLHs in Africa, which is a promising new market under development. As detailed in Section 2.2, the requirements of the industrial partner brought us to choose Fuzzy TOPSIS as a general framework, but to define a new fuzzy distance between two solutions, so that to attach a degree of confidence to the experts' evaluations.

The article is structured as follows: Section 2 discusses the specificities of logistic hub location in Africa and details the requirements of the industrial partner. Section 3 gives an overview of the literature on the location criteria and on the different types of methods used for aggregating these criteria. This literature review shows the limitations of standards methods for addressing the needs of the industrial partner, justifying the proposal described in Section 4. The suggested framework is illustrated on a simplified but realistic example in Section 5.

2. Context of the study

2.1. Specificities of Africa

Africa has a huge potential in terms of market but also in terms of natural and human resources availability: the continent has more than 1.1 billion inhabitants, holds 40% of the world's natural resources (mining and petroleum, flora and fauna) and 65% of the remaining unexploited agricultural land on the planet; half of the total population is less than 25 years old).[1] According to the Africa Research Institute[2], the investments in Africa are constantly growing and should reach $144 billion by 2020. Nevertheless, Africa suffers from limitations that hinder its economic development and attractiveness:

- ***Weakness of transport infrastructure***. A lower density of regional inter-state infrastructure characterizes Africa. Road infrastructure - insuring 80–90% of intra-regional traffic - represents only 6.84 km per 100 km^2. The rail infrastructure network remains limited with only 2.96 km per 1000 km^2. There is also a great disparity between African countries concerning port infrastructures[2].
- ***High transport costs***. Due to the poor conditions of inland transport infrastructure, transportation costs are higher in Africa than in other regions[3].
- ***Heaviness of Customs regulation***. Despite the abolition of custom duties within some regional communities, regulation hindrances increase transaction costs and limit the cross-border movements of goods. Some countries suffer from a multiplication of customs barriers, with a frequency that may be exceed 1 every 14 km (for example, there are 69 control points on the Lagos-Abidjan axis which is 987 km long)[2].
- ***Institutions and regulation***. Administrative costs are higher in Africa than anywhere (World Bank, 2012).
- ***Lack of intra-stability.*** Some African countries still suffer from violence, creating economic turbulences, such as Niger, Sudan, Somalia, Mali and Libya (Abodohoui, Aïhounhin, Mayuto, Marif, & Montreuil, 2014).
- ***Weakness of intra-regional integration.*** The tension between Africans countries has a deep impact on the economic relations between African regions. Indeed, commercial exchanges within the continent represent less than 20% of Africa's total trade, far behind the 60 and 50% parts that are hold by intra-European and intra-Asian trade (African Bank, 2010).

The location of a GLH in Africa should take into account Africa's potential strengths and weaknesses, including the large disparities between its countries regarding both strong and weak points (Fig. 1). In this context, the requirements of the logistic provider at the origin of this study are detailed in next section.

2.2. Requirements

The expectations of the industrial partner were the followings:

(1) to define a global assessment framework for exploring systematically the relevant criteria of choice. Indeed, many criteria have already been defined in the literature on hub location (see Section 3.3). For the industrial partner, what was missing was a global analysis of the hub location problem allowing to justify the relevance and completeness of a given set of location criteria.
(2) to reuse when possible criteria assessments coming from international organizations (World Bank, World Economic Forum, etc.), considered as trustable. It may be difficult to find reliable and objective information on some sensitive criteria, like the political stability of a country or the efficiency of governmental institutions. Nevertheless, several trustable international organizations periodically produce rankings of all countries on different criteria. If some of these criteria can be reused in the context of logistic hub location, it may address the problem of the scarcity or objectivity of local data.
(3) to complete these external assessments with others coming from internal experts, under condition to take into account the confidence that the expert has in its own judgment regarding the assessment of a criterion for a given location. Some criteria very specific to the logistic activity are not addressed by international

[1] http://www.africa-onweb.com/economie/transports-afrique.htm.
[2] http://www.africaresearchinstitute.org.
[3] http://unctad.org/en/Pages/statistics.aspx.

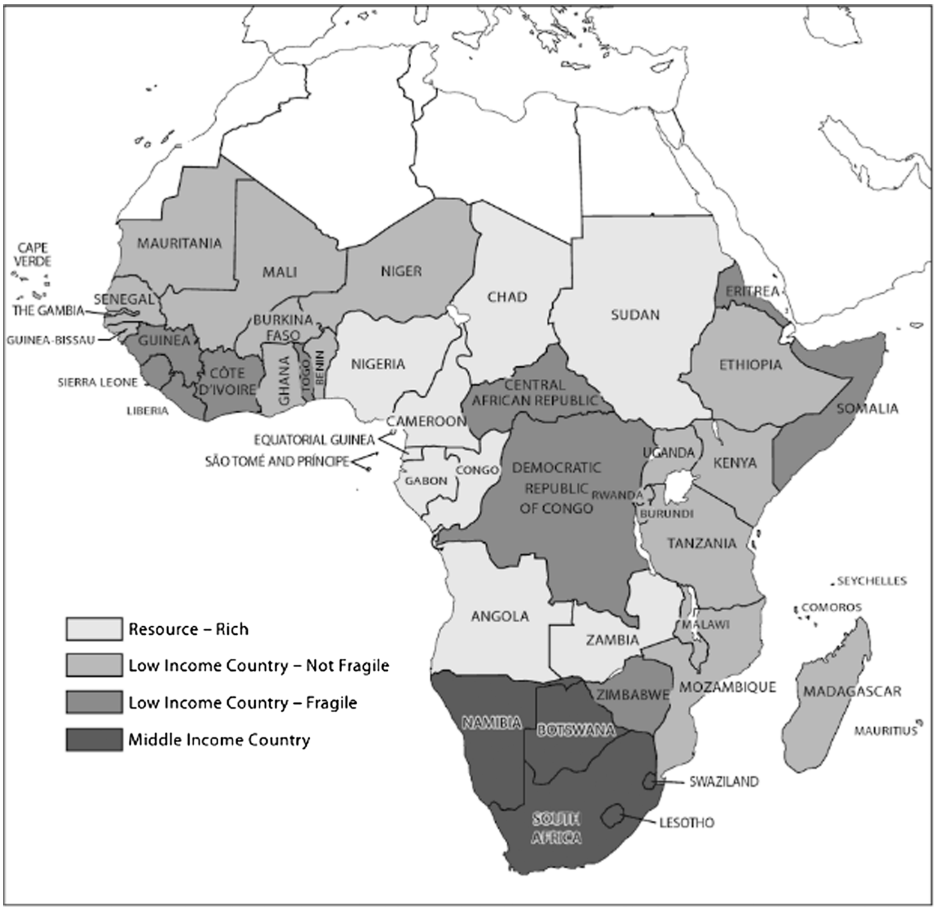

Fig. 1. Disparities between Sub-Saharan African countries (Gwilliam, 2011).

organizations, that have higher-level objectives (assessing the most peaceful countries or the global competitiveness of a country for instance). In that case, rough and subjective assessment may be produced by the logistic experts of the industrial partner. Nevertheless, these experts may be more or less confident on their own judgement regarding a given criterion. This confidence is a part of their knowledge and as such, should be taken into account in the global assessment.

Since expert judgement is often subject to imprecision, fuzzy set theory is adopted as a global information modelling framework. Analytical Hierarchy Process (AHP) is used to weight decision criteria while a modified version of Fuzzy TOPSIS is used as scoring method: we suggest in this article to modify the distance between two solutions commonly used in Fuzzy TOPSIS, with two main objectives: avoid an early defuzzification of knowledge which may set into question the interest of fuzzy information modelling, and take into account the confidence of the experts in the final appreciation.

3. Literature review

3.1. Definition of the problem

The first section of this survey aims at positioning previous works performed on four key points: hub type, hub location, decision sequence and assessment data (Table 1). The focus is set on recent papers frequently cited, and more precisely on papers dealing with GLH ecosystems based on port terminals rather than on airport terminals (90% of the international commercial traffic in Africa is carried by sea, while air transport represents only 1% of the traffic)[2].

- **Hub type**

As stated before, several types of logistic hubs may be distinguished according to their geographical coverage and/or their usage and activities (Essaadi, Grabot, & Fénies, 2016; Essaadi, Grabot, & Giard, 2016; Rimienė & Grundey, 2007; Skowron-Grabowska, 2008). However, few papers dedicated to the location of global logistic hubs can be found (Lee et al., 2009; Shiau, Lin, Ding, & Chou, 2011; Uysal & Yavuz, 2014; Yang & Chen, 2016).

- **Geographical location of the hub**

Several articles focus on theoretical aspects of hub location without considering a specific example (Awasthi et al., 2011; Kayikci, 2010; Shiau et al., 2011; Wang & Liu, 2007). Very few address the specificities of hub location in Africa (see Table 1).

- **Sequence of decision**

In the literature, the choice of a hub location may be done at different levels, leading to different criteria of choice (Essaadi, Grabot, & Fénies, 2016):

(a) ***Choice of a country***: it consists in selecting the country where a hub will be installed (Shiau et al., 2011; Wang & Liu, 2007; Yang & Chen, 2016). The criteria of choice should denote the attractiveness of the country compared to the others.
(b) ***Choice of an area inside a country***: in that case, candidate hub locations belonging to the same country are compared (Chen & Qu, 2006; Elevli, 2014; Portugal, Morgado, & Júnior, 2011; Uysal &

Table 1
Review of recent articles on hub location.

Paper	Geographical location	Hub type			Sequence of decision				Assessment Data source				Data precision		Scoring Method
		Global Logistic Hub	Regional Logistic Hub	Urban Logistic Hub	Choice of a country	Choice of an area inside a country	Sequential choice	Simultaneous choice	Expert Judgement	Online reports	International Organization indexes	Other	Exact	Fuzzy	
Lirn et al. (2004)	Taiwan	X				X			X				X		AHP
Ugboma et al. (2006)	Nigeria	X				X						X		X	AHP
Lee et al. (2009)	Asia	X						X	X					X	Fuzzy AHP
Kayikci (2010)	–		X					X	X				X		ANN
Eskilsson and Hansson (2010)	Sweden	X			X				X	X	X		X		AHP
Awasthi et al. (2011)	–			X		X						X		X	Fuzzy TOPSIS
Portugal et al. (2011)	Brazil		X			X			X	X		X	X		AHP
Yu et al. (2011)	China			X		X						X		X	Fuzzy AHP
Shiau et al. (2011)	–	X			X									X	Fuzzy MCDM
Long and Grasman (2012)	United States		X			X			X				X		AHP
Elevli (2014)	–			X		X			X					X	Fuzzy PROMETHEE
Żak and Węgliński (2014)	–			X			X		X	X			X		ELECTRE III/IV
Uysal and Yavuz (2014)	Turkey		X			X			X				X		ELECTRE III/IV
Van Dyck and Ismael (2015)	West Africa	X				X		X	X	X		X	X		AHP
Roso, Brnjac, and Abramovic (2015)	Croatia	X				X			X				X		AHP
Dey, Bairagi, Sarkar, and Sanyal (2015)	Est Asia	X						X	X					X	Fuzzy TOPSIS
Peker, Baki, Tanyas, and Ar (2016)	Turkey			X		X			X				X		ANP
Yang and Chen (2016)	Asia	X			X				X				X		Grey Analysis
Chen, Cheung, Chu, and Xu (2017)	Asia	X				X			X				X		AHP
US	Africa	X						X	X	X	X		X	X	Improved Fuzzy TOPSIS

Yavuz, 2014; Yu, Liu, Chang, Ma, & Yang, 2011).

(c) ***Sequential (or hierarchical) choice***: countries are firstly compared based on dedicated criteria, then possible locations inside the selected country are compared (Żak & Węgliński, 2014).

(d) ***Simultaneous choice***: hubs locations belonging to different countries are compared, based on criteria taking into account both global and local aspects (Kayikci, 2010; Lee et al., 2009).

The surveyed articles mainly use strategies (a), (b) or (c), leading to different limitations: (a) does not take into account the disparity between the areas inside a given country. This can be acceptable in the case of small/homogeneous countries as in Europe, but it is hardly compatible with the African context. In case (c), a favourable area located in a poorly attractive country will probably not be considered. Therefore, we have selected strategy (d) for allowing a global/local comparison of all favourable areas.

- **Assessment data**

The score of a location according to a given criterion may be based on classical global indexes if accurate data exist (population, distance from highway, etc.) or on more elaborated yet still precise data found in online reports (Portugal et al., 2011). It may also be based on experts' judgment for qualitative aspects. In that case, the qualitative assessment of the expert is often translated on a numerical scale, like low = 1, average = 2, good = 3, etc. Fuzzy logic may be an interesting alternative to model such imprecise information, allowing to decrease the influence of arbitrary thresholds (Awasthi et al., 2011; Chen & Qu, 2006; Elevli, 2014; Shiau et al., 2011; Yu et al., 2011). In many cases, a utility function is used for translating a quantitative value into a satisfaction degree. This is for instance useful when thresholds have to be reached for giving full satisfaction to the decision maker (see Section 5).

3.2. MCDM approaches

Multi-Criteria Decision Methods (MCDM) are well adapted to derive complex decision making from different types of data and from experts' preferences (Long & Grasman, 2012). According to (Zavadskas & Turskis, 2011), there are two schools of thought in MCDM:

- *MCDM American School,* based on multi-attribute value functions and multi-attribute utility theory, the best-known methods being:
  - ***Analytical Hierarchy Process (AHP):*** this method uses pairwise comparisons based on experts' judgment to derive priority scales between criteria (Saaty, 2008). As a second step, numerical priorities are calculated for each decision alternative. The method has been widely used in the literature on planning, facility location, resource allocations, forecasting, etc. (De F.S.M. Russo & Camanho, 2015). AHP can be combined with other multi-criteria decision tools, like ELECTRE (Ka, 2011) or TOPSIS (Wang & Liu, 2011). In this case, AHP is most of the time used to determine criteria weights, which is its strong point, while the other method is used to compute the final score of an alternative.
  - ***Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)*** consists in choosing the best alternative based on the maximization of the distance to an "ideal negative" solution and the minimization of the distance to an "ideal positive" solution. TOPSIS is usually considered as easy to use and received great attention from researchers and practitioners (Behzadian, Khanmohammadi Otaghsara, Yazdani, & Ignatius, 2012). Tools often integrated with TOPSIS are AHP for weighting criteria and fuzzy logic to handle imprecise information.
- *MCDM French School.* It mainly promotes outranking methods for the evaluation of discrete alternatives, mainly:
  - ***ELECTRE (I, II, III) (Elimination and Choice Expressing Reality)*** (Roy, 1991): it is based on the principle of comparing pairs of alternatives either for the selection of a subset of alternatives offering the best possible compromise (ELECTRE I) or for the classification of alternatives based on an index of concordance and discordance (ELECTRE II, III) (see the survey (Govindan & Jepsen, 2016)).
  - ***PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations):*** (Brans & Mareschal, 2005) ranks candidate alternatives from the best to the worst, based on a pairwise comparison of alternatives related to each criterion, either partial (PROMETHEE I) or complete (PROMETHEE II). It has been applied to many real-life problems (see the survey Behzadian, Kazemzadeh, Albadvi, & Aghdasi, 2010).

Many decision problems involve imprecise information or preferences. Therefore, the use of Fuzzy logic has been suggested in all the MCDM (Kahraman, 2008). It can be seen in Table 1 that AHP (Portugal et al., 2011; Ugboma, Ugboma, & Ogwude, 2006) and Fuzzy AHP (Chen & Qu, 2006; Lee et al., 2009; Yu et al., 2011) have been extensively used in previous studies, especially when the total number of criteria is low. On the other hand, the classification of the alternatives based on ELECTRE or PROMETHEE requires assessing a « preference function » for PROMETHEE and a discordance and concordance matrix for ELECTRE, that may be complex. On the contrary, TOPSIS (Wang & Liu, 2007) or Fuzzy TOPSIS (Chen, 2000) have been often selected because of their flexibility and ease of use even with a high number of criteria (Behzadian et al., 2012). We have therefore chosen AHP to weight the location criteria and Fuzzy TOPSIS to provide a global framework to score the candidate locations.

3.3. Decision criteria

Table 2 summarizes current criteria for hub location in the literature. We have identified a total of 102 criteria in the considered literature. To focus on recognized criteria, we have decided to only list here the criteria cited at least by two different authors (20 criteria).

Table 2 shows that some studies mainly focus on the country attractiveness to foreign investment (El-Nakib, 2010; Muñoz, Virgüez, & Liliana, 2010; Oum & Park, 2004; Tongzon, 2004); others try to assess the logistical performance of port facilities, including harbour administration efficiency and handling services (Lirn, Thanopoulou, Beynon, & Beresford, 2004; Shiau et al., 2011). Very few papers consider both country attractiveness and logistic ecosystem performance, like in Yang and Chen (2016). This disparity suggests that a global framework including a structured taxonomy would be useful in order to check the exhaustiveness of a given set of criteria.

4. Proposed approach for the selection of a regional logistic hub

4.1. A reference framework for hub location criteria

4.1.1. Reference model

The suggested reference framework is deduced from the basic paradigm of hub location, expressed as follows: "Delivering products to regional markets requires *logistic services* (e.g. a maritime line) insured by a *hub* using *resources* (skilled human resources, roads, railroads, etc.). The use of logistic services and resources is constrained by a *legislation* (custom regulations for logistic services; labour legislation for human resources; security regulations for material resources, etc.). The welfare of the human resources so that the equity of the legislation depends on the *stability* and *ethics* of the administration, and therefore of the government". The criteria can so be grouped in two main families: those denoting the *country attractiveness* and those assessing the *logistic ecosystem* of the hub.

We have enriched this basic paradigm and modelled the resulting framework using the UML class diagram (Fowler, 2004). It can be seen in Fig. 2 that a hub has a *location* and is related to a *port terminal* and to

Table 2
Location criteria in the literature.

	Lirn et al. (2004)	Oum and Park (2004)	Chen and Qu (2006)	Lu and Yang (2006)	Ugboma et al. (2006)	Lee et al. (2009)	Kayikci (2010)	Eskilsson and Hansson (2010)	El-Nakib (2010)	Muñoz et al. (2010)	Awasthi et al. (2011)
Infrastructure availability and quality	X		X			X		X		X	X
Border administration efficiency	X	X			X		X	X	X	X	
Land availability		X		X		X			X		
Skilled labour availability		X		X					X	X	X
Labour cost		X		X					X		
Input cost		X		X					X		
Land cost		X	X	X				X	X		X
Macro-economic stability				X		X	X			X	
Political stability and security		X		X		X	X	X	X		
Government institutions efficiency				X				X		X	
Port terminal infrastructure	X				X	X		X	X		
Port terminal performance	X			X	X	X		X			
Quality of port service	X			X	X	X	X				
Intermodal transport availability	X			X	X						
Port charges	X			X	X		X				
Proximity to markets	X			X				X	X		X
Port connectivity	X			X				X			X

	Shiau et al. (2011)	Yu et al. (2011)	Long and Grasman (2012)	Elevli (2014)	Żak and Węgliński (2014)	Uysal and Yavuz (2014)	Van Dyck and Ismael (2015)	Roso et al. (2015)	Dey et al. (2015)	Peker et al. (2016)	Yang and Chen (2016)	Chen et al. (2017)
Infrastructure availability and quality	X			X	X	X	X		X	X		
Border administration efficiency		X	X				X				X	X
Land availability			X	X		X			X			X
Skilled labour availability	X		X		X	X						
Labour cost											X	
Input cost												
Land cost					X				X	X		
Macro-economic stability												
Political stability and security							X		X			

(*continued on next page*)

Table 2 (*continued*)

	Shiau et al. (2011)	Yu et al. (2011)	Long and Grasman (2012)	Elevli (2014)	Żak and Węgliński (2014)	Uysal and Yavuz (2014)	Van Dyck and Ismael (2015)	Roso et al. (2015)	Dey et al. (2015)	Peker et al. (2016)	Yang and Chen (2016)	Chen et al. (2017)
Government institutions efficiency		X									X	
Port terminal infrastructure	X	X					X					
Port terminal performance	X	X					X	X				
Quality of port service		X										X
Intermodal transport availability		X						X				
Port charges		X										X
Proximity to markets		X				X			X			X
Port connectivity		X					X	X				X

transportation infrastructures (roads, railways, etc.). The hub provides *logistic services* requiring *human* and *material resources* used according to *regulations* defined by a *government*. A logistic service allows to feed a *market* with *products*.

4.1.2. Definition of the criteria

Many criteria concerning the *country attractiveness* are regularly assessed by international entities, like the World Bank or the World Economic Forum through some indices such as the Enabling to Trade Index (ETI)[4], the Global Competitiveness Index (GCI)[5] and the Global Peace Index (GPI)[6] (Table 3). The Logistic Performance Index (LPI)[7] is also of interest for a global appreciation of the infrastructure of a country. More often, those indices are assessed based on international surveys, involving multinational experts that score countries over quantitative and qualitative criteria, some of them being relevant for the literature on hub location (Table 2). The criteria concerning the *logistic ecosystem* of the hub have been more precisely defined with the help of the literature survey of Section 3, then discussed with the experts of the 3PL.

For a better legibility, the criteria are hierarchized in two levels: macro-criteria and sub-criteria (see Tables 3 and 4). The case study of Section 5 will show that the categories denoted by macro-criteria are rather robust (they should be used in all applications) while the sub-criteria have to be chosen/adapted for a given application (some criteria may for instance be expressed differently according to the type of goods to be distributed).

In Table 3 are shown the macro-criteria defined for assessing the country attractiveness, and examples of possible sub-criteria (column 2). The last column lists the sub-criteria selected for the simplified case study of Section 5, together with their source (ETI, GCI, GPI, LPI), the scale on which they were initially assessed (they are then normalized), their type (qualitative or quantitative) and the way their value is modelled (precise or fuzzy number).

The criteria related to the logistic ecosystem are a bit different. Some of them, like the three first ones in Table 4, are linked to quantitative measures that need to be interpreted using a utility function, denoted here by a trapezoidal fuzzy number (see Section A.1.2, Appendix A). For example, Fig. 3 expresses that under 10 m, water depth is not sufficient enough (satisfaction = 0), between 10 m and 15 m, the satisfaction degree increases while above 15 m, satisfaction is complete. The value of the other criteria (coming either from experts or from public information) have to minimized or maximized. The use of Fuzzy TOPSIS allows to normalize the assessments before aggregation.

Linguistic values are used to translate qualitative assessments from the experts, like "Fair" or "Good", by a fuzzy set represented by a trapeze (see Fig. 4). The overlapping of the categories allows decreasing the threshold effect occurring when crisp numbers (1, 2, 3 …) are used, which is very important when the experts assess complex/multi-facets criteria. To the fuzzy set describing the opinion of the experts is associated a number between 0 and 1 denoting the confidence of the expert on his assessment.

4.2. Computation of an aggregated index

As shown in Section 2, using AHP for computing the weights between criteria and Fuzzy TOPSIS for calculating a global index is now classical. For better legibility, the description of the methods is rejected in the appendix (Sections A.2 and A.3). Nevertheless, we give hereafter a short summary in order to justify the modifications that have been done and the global approach suggested (see Fig. 5).

[4] https://www.weforum.org/reports/global-enabling-trade-report-2014/.
[5] http://reports.weforum.org/global-competitiveness-report-2015-2016/.
[6] http://static.visionofhumanity.org/.
[7] http://lpi.worldbank.org/international/global.

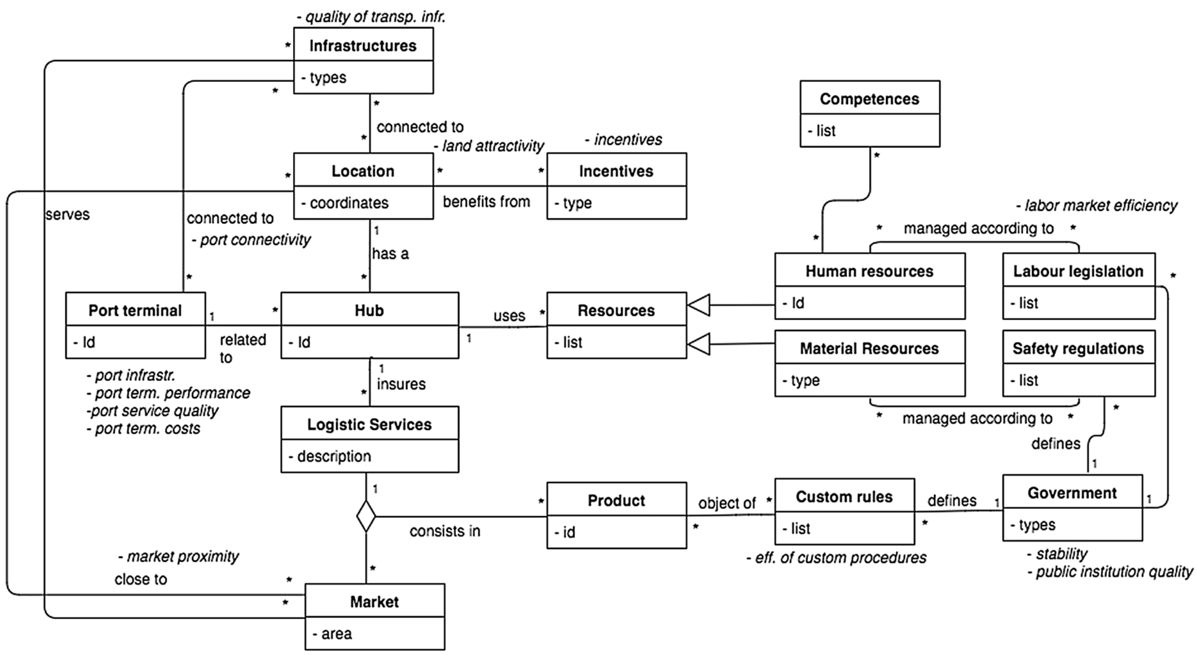

Fig. 2. Class diagram of the context.

Table 3
Country attractiveness criteria.

Macro-criteria	Definition and examples of sub-criteria	Selected sub-criteria: Source (Scale); Qual./Quant; Prec./Fuzzy
Country Stability	Evaluates the stability factors and the ability of a country to attract, drain and secure foreign investment.	Political stability and security: GPI (1–5), Qual. Prec. Macroeconomic stability: GPI (1–5), Qual. Prec.
Public institutions quality	Evaluates the quality and efficiency of public institutions that govern, regulate and protect investors (control of corruption, protection of investors rights, transparency of government policies, efficiency of business regulations, availability of government incentives)	Public institutions quality: GPI (1–7), Qual. Prec.
Transport infrastructure	Assesses the availability of qualified infrastructure needed for the movement of goods within the country and across borders (railroad infrastructure, port infrastructure, roads, highways, and related information technology).	Transport infrastructure: LPI (1–5), Qual. Prec.
Efficiency of customs procedures	Assesses the ease of international transit related to the entry and exit of merchandises across terminal borders of the country.	Efficiency of customs procedures: GPI (1–5), Qual. Prec.
Labor market efficiency	Evaluates the attractiveness of the labor market in terms of availability of qualified workforce at affordable costs (availability of qualified workers, labor cost, workforce productivity, labor regulation flexibility).	Labor market efficiency: GPI (1–7), Qual. Prec.

Step 1: Definition of the context

The Decision Maker (DM) firstly specifies the characteristics of its location problem, i.e. type of packaging used, catchment area that delimits the targeted regional market, etc. This step allows adjusting the list of sub criteria to the decision context. For example, if the goods are fertilizers shipped in bulk carrier, then the facilities of the port for handling bulk goods have to be assessed. The Decision Maker may also adjust the list of criteria according to the desired accuracy. For instance, the criterion "Public institutions quality" (see Table 3) can be expressed by several sub-criteria (e.g. control of corruption, protection of investors rights, transparency of government policies, efficiency of business regulations, availability of government incentives in column 2 of Table 3) or can be globally assessed by an expert as suggested in column 3 of Table 3.

Step 2: Computation of criteria weights

The DM gives his judgment on the relative weights of the criteria belonging to the same macro-criterion. The final weights are computed using the AHP method (Saaty, 2008) (see Appendix A).

Step 3: Decision matrix

A decision matrix is built, composed of the assessment of all the alternatives (in rows) according to all the criteria (in columns). The matrix is then normalized so that the relative importance of the criteria is expressed by their weights with no interference of their scale.

Steps 4 and 4′: Evaluation of the country attractiveness and logistic ecosystem of each location

Table 4
Logistic ecosystem quality criteria.

Criteria	Sub criteria	Measure description	Measure scale	Interpretation	Measure source
Port terminal infrastructure	Water depth	Permissible drafts for vessels under full load	Meters	Utility	Expert/judgement
	Linear berth length	Total length of docks	Kilometers	Utility	Port terminal website
	Terminal size	Total physical capacity of port	Hectare	Utility	Port terminal website
	Port equipment	Availability of well-developed handling equipment	Linguistic variable	Utility	Expert/judgement
	Intermodal links	Efficiency of intermodal transport network	Linguistic variable	Utility	Expert/judgement
	Port logistic facilities	Effectiveness and quality of port logistic facilities	Linguistic variable	Utility	Expert/judgement
Port terminal performance	Average waiting time (delays)	Total time that a vessel spends from its entry to the area anchorage before being processed	Days	Cost	Port terminal website
	Average cargo dwelling time	Speed of service for cargo	Days/hours	Cost	Port terminal website
	Ship turnaround time	Time required to charge or discharge a vessel	Hours	Cost	Port terminal website
Port service quality		Port reputation for cargo damage	Linguistic variable	Utility	Expert/judgement
Port terminal costs	Handling cost at import	Total handling cost: vessels, freight	USD/unit of packaging flows	Cost	Port terminal website
	Handling cost at import				
	Taxes at port	Fees incurred by using port infrastructure while transiting	USD	Cost	Port terminal website
Port connectivity		Number of maritime connections	%	Utility	Port terminal website
Land attractiveness	Availability of logistic land	Availability of empty land and eventual extension development	Linguistic variable	Cost	Expert/judgement
	Land price	Average rent cost/m^2	Linguistic variable	Cost	Expert/judgement
Market proximity	Travel distance time	Travel distance time to each country of market region by optimal mode	Days	Cost	Online report
Incentive attractiveness		Availability of fiscal and non-fiscal incentives within this terminal such as logistical free zones or fiscal incentives for investors	Linguistic variable	Utility	Expert/judgement

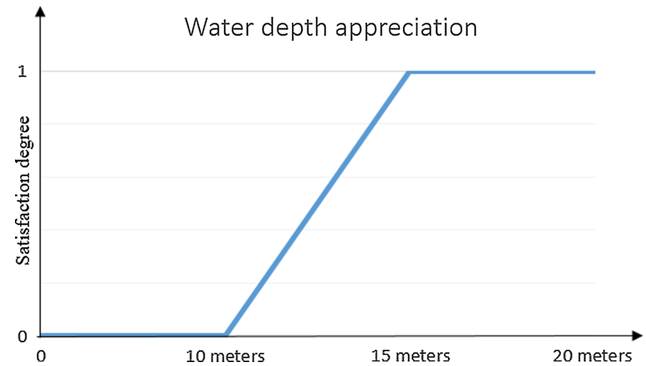

Fig. 3. Water depth appreciation.

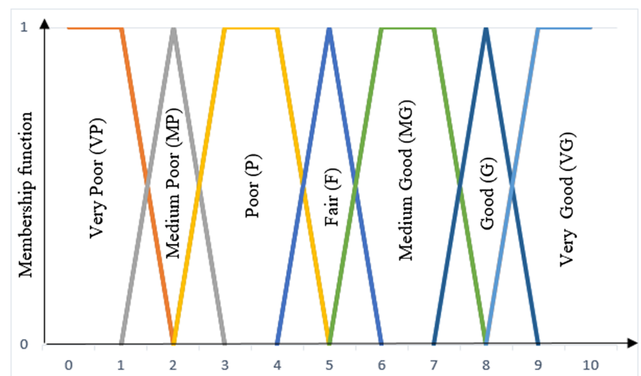

Fig. 4. Example of linguistic variables for rating qualitative data (Hatami-Marbini & Tavana, 2011).

The weights obtained using AHP (Step 2) are now applied on the decision matrix to construct the weighted normalized fuzzy decision matrix. The next step of TOPSIS is to compute the "ideal" (best) and "negative ideal" (worst) solutions, the best alternative being at the same time close to the ideal solution and far from the negative ideal one. Using ideal solutions and criteria assessments denoted by fuzzy numbers sets the problem of calculation of a distance. The distance between two fuzzy numbers is usually defined as a crisp number, essentially for simplification purpose. It is also the case in Fuzzy TOPSIS in which the crisp distance suggested in Chen (2000) is often used. Using a fuzzy distance in Fuzzy TOPSIS has in our opinion three main interests:

- The distance between fuzzy numbers should logically be fuzzy. Voxman (1998) first noticed that there is a paradox in the definition of a crisp distance between two fuzzy numbers: "*if we are not certain about the numbers themselves, how can we be certain about the distances among them?*" (Voxman, 1998).
- Keeping the distance fuzzy allows to postpone the defuzzification phase, a major step in the calculation of fuzzy quantities that always results in a loss of information. Keeping fuzziness as long as possible in the calculations allows a better propagation of the rich (even if more difficult to interpret) information on knowledge imprecision.
- As shown hereafter, a fuzzy distance may provide a framework allowing also to take into account the confidence of an expert on a specific evaluation. This can be useful in a problem in which the uncertainty on the data may be important.

Voxman suggested the definition of a fuzzy distance in Voxman (1998), but Chakraborty and Chakraborty (2006) showed that this

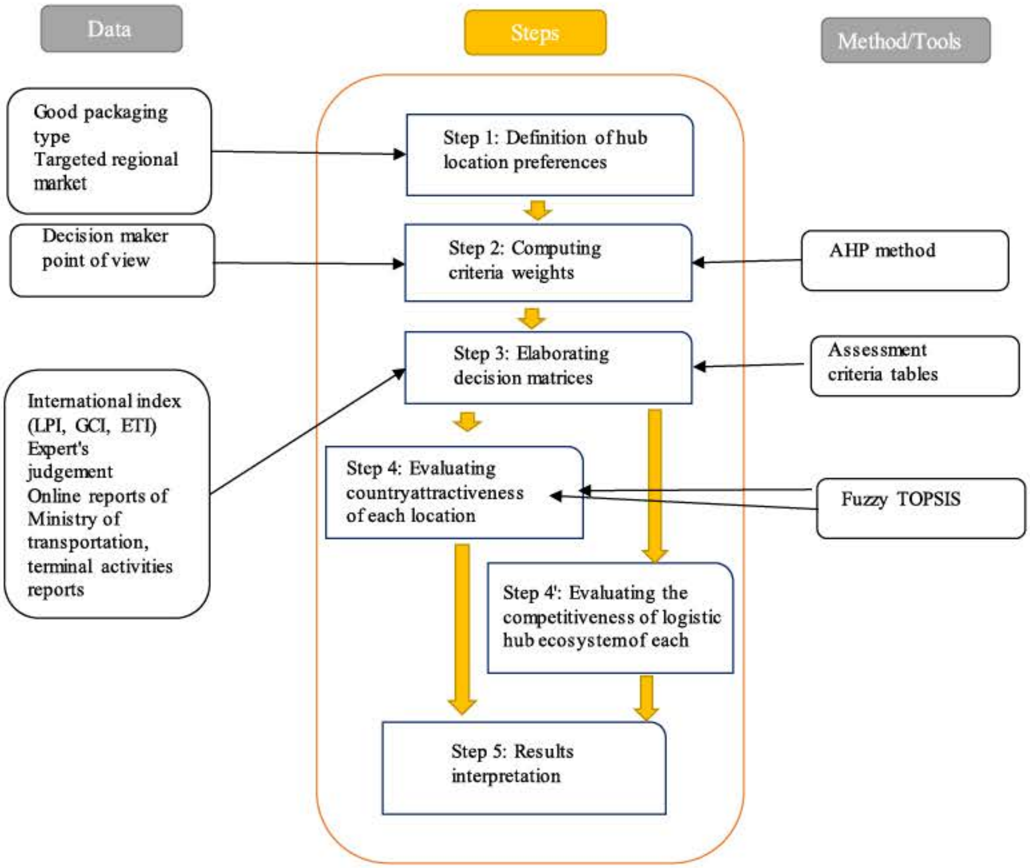

Fig. 5. Decision making framework.

distance induces a lot of fuzziness and ambiguity, and suggested another definition. Guha and Chakraborty (2010) showed that the latter may lead to counter-intuitive results in some cases: for instance, the distance between two different fuzzy numbers may be null. Therefore, they suggested a fuzzy distance for generalized fuzzy sets, with the additional interest that this distance also depends on a confidence attached to each number. Although they improved the previous fuzzy distance measure, their proposal has still some shortcomings (Abbasbandy & Salahshour, 2013; Beigi, Khani, & Hajjari, 2015; Jahantigh, Hajighasemi, & Allahviranloo, 2014). Indeed, the distance between a fuzzy number A and zero is not A and the distance between two identical fuzzy numbers is not equal to zero. Jahantigh et al. (2014) suggests a new fuzzy distance measure based on the previous work of Abbasbandy and Hajighasemi (2010), including a confidence level attached to the expert judgement. However, their measure can only be applied to triangular fuzzy numbers. Recently, Beigi et al. (2015) surveyed the previously developed fuzzy distance measures and proposed a fuzzy distance with better properties, but not including the confidence level on the expert judgement.

The literature on the use of a fuzzy distance in Fuzzy TOPSIS is scarce. Hatami-Marbini and Kangi (2017) applied a fuzzy distance in Fuzzy TOPSIS on a case study. However, they used the distance measure proposed by Guha and Chakraborty (2010) which suffers from known limitations. Therefore, we propose a new distance measure which expands the one proposed in Jahantigh et al. (2014) and has a better (even if not perfect) consistence with good sense properties, while allowing to integrate the confidence in the calculation of the decision matrix, which has not been suggested before.

Let us consider two generalized trapezoidal fuzzy numbers $\tilde{X}$ and $\tilde{Y}$: $\tilde{X} = (x_1, x_2, x_3, x_4, \omega_x)$ and $\tilde{Y} = (y_1, y_2, y_3, y_4, \omega_y)$ where $\omega_x, \omega_y \in [0, 1]$ are the degrees of confidence of the decision makers' judgement about the two fuzzy numbers respectively. $\omega_{\min} = \min(\omega_x, \omega_y)$ and $\omega_{\max} = \max(\omega_x, \omega_y)$

Table 5
Numerical illustration of the proposed Fuzzy distance measure.

$\tilde{X}$	$\tilde{Y}$	Our proposed distance measure			Guha and Chakraborty (2010)
		$d(\tilde{X}, \tilde{Y})$	$d^g_\infty(\tilde{X}, \tilde{Y})$	$\tilde{d}(\tilde{X}, \tilde{Y}) = (\theta, d(\tilde{X}, \tilde{Y}), x, d^g_\infty(\tilde{X}, \tilde{Y}))$	
(1, 2, 3, 4)	(1, 2, 3, 4)	0	0	(0, 0, 0, 0)	(0, 0, 0, 0)
(1, 2, 3, 4)	(0, 0, 0, 0)	1.6	4	(1.2, 1.6, 2.8, 4)	(2.5, 3, 3, 4.5)
(1, 2, 3, 4)	(2, 3, 4, 5)	0.5	1	(0.25, 0.5, 0.75, 1)	(0, 1, 1, 2)
(2, 3, 4, 5)	(1, 2, 3, 4)	0.5	1	(0.25, 0.5, 0.75, 1)	(0, 1, 1, 2)

Table 6
Example of suggestions for evaluating hub locations.

Closeness Index _Logistic Ecosystem CI (L)	Closeness Index _Country CI (C)	Suggestion
$CI(L) \in [0,0.2)$	$\forall\ CI(C)$	Not recommended
$CI(L) \in]0.2,0.5)$	$CI(C) \in [0,0.2)$	Not recommended
	$CI(C) \in]0.2,0.5)$	Recommended with low potential
	$CI(C) \in]0.5,0.75]$	Recommended with less important potential
	$CI(C) \in]0.75,1]$	Recommended with acceptable potential
$CI(L) \in]0.5,0.75]$	$CI(C) \in [0,0.2)$	Not recommended
	$CI(C) \in]0.2,0.5)$	Recommended with low potential
	$CI(C) \in]0.5,0.75]$	Recommended with less important potential
	$CI(C) \in]0.75,1]$	Recommended with acceptable potential
$CI(L) \in]0.75,1]$	$CI(C) \in [0,0.2)$	Not recommended
	$CI(C) \in [0.2,0.5)$	Recommended with acceptable potential
	$CI(C) \in]0.5,0.75]$	Recommended with high potential
	$CI(C) \in]0.75,1]$	Recommended with very high potential

Table 7
Candidate locations for a regional logistic hub.

Candidates locations	Country	Landlocked served countries
Djibouti	Djibouti	Ethiopia
Mombasa	Kenya	Uganda-Burundi-Democratic Republic of Congo “RDC”-South Sudan-Rwanda
Dar Es Salam	Tanzania	Rwanda-Burundi-Uganda-Malawi-RDC
Walvis Bay	Namibia	Zimbabwe
Durban	South Africa	Zambia-Zimbabwe-Botswana
Maputo	Mozambique	Zimbabwe-Zambia

The α-cut of $\widetilde{X}$ and $\widetilde{Y}$ is respectively:

$$\forall\ \alpha \in [0, \omega_x] | [\widetilde{X}]_\alpha = [X^L(\alpha), X^R(\alpha)] \text{ and } \forall\ \alpha \in [0, \omega_y] | [\widetilde{Y}]_\alpha = [Y^L(\alpha), Y^R(\alpha)]. \quad (1)$$

We define the new fuzzy distance between $\widetilde{X}$ and $\widetilde{Y}$ as follows:

$$\widetilde{d}(\widetilde{X}, \widetilde{Y}) = (\theta, d(\widetilde{X}, \widetilde{Y}), x, d_\infty^g(\widetilde{X}, \widetilde{Y})) \quad (2)$$

where

$$\theta = \frac{d_\infty^g(\widetilde{X}, \widetilde{Y}) - d(\widetilde{X}, \widetilde{Y})}{2} \quad (3)$$

$$x = \frac{d_\infty^g(\widetilde{X}, \widetilde{Y}) + d(\widetilde{X}, \widetilde{Y})}{2} \quad (4)$$

- $d(\widetilde{X}, \widetilde{Y})$ is the crisp distance between $\widetilde{X}$ and $\widetilde{Y}$ defined by Jahantigh et al. (2014) (see Section A.5 of the Appendix A).
- $d_\infty^g(\widetilde{X}, \widetilde{Y})$ is the generalized Hausdorff metric (see Section A.6 of the Appendix A).

Table 5 shows on some examples a comparison between the most recent fuzzy distance between two trapezoidal fuzzy numbers and our

Table 9
Final weights of country level criteria.

Criteria	Final weights
Political stability	46%
Economic stability	5%
Efficiency of public institutions	16%
Transport infrastructure	11%
Labor market attractiveness	10%
Efficiency of customs procedures	10%

Table 10
Final weights of the criteria on the logistic ecosystem.

Criterion	Final weights
Water depth	4%
Linear berth length	1%
Terminal size	3%
Port equipment	4%
Intermodal links	11%
Port facilities	3%
Port service quality	14%
Average waiting time	11%
Average cargo dwelling time	2%
Ship turnaround time	4%
Handling cost at import	5%
Handling cost at export	5%
Taxes at port	5%
Port terminal connectivity	12%
Availability of land	1%
Land price	2%
Incentives attractiveness	2%
Market proximity	12%

Table 8
Pairwise comparison matrix of country attractiveness criteria.

Country attractiveness criteria	Stability	Efficiency of public institutions	Transport infrastructure	Labor market attractiveness	Efficiency of customs procedures
Stability	1	9	3	9	9
Efficiency of public institutions	0.11	1	3	5	0.33
Transport infrastructure	0.33	0.33	1	3	1
Labor market attractiveness	0.11	0.2	0.33	1	5
Efficiency of customs procedures	0.11	3	1	0.2	1
Consistency index (CI)	9%				
Consistency ratio (CR)	8%				

Table 11
Decision matrix with respect to country attractiveness criteria.

Logistic hub	Evaluation Source	Confidence level	Djibouti	Mombasa	Dar es Salam	Walvis bay	Durban	Maputo
Political stability	(GPI, 2016)	1	2.3	2.4	2	2	2	2
Economic stability	(GCI, 2016)	1	4.7	3.6	5	5	5	4.7
Efficiency of public institutions	(GCI, 2016)	1	3.7	3.5	4	4	4	3
Transport Infrastructure	(LPI, 2016)	1	2.3	3.2	3	3	4	2.2
Labor market attractiveness	(GCI, 2016)	1	4.3	4.6	4	4	3	4
Efficiency of customs procedures	(LPI, 2016)	1	2.4	3.2	3	3	4	2.5

proposed measure, that leads to more accurate results than (Guha & Chakraborty, 2010). This distance is used to calculate the Closeness Index (CI) of each alternative. The CI is an aggregation of the distances between each alternative and the ideal and negative ideal solutions. Two CI are obtained resp. for the country attractiveness and logistic ecosystem competitiveness.

Obviously, the Closeness Indexes derived from fuzzy distances are also fuzzy numbers. We can compute them using the classical measure of the crisp CI applied to Fuzzy numbers (see formula (30) in Section A.4 of the Appendix A). The alternatives have then to be ranked. Several fuzzy ranking methods have been developed in the past (Brunelli & Mezei, 2013) that may lead to different results. All these methods express the fuzzy numbers by crisp scores before ranking them, which is an implicit defuzzification. In order to keep trace of the imprecision on the assessments, we propose to rank the fuzzy CI according to a pessimistic and an optimistic point of view, using respectively the minimum $Inf\widetilde{CI}$ and the maximum $Sup\widetilde{CI}$ of the α-cut sets of the Fuzzy CI (see formulae (31) and (32) in Section A.4 of the Appendix A). The pessimistic and optimistic Closeness Indexes are derived from the normalization of the minimum and maximum of the α-cut sets (see formulae (33) and (34) in Section A.4 of the Appendix A).

Step 5: Results interpretation

We can now help the DM to classify the locations, based on the global indexes related to country attractiveness and logistic ecosystem competitiveness. We suggest not to aggregate these indexes since they denote different aspects of the choice of a location, that should not be compensated by an aggregation. If needed, the different possible combinations of closeness indices values may be associated to standard recommendations as in Table 6.

Note that these rules may also be applied to the pessimistic $CI^{-}(L)$, $CI^{-}(C)$ and optimistic $CI^{+}(L)$, $CI^{+}(C)$ closeness Index defined in step 4.

5. Case study

In order to validate the interest of the suggested approach, a case study has been conducted with our industrial partner. For confidentiality reasons, this case has been slightly modified here (criteria and assessments) but is still realistic.

The aim of this illustrative case study is twofold: (1) first, we analyse the impact of considering the confidence level attached to expert judgement on a specific evaluation, and the impact of postponing deffuzification by defining fuzzy distances. To support this computational comparison, we consider three cases: (a) case 1: use of the classical Fuzzy TOPSIS (with crisp distances and all confidence levels equal to one), (b) case 2: use of the modified Fuzzy TOPSIS with fuzzy distances and all confidence levels equal to one, (c) case 3: use of the modified Fuzzy TOPSIS with fuzzy distances and different confidence levels (with 80% of the confidence levels set to 1 and 20% set to 0.5). (2) We will illustrate the effect of considering the criteria related to country attractiveness and logistic ecosystem attractiveness separately, then simultaneously.

5.1. Computational results

Step 1: Definition of hub location preferences

We consider six candidate locations in different ports. All of them have a good potential but, according to African Bank (2010), this potential varies according to the catchment area they serve (Table 7). Good flows are packaged in containers, with the consequence that the terminal attractiveness focusses on container ports.

Step 2: Computation of criteria weights

Pairwise comparison matrices are built by the 3PL following AHP method (see Section A.3 of the Appendix A), concerning the sub-criteria related to the countries (Table 8) and to the logistic ecosystems (not shown here).

Tables 9 and 10 represent the final weights of the criteria belonging to the two aspects assessed (country attractiveness and logistic eco system performance).

Step 3: Elaborating decision matrices

A decision matrix is then built for each level. The country level criteria are mainly based on recent ratings given by the international organizations (Table 11). The second decision matrix (Table 12) is based on quantitative information gathered from several sources[8,9] and from the qualitative judgement of experts of the 3PL. The assessments represented by linguistic variables are then modelled by trapezoidal fuzzy numbers thanks to Fig. 4.

Step 4: Evaluating the competitiveness of the logistic hub ecosystem of each location

Fuzzy TOPSIS is then used to evaluate each potential location based on the criteria linked to the ecosystem level. We use the conversion scale suggested in Fig. 4 to transform the rough decision matrices of Tables 11 and 12, including crisp numbers, intervals and linguistic labels, into a fuzzy decision matrix containing only fuzzy numbers (not provided here). We use formulae (8)–(10) (Section A.1 of the Appendix A) to normalize the fuzzy decision matrix. Using the weights (Tables 9 and 10), we compute the weighted normalized fuzzy decision matrix (Table 13) which depends on the confidence levels given by the experts.

- ***Computation of the fuzzy ideal solutions***

The fuzzy positive ideal solution (FPIS+) and the fuzzy negative ideal solution (FNIS−) are assessed (Table 14) based on formulae (19)

[8] UNCTAD: http://unctad.org/en/Pages/statistics.aspx.

[9] SCEA, 2015. East Africa logistics performance survey. (http://www.shipperscouncilea.org/index.php/media-centre/logistics-performance-survey).

Table 12
Decision matrix with respect to logistic ecosystem attractiveness criteria.

N°	Sub criteria	Confidence level		Djibouti	Mombasa	Dar es Salaam	Walvis Bay	Durban	Maputo
		Case 1 and 2	Case 3						
SC1	Water depth	1	1	16.5	10	13	13	12	11
SC2	Linear berth length	1	1	1050	839	725	600	2578	300
SC3	Terminal size	1	1	22	13.7	18.75	40	185	10
SC4	Port equipment quality	1	1	VG	G	MG	MG	VG	G
SC5	Intermodal links	1	1	P	P	MG	VG	VG	G
SC6	Port facilities	1	1	VG	P	G	VG	VG	G
SC7	Port service quality	1	0.5	VG	G	MG	VG	VG	MG
SC8	Average delays time	1	0.5	VG	G	MG	MG	MP	G
SC9	Average dwell time	1	1	7–8	4–5	4–9	7–8	3–5	3–5
SC10	Average turnaround time	1	1	VG	G	MG	G	MP	G
SC11	Handling cost at import	1	1	272–300	105–160	90–135	5145–8191	1603–3133	200–300
SC12	Handling cost at export	1	1	273–300	56–80	20–90	5145–10,192	1603–3134	212–285
SC13	Taxes at port	1	1	274–300	62–125	80–120	2165–3808	1064–3133	212–234
SC14	Port terminal connectivity	1	0.5	G	MP	P	MP	VG	P
SC15	Availability of land	1	1	G	G	G	G	MP	P
SC16	Land price	1	1	MP	G	VG	P	P	G
SC17	Attractiveness of incentives	1	1	MP	VG	MG	VG	MP	VG
SC18	Transit time to Rwanda	1	1	G	P	MP	VP	VP	VG
SC19	Transit time to Burundi	1	1	VP	P	MP	VP	VP	VP
SC20	Transit time to Uganda	1	1	VP	P	MP	VP	VP	VP
SC21	Transit time to RDC	1	1	VP	P	MP	VP	VP	VP
SC22	Transit time to Zambia	1	1	VP	VP	MP	VP	P	VP
SC23	Transit time to Zimbabwe	1	1	VP	VP	VP	MP	P	P
SC24	Transit time to Malawi	1	1	VP	VP	MP	VP	VP	VP

and (20) in (Section A.2 of the Appendix A).

- ***Computation of the distance from each alternative to the ideal solutions***

Let us recall that case 1 uses the classical Fuzzy TOPSIS (crisp distances; all confidence levels equal to one); case 2 uses Fuzzy TOPSIS with fuzzy distances, and case 3, Fuzzy TOPSIS with fuzzy distances and different confidence levels.

Formula (12) in Section A.1 of the appendix allows calculating the crisp distances between the candidate locations and the ideal and negative ideal solutions related to case 1 (see Table 15). Based on the fuzzy distance suggested in Section 4.2 we compute the fuzzy distances between the candidate locations and the ideal and negative ideal solutions related to cases 2 and 3 (see Table 15).

- ***Determination of the closeness index***

Finally, we compute for each alternative the crisp closeness index CI and the fuzzy closeness index $\widetilde{C}I$ (as defined in steps 4 and 4′ of Section 4.2) allowing to evaluate the logistic ecosystem competitiveness (Table 16) and country attractiveness (Table 17).

5.2. Analysis of the results

The results of Table 17 first show that taking into account a fuzzy distance allows to get a richer information on the ranking. Dar es Salaam is the best location in case 1 and in the pessimistic assessment of case 2, but it can be seen that Djibouti, ranked 1 in the optimistic assessment of case 2, has a better potential than Dar es Salaam (its maximum satisfaction of the criteria is much better). In all the cases, distinguishing the pessimistic and optimistic ranking allows the DM to access to a richer information, providing an indirect measure of the risk he may take by adopting an optimistic or pessimistic strategy.

The poor ranking of Durban and Maputo in case 1 comes from their proximity to the negative ideal solution, caricatured by the calculation of the crisp distance. The fuzzy distances show that in fact, these solutions are close to the others: Durban is even considered as the second solution in case 2, and the best one in case 3.

Even with the low level of uncertainty introduced in case 3 (80% of the assessments with a confidence = 1; 20% with a confidence = 0.5), it can indeed be seen that taking into account this confidence may set into question the ranking: even if the optimistic rankings of cases 2 and 3 are close, the pessimistic ones appear as quite different.

To a less extent, similar comments can be made on the results on the country attractiveness (cases 2 and 3 are similar since the experts' assessments including confidence only concern the logistic attractiveness).

In Figs. 6 and 7 is shown a synthesis of the normalized pessimistic (resp. optimistic) scores of each location with respect to each index, obtained using Table 6, that summarizes the results for the Decision Maker.

6. Conclusion

The consumer market offered by Africa attracts many industrial investors. In order to access these markets, it is important to position efficiently the logistic hubs that will allow to deliver the products in a given area. Implanting hubs in Africa has nevertheless specific difficulties, among which the weakness of the transport infrastructure, the heaviness of custom regulations and the political instability in many countries.

In order to address this problem, we suggest to evaluate separately the *country attractiveness* and the *logistic ecosystem competitiveness* of candidate hub locations. On the base of the requirements expressed by a 3PL provider, the sub-criteria of each category have been defined using criteria from the literature, criteria suggested by international organizations, and by a collaboration with the experts of the logistic partner.

Table 13
Normalized and weighted Fuzzy decision matrix with respect to logistic attractiveness criteria.

	Djibouti	Mombasa	Dar es Salaam	Walvis Bay	Durban	Maputo
SC1	(0.04, 0.04, 0.04, 0.04; 1)	(0, 0, 0, 0; 1)	(0.024, 0.024, 0.024, 0.024; 1)	(0.024, 0.024, 0.024, 0.024; 1)	(0.008, 0.008, 0.008; 1)	(0.004, 0.004, 0.004, 0.004; 1)
SC2	(0.008, 0.008, 0.008, 0.008; 1)	(0.003, 0.003, 0.003, 0.003; 1)	(0.002, 0.002, 0.002, 0.002; 1)	(0.001, 0.001, 0.001, 0.001; 1)	(0.01, 0.01, 0.01, 0.01; 1)	(0, 0, 0, 0; 1)
SC3	(0.03, 0.03, 0.03, 0.03; 1)	(0, 0, 0, 0; 1)	(0.024, 0.024, 0.024, 0.024; 1)	(0.03, 0.03, 0.03, 0.03; 1)	(0.03, 0.03, 0.03, 0.03; 1)	(0, 0, 0, 0; 1)
SC4	(0.032, 0.036, 0.04, 0.04; 1)	(0.028, 0.032, 0.032, 0.036; 1)	(0.02, 0.024, 0.028, 0.032; 1)	(0.02, 0.024, 0.028, 0.032; 1)	(0.032, 0.036, 0.04, 0.04; 1)	(0, 0, 0, 0; 1)
SC5	(0.011, 0.022, 0.022, 0.033; 1)	(0.011, 0.022, 0.022, 0.033; 1)	(0.055, 0.066, 0.077, 0.088; 1)	(0.088, 0.099, 0.110, 0.11; 1)	(0.088, 0.099, 0.11, 0.11; 1)	(0.028, 0.032, 0.032, 0.036; 1)
SC6	(0.024, 0.027, 0.03, 0.03; 1)	(0.003, 0.006, 0.006, 0.009; 1)	(0.021, 0.024, 0.024, 0.027; 1)	(0.024, 0.027, 0.03, 0.03; 1)	(0.024, 0.027, 0.03, 0.03; 1)	(0.077, 0.088, 0.088, 0.099; 1)
SC7	(0.112, 0.126, 0.14, 0.14; 1)	(0.098, 0.112, 0.112, 0.126; 1)	(0.07, 0.084, 0.098, 0.112; 1)	(0.112, 0.126, 0.14, 0.14; 1)	(0.112, 0.126, 0.14, 0.14; 1)	(0.021, 0.024, 0.024, 0.027; 1)
SC8	(0.088, 0.099, 0.11, 0.11; 1)	(0.077, 0.088, 0.088, 0.099; 1)	(0.055, 0.066, 0.077, 0.088; 1)	(0.055, 0.066, 0.077, 0.088; 1)	(0.022, 0.033, 0.044, 0.055; 1)	(0.07, 0.084, 0.098, 0.112; 1)
SC9	(0.016, 0.016, 0.018, 0.018; 1)	(0.009, 0.009, 0.011, 0.011; 1)	(0.009, 0.009, 0.02, 0.02; 1)	(0.016, 0.016, 0.018, 0.018; 1)	(0.007, 0.007, 0.011, 0.011; 1)	(0.007, 0.007, 0.011, 0.011; 1)
SC10	(0.032, 0.036, 0.04, 0.04; 1)	(0.028, 0.032, 0.032, 0.036; 1)	(0.02, 0.024, 0.028, 0.032; 1)	(0.028, 0.032, 0.032, 0.036; 1)	(0.008, 0.012, 0.016, 0.02; 1)	(0.028, 0.032, 0.032, 0.036; 1)
SC11	(0.015, 0.015, 0.017, 0.017; 1)	(0.028, 0.028, 0.043, 0.043; 1)	(0.033, 0.033, 0.05, 0.05; 1)	(0.001, 0.001, 0.001, 0.001; 1)	(0.001, 0.001, 0.003, 0.003; 1)	(0.015, 0.015, 0.023, 0.023; 1)
SC12	(0.003, 0.003, 0.004, 0.004; 1)	(0.013, 0.013, 0.018, 0.018; 1)	(0.011, 0.011, 0.05, 0.05; 1)	(0, 0, 0, 0; 1)	(0, 0, 0…01, 0.001; 1)	(0.004, 0.004, 0.005, 0.005; 1)
SC13	(0.01, 0.01, 0.11, 0.11; 1)	(0.025, 0.025, 0.05, 0.05; 1)	(0.026, 0.026, 0.039, 0.039; 1)	(0.001, 0.001, 0.001, 0.001; 1)	(0.001, 0.001, 0.003, 0.003; 1)	(0.013, 0.013, 0.015, 0.015; 1)
SC14	(0.084, 0.096, 0.096, 0.108; 1)	(0.024, 0.036, 0.048, 0.06; 1)	(0.012, 0.024, 0.024, 0.036; 1)	(0.024, 0.036, 0.048, 0.06; 1)	(0.096, 0.108, 0.12, 0.12; 1)	(0.012, 0.024, 0.024, 0.036; 1)
SC15	(0.008, 0.009, 0.009, 0.01; 1)	(0.008, 0.009, 0.009, 0.01)	(0.008, 0.009, 0.009, 0.01; 1)	(0.008, 0.009, 0.009, 0.01; 1)	(0.002, 0.003, 0.004, 0.006; 1)	(0.001, 0.002, 0.002, 0.003; 1)
SC16	(0.004, 0.006, 0.008, 0.01; 1)	(0.014, 0.016, 0.016, 0.018; 1)	(0.016, 0.018, 0.02, 0.02; 1)	(0.002, 0.004, 0.004, 0.006; 1)	(0.002, 0.004, 0.004, 0.006; 1)	(0.014, 0.016, 0.016, 0.018; 1)
SC17	(0.004, 0.006, 0.008, 0.01; 1)	(0.016, 0.018, 0.02, 0.02; 1)	(0.01, 0.012, 0.014, 0.016; 1)	(0.016, 0.018, 0.02, 0.02; 1)	(0.004, 0.004, 0.004, 0.006; 1)	(0.016, 0.018, 0.02, 0.02; 1)
SC18	(0.014, 0.016, 0.016, 0.018; 1)	(0.002, 0.004, 0.004, 0.006; 1)	(0.004, 0.006, 0.008, 0.01; 1)	(0, 0, 0.002, 0.004; 1)	(0, 0, 0.002, 0.004; 1)	(0.016, 0.018, 0.02, 0.02; 1)
SC19	(0, 0, 0.004, 0.008; 1)	(0.004, 0.008, 0.008, 0.012; 1)	(0.008, 0.012, 0.016, 0.02; 1)	(0, 0, 0.004, 0.008; 1)	(0, 0, 0.004, 0.008; 1)	(0, 0, 0.004, 0.008; 1)
SC20	(0, 0, 0.004, 0.008; 1)	(0.004, 0.008, 0.008, 0.012; 1)	(0.008, 0.012, 0.016, 0.02; 1)	(0, 0, 0.004, 0.008; 1)	(0, 0, 0.004, 0.008; 1)	(0, 0, 0.004, 0.008; 1)
SC21	(0, 0, 0.004, 0.008; 1)	(0.004, 0.008, 0.008, 0.012; 1)	(0.008, 0.012, 0.016, 0.02; 1)	(0, 0, 0.004, 0.008; 1)	(0, 0, 0.004, 0.008; 1)	(0, 0, 0.004, 0.008; 1)
SC22	(0, 0, 0.004, 0.008; 1)	(0, 0, 0.004, 0.008; 1)	(0.008, 0.012, 0.016, 0.02; 1)	(0, 0, 0.004, 0.008; 1)	(0.004, 0.008, 0.008, 0.012; 1)	(0, 0, 0.004, 0.008; 1)
SC23	(0, 0, 0.004, 0.008; 1)	(0, 0, 0.004, 0.008; 1)	(0, 0, 0.004, 0.008; 1)	(0.008, 0.012, 0.016, 0.02; 1)	(0.004, 0.008, 0.008, 0.012; 1)	(0.004, 0.008, 0.008, 0.012; 1)
SC24	(0, 0, 0.004, 0.008; 1)	(0, 0, 0.004, 0.008; 1)	(0.008, 0.012, 0.016, 0.02; 1)	(0, 0, 0.004, 0.008; 1)	(0, 0, 0.004, 0.008; 1)	(0, 0, 0.004, 0.008; 1)

Table 14
Fuzzy ideal solutions FPIS +, FNIS-

	FPIS +	FNIS −
SC1	(0.04, 0.04, 0.04, 0.04; 1)	(0, 0, 0, 0; 1)
SC2	(0.01, 0.01, 0.01, 0.01; 1)	(0, 0, 0, 0; 1)
SC3	(0.03, 0.03, 0.03, 0.03; 1)	(0, 0, 0, 0; 1)
SC4	(0.032, 0.036, 0.04, 0.04; 1)	(0.02, 0.02, 0.03, 0.03; 1)
SC5	(0.088, 0.099, 0.11, 0.11; 1)	(0.01, 0.02, 0.02, 0.03; 1)
SC6	(0.024, 0.027, 0.03, 0.03; 1)	(0, 0.01, 0.01, 0.01; 1)
SC7	(0.112, 0.126, 0.14, 0.14; 1)	(0.07, 0.08, 0.1, 0.11; 1)
SC8	(0.088, 0.099, 0.11, 0.11; 1)	(0.02, 0.03, 0.04, 0.06; 1)
SC9	(0.016, 0.016, 0.02, 0.02; 1)	(0.01, 0.01, 0.01, 0.01; 1)
SC10	(0.032, 0.036, 0.04, 0.04; 1)	(0.01, 0.01, 0.02, 0.02; 1)
SC11	(0.033, 0.033, 0.05, 0.05; 1)	(0, 0, 0, 0; 1)
SC12	(0.013, 0.013, 0.05, 0.05; 1)	(0, 0, 0, 0; 1)
SC13	(0.026, 0.026, 0.05, 0.05; 1)	(0, 0, 0, 0; 1)
SC14	(0.096, 0.108, 0.120, 0.12; 1)	(0.01, 0.02, 0.02, 0.04; 1)
SC15	(0.008, 0.009, 0.009, 0.01; 1)	(0, 0, 0, 0; 1)
SC16	(0.016, 0.018, 0.02, 0.02; 1)	(0, 0, 0, 0; 1)
SC17	(0.016, 0.018, 0.02, 0.02; 1)	(0, 0.01, 0.01, 0.01; 1)
SC18	(0.016, 0.018, 0.02, 0.02; 1)	(0, 0, 0, 0; 1)
SC19	(0.008, 0.012, 0.016, 0.02; 1)	(0, 0, 0, 0. 01; 1)
SC20	(0.008, 0.012, 0.016, 0.02; 1)	(0, 0, 0, 0.01; 1)
SC21	(0.008, 0.012, 0.016, 0.02; 1)	(0, 0, 0, 0.01; 1)
SC22	(0.008, 0.012, 0.016, 0.02; 1)	(0, 0, 0, 0.01; 1)
SC23	(0.008, 0.012, 0.016, 0.02; 1)	(0, 0, 0, 0.01; 1)
SC24	(0.008, 0.012, 0.016, 0.02; 1)	(0, 0, 0, 0.01; 1)

Fuzzy logic has provided the integration framework allowing to consider simultaneously criteria assessments consisting in crisp numbers, intervals and subjective judgments, coming from various sources. AHP is used for defining the weights of the criteria, while Fuzzy TOPSIS allows to aggregate the criteria and rank the solutions.

The main contributions of the study are:

- the suggestion of a global assessment framework allowing to structure the many criteria already suggested in the literature;
- the integration of several knowledge sources in the assessment framework (public or semi-public entities, public information or information from experts);
- the improvement of the fuzzy distance between two solutions included in Fuzzy TOPSIS, allowing to defuzzify the information later than in the classical Fuzzy TOPSIS, and with more consistence than in the previous propositions of fuzzy distance;
- the association of a confidence level to each expert assessment, in order to take into account the possibility that the expert is wrong, and the use of this confidence level in the final decision matrix suggested by Fuzzy TOPSIS.

The method has been applied for validation on a realistic case, showing that the suggested improvements allow to access a richer information that may be quite different from the results obtained using the classical Fuzzy TOPSIS. Even if this information may seem to be more difficult to interpret, we think that it provides a measure of the potential interest of some risky solutions that worth being considered in our competitive world.

After this first step allowing to provide decision support for positioning a GLH in a geographical area serving multiple industrial firms, our ongoing research is now oriented on the design of the whole distribution network for mass-customization in Africa under uncertain markets dynamics (markets demand, distribution conditions, etc..). This design will be based on Multi-Objective Mixed Integer Programming models and will use simulation techniques to analyse the robustness of network configurations. The designed network will integrate the selected GLHs, distribution and customization platforms, international/local manufacturing plants and point of sales, its topology being based on the specificities of the region in which it is implemented.

Table 15
Distance between each alternative and FPIS and FNIS (logistic ecosystem criteria).

	Crisp Distances (case 1)		Fuzzy distances (case 2)		Fuzzy distances case (3)	
	from FPIS +	from FNIS –	from FPIS +	from FNIS –	from FPIS +	from FNIS –
Djibouti	1.34	1.2	(0.08, 0.15, 0.23, 0.31)	(0.15, 0.24, 0.51, 0.7)	(0.11, 0.17, 0.28, 0.38)	(0.143, 0.2, 0.35, 0.49)
Mombassa	1.28	1.09	(0.28, 0.29, 0.56, 0.85)	(0.13, 0.19, 0.32, 0.45)	(0.15, 0.22, 0.36, 0.51)	(0.14, 0.17, 0.31, 0.45)
Dar es Salaam	1.07	1.09	(0.16, 0.14, 0.3, 0.46)	(0.16, 0.25, 0.42, 0.58)	(0.11, 0.16, 0.27, 0.37)	(0.09, 0.11, 0.2, 0.29)
Walvis Bay	1.41	0.85	(0.26, 0.27, 0.53, 0.79)	(0.13, 0.22, 0.34, 0.47)	(0.13, 0.2, 0.33, 0.46)	(0.15, 0.23, 0.39, 0.54)
Durban	1.54	0	(0.11, 0.18, 0.28, 0.39)	(0.13, 0.21, 0.35, 0.48)	(0.13, 0.2, 0.33, 0.46)	(0.17, 0.27, 0.44, 0.62)
Maputo	1.35	0	(0.2, 0.21, 0.41, 0.61)	(0.12, 0.18, 0.31, 0.43)	(0.15, 0.236, 0.38, 0.54)	(0.16, 0.21, 0.37, 0.53)

Table 16
The final ranking of the alternatives with respect to logistic ecosystem attractiveness.

	Case 1		Case 2			Case 3		
	CI(L)	Ranking	CI(L)	Pessimistic ranking	Optimistic ranking	CI(L)	Pessimistic ranking	Optimistic ranking
Djibouti	0.472	2	(0.15, 0.33, 1.3, 3)	2	1	(0.16, 0.33, 0.93, 1.95)	1	2
Mombassa	0.46	3	(0.1, 0.22, 0.66, 1.1)	4	6	(0.15, 0.26, 0.79, 1.58)	2	5
Dar es Salaam	0.505	1	(0.16, 0.35, 1.05, 1.81)	1	3	(0.13, 0.24, 0.74, 1.48)	3	6
Walvis Bay	0.377	4	(0.1, 0.25, 0.71, 1.2)	4	5	(0.15, 0.33, 0.9, 1.89)	2	3
Durban	0	5	(0.15, 0.34, 0.89, 2)	2	2	(0.16, 0.35, 0.94, 2.06)	1	1
Maputo	0	5	(0.12, 0.26, 0.78, 1.32)	3	4	(0.15, 0.28, 0.84, 1.71)	2	4

Table 17
The final ranking of alternatives with respect to country attractiveness.

	Case 1		Case 2 and 3		
	CI(C)	Ranking	CI(C)	Pessimistic ranking	Optimistic ranking
Djibouti	0.679	4	(0.08, 0.2, 0.4, 1.6)	5	5
Mombassa	0.912	4	(0.1, 0.25, 0.5, 2)	4	4
Dar es Salaam	0.969	2	(0.22, 0.58, 1.3, 3.45)	1	1
Walvis Bay	0.969	2	(0.22, 0.58, 1.3, 3.45)	1	1
Durban	0.983	1	(0.2, 0.52, 1.18, 3.14)	2	2
Maputo	0.934	3	(0.11, 0.28, 0.55, 2.2)	3	3

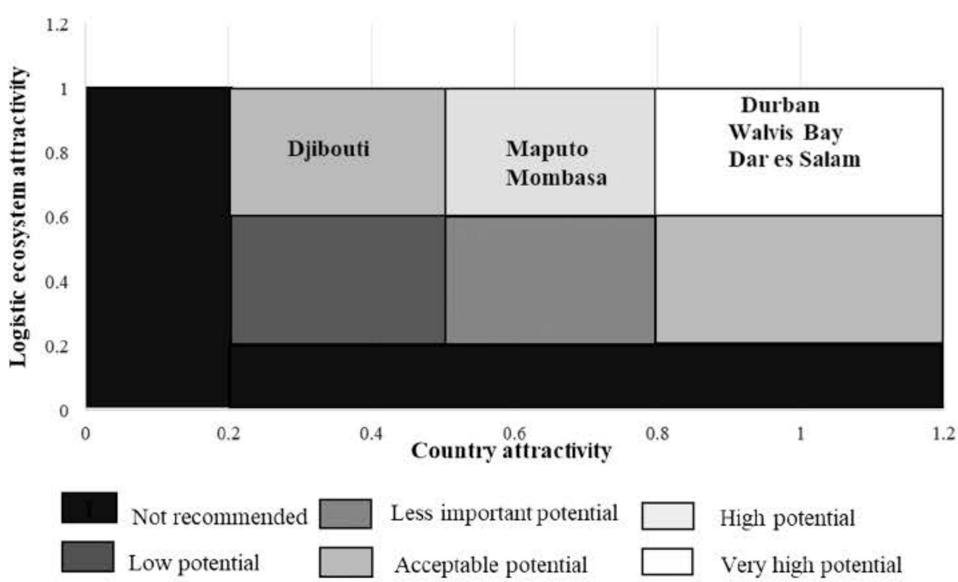

Fig. 6. Optimistic final scoring.

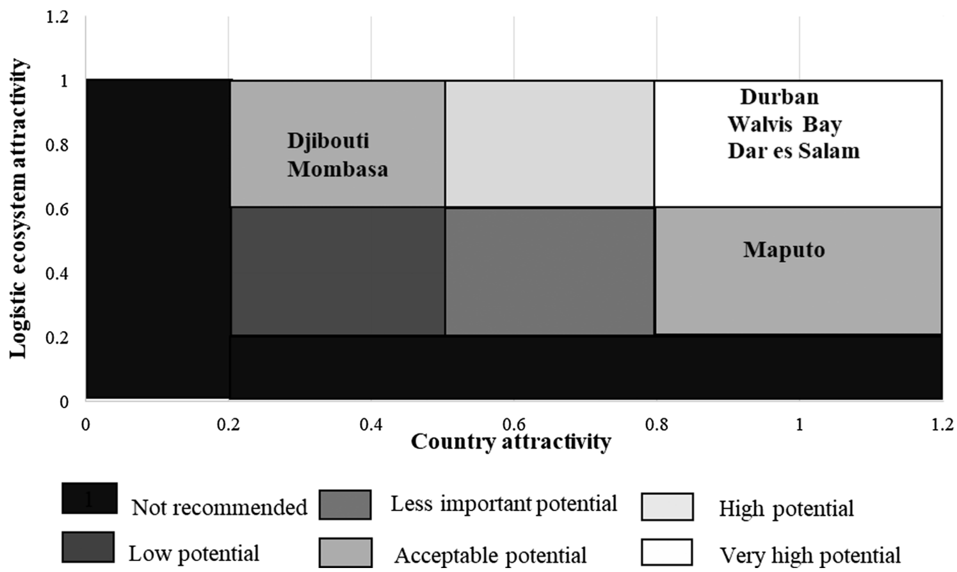

Fig. 7. Pessimistic final scoring.

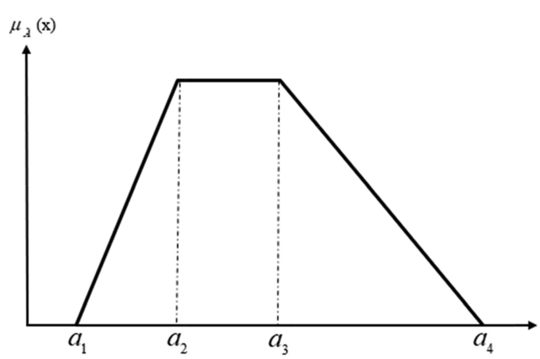

Fig. 8. Generalized Trapezoidal fuzzy number.

Table 18
Relative scores.

Value of aij	Interpretation
1	Criterion i and j are equally important
3	Criterion i is slightly more important than criterion j
5	Criterion i is more important than criterion j
7	Criterion i is strongly more important than criterion j
9	Criterion i is absolutely more important than criterion j

Table 19
Random consistency index (Saaty, 2008).

n	1	2	3	4	5	6	7	8	9	10	11	12
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.53

A. Theoretical background

A.1. Fuzzy set theory

Fuzzy logic was suggested by Zadeh (1965) in order to model and process information pervaded by imprecision. As a basis of the method, the membership of an element to a set is not anymore binary like in classical logic but becomes a matter of degree.

Let $\tilde{A}$ be a fuzzy set, $\tilde{A} = \{(x, \mu_A(x), x \in X\}$. $\mu_A(x) \in [0, 1]$ expresses to what extent x belongs to $\tilde{A}$ (Zadeh, 1965). μ is called the membership function of the set.

A.1.1. Linguistic variable

A linguistic variable is a variable which value is a word or a sentence in a natural language (Zadeh, 1975). For instance, "humidity" is a linguistic variable if its values are expressed by linguistic labels rather than numerically, e.g. high, medium, low.

A.1.2. Generalized trapezoidal fuzzy numbers

According to Cheng (1998) a generalized trapezoidal fuzzy number (GTFN) $\widetilde{A}$ is represented as $\widetilde{A} = (a_1, a_2, a_3, a_4, \omega)$ where a_1, a_2, a_3, a_4 are real numbers and $0<\omega \leqslant 1$ represents the degree of confidence of expert regarding the fuzzy number $\widetilde{A}$. The generalized fuzzy number is a fuzzy subset on the real line R, which membership $\mu_{\widetilde{A}}$ can be defined as denoted in Fig. 8. In practice, trapezoidal fuzzy numbers are often sufficient to model expert knowledge, and allow easy calculations (Chou, Chang, & Shen, 2008).

A normal trapezoidal fuzzy number $\widetilde{A} = (a_1, a_2, a_3, a_4)$ is obtained from GTFN by setting the confidence level to one $\omega = 1$.

The α-cut representation of $\widetilde{A}$ is an interval number denoted by:

$$[\widetilde{A}]_\alpha = [A^L(\alpha), A^R(\alpha)] = [(a_2 - a_1)\alpha + a_1, -(a_4 - a_3)\alpha + a_4] \tag{5}$$

Different choices are possible for defining operations on fuzzy numbers. When trapezoidal numbers are considered, the simplest arithmetic operations are those defined in Chen and Chang (2006):

$$\widetilde{A}(+)\widetilde{B} = (a_1 + b_1, a_2 + b_2, a_3 + b_3, a_4 + b_4) \tag{6}$$

$$\widetilde{A}(-)\widetilde{B} = (a_1 - b_4, a_2 - b_3, a_3 - b_2, a_4 - b_1) \tag{7}$$

$$\widetilde{A}(\times)\widetilde{B} = (a_1 b_1, a_2 b_2, a_3 b_3, a_4 b_4) \tag{8}$$

$$k \otimes \ \widetilde{A} = (ka_1, ka_2, ka_3, ka_4) \tag{9}$$

$$(\widetilde{A})^{-1} = \left(\frac{1}{a_4}, \frac{1}{a_3}, \frac{1}{a_2}, \frac{1}{a_1}\right) \tag{10}$$

$$-(\widetilde{A}) = (-a_4, -a_3, -a_2, -a_1) \tag{11}$$

According to Chen (2000) the distance between two fuzzy number D ($\tilde{n}_1$ $\tilde{n}_2$) is equal to:

$$D(\tilde{n}_1 \ \tilde{n}_2) = \sqrt{\frac{1}{4}[(a_1 - a_2)^2 + (b_1 - b_2)^2 + (c_1 - c_2)^2 + (d_1 - d_2)^2]} \tag{12}$$

A.2. Scoring method: the classical fuzzy TOPSIS

The classical TOPSIS method uses crisp weights and rates alternatives in an accurate way. The fuzzy version of TOPSIS allows handling fuzzy weights and results in a fuzzy assessment of a solution (Behzadian et al., 2012). This approach involves six steps:

Step 1: Construction of the fuzzy decision matrix

Let us consider m alternatives ($A_1, A_2, \dots, A_m$) to be compared and n decision criteria ($C_1, C_2, \dots, C_n$); this leads to the decision matrix D (Eq. (13)) where r_{ij} is a linguistic value that represents the performance rating of the ith alternative with respect to jth criterion.

$$D = \begin{array}{c|cccc|} & C_1 & C_2 & \cdots & C_n \\ A_1 & r_{11} & r_{12} & \cdots & r_{1n} \\ A_2 & r_{21} & r_{22} & \cdots & r_{2n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ A_m & r_{m1} & r_{m2} & \cdots & r_{mn} \end{array} \tag{13}$$

In each rating performance r_{ij} is then translated to a fuzzy number $\check{r}_{ij} = (a_i, b_i, c_i, d_i)$ using a specific conversion scale. The fuzzy decision matrix becomes D (Eq. (14)).

$$Đ = \begin{array}{c|cccc|} & C_1 & C_2 & \cdots & C_n \\ A_1 & \check{r}_{11} & \check{r}_{12} & \cdots & \check{r}_{1n} \\ A_2 & \check{r}_{21} & \check{r}_{22} & \cdots & \check{r}_{2n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ A_m & \check{r}_{m1} & \check{r}_{m2} & \cdots & \check{r}_{mn} \end{array} \tag{14}$$

Step 2: Normalization of the fuzzy decision matrix

The criteria may be assessed according to different scales. Normalization allows to consider them on a similar scale so that their relative importance is only expressed by their weights. The computation of the normalization depends on whether a criterion is a cost criterion (to be minimized; set C) or a benefit criterion (to be maximized; set B). Thus, the normalized fuzzy decision matrix can be assessed as shown in Eqs. (15)–(17).

$$\check{r}n_{ij} = \left(\frac{a_{ij}}{d_j^+}, \frac{b_{ij}}{d_j^+}, \frac{c_{ij}}{d_j^+}, \frac{d_{ij}}{d_j^+}\right), j \in B \tag{15}$$

$$\check{r}n_{ij} = \left(\frac{a_j^-}{d_{ij}}, \frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right), j \in C \tag{16}$$

$$\text{where} \quad d_j^+ = \max_i d_{ij} \ \text{ if } \ j \in B \ \text{ and } \ a_j^- = \min_i a_{ij}, j \in C \tag{17}$$

Step 3: Construction of the weighted normalized fuzzy decision matrix

Let $\tilde{x}_{ij}$ be the weighted normalized rating of the ith alternative with respect to jth criterion. $\tilde{x}_{ij}$ is computed according to Eq. (18):

$$\tilde{x}_{ij} = \check{r}nij \otimes \ w_j \tag{18}$$

Step 4: Computation of the fuzzy ideal solutions

In this step, we define the fuzzy ideal positive solution $FPIS^+$ and the negative ideal solution $FPNS^-$ as vectors of the best (resp. worst) performance with respect to each criterion. We deduce these values from the decision matrix built in step 3.

$$FPIS^+ = (\tilde{x}_1^+, \tilde{x}_2^+, \cdots, \tilde{x}_n^+) \tag{19}$$

$$FNIS^- = (\tilde{x}_1^-, \tilde{x}_2^-, \cdots, \tilde{x}_n^-) \tag{20}$$

$$\text{Where} \tilde{x}_{ij} = (\tilde{x}_{ij1}, \tilde{x}_{ij2}, \tilde{x}_{ij3}, \tilde{x}_{ij4}); \tilde{x}_j^+ = \max_i \tilde{x}_{ij4}; \ \tilde{x}_j^- = \min_i \tilde{x}_{ij1}; \ i = 1, 2, .., m; \ j = 1, 2, .., n \tag{21}$$

Step 5: Computation of the distance between each alternative and the ideal solution

The distance between each alternative and the fuzzy positive ideal (resp. negative ideal) solution $FPIS^+$ (resp. $FNIS^-$) can be calculated respectively in Eq. (22) (resp. (23)).

$$d_i^+ = \sum_{j=1}^{n} d(\tilde{x}_{ij}, \tilde{x}_j^+), \ i = 1, 2, .., m \tag{22}$$

$$d_i^- = \sum_{j=1}^{n} d(\tilde{x}_{ij}, \tilde{x}_j^-), \ i = 1, 2, .., m \tag{23}$$

Where the elementary distances $d(\tilde{x}_{ij}, \tilde{x}_j^+)$ and $d(\tilde{x}_{ij}, \tilde{x}_j^-)$ are computed using Eq. (12).

Step 6: Determination of the closeness index

Finally, we compute the Closeness index CI_i for each alternative to rank alternatives according to the descending order. The best alternative is the one with the highest closeness coefficient.

$$CI_i = \frac{d_i^-}{d_i^- + d_i^+}, \ i = 1, 2, .., m \tag{24}$$

A.3. Weighting method: AHP

All the criteria clearly do not have the same importance. The robustness of the choice of the weights expressing their relative importance may be increased by using a weighting method like AHP. The particularity of AHP is that it structures the decision-making problem according to a transparent and easy-to-follow hierarchy, usually in the form of a tree. This is done according to a top-down approach, starting from the overall goal to various criteria and sub criteria forming a homogenous clusters of criteria. Finally the decision alternatives are laid down at the last level of the structure. The section of AHP concerning the weights of the criteria is structured around three steps: construction of pairwise matrices, aggregation of the final weights and verification of consistency.

Step 1: Construction of pairwise matrices

Once the hierarchical structure has been built, the next step will be to determine the relative importance of each criterion with respect to other criteria belonging to the same cluster. For each cluster, we create a pairwise matrix. The pairwise comparison is given in terms of how much a criterion is more or less important to another one. Note that as we have n criteria, the number of pairwise comparisons to built is $\frac{n(n-1)}{2}$.

Let A be the pairwise comparison matrix which rows give the ratios of weights of each criterion with respect to all others. Each ratio a_{ij} is obtained by comparing the importance of the ith criterion to the jth criterion using the qualitative scale of Saaty (2008) (Table 18). Thus, if $a_{ij} > 1$, then the ith criterion is more important than the jth one. If two criteria have the same importance then $a_{ij} \times a_{ji} = 1$. The pairwise comparisons matrix is in the form:

$$A=\begin{bmatrix}a_{11} & \cdots & a_{1n}\\ \vdots & \ddots & \vdots\\ a_{n1} & \cdots & a_{nn}\end{bmatrix}=\begin{bmatrix}w_1/w_1 & \cdots & w_1/w_n\\ \vdots & \ddots & \vdots\\ w_n/w_1 & \cdots & w_n/w_n\end{bmatrix} \tag{25}$$

where $\mathbf{w_j}$ is the relative weight of the jth criterion. Let $\mathbf{w} = [w_1, w_2, w_3, \ldots, w_n]$ be the vector of criteria weights. According to Saaty (2008), w corresponds to the eigenvector of **A**. To determine **w**, we have to resolve the following equation:

$$A=\begin{bmatrix}w_1/w_1 & w_1/w_2 & \cdots & w_1/w_n\\ w_2/w_1 & w_2/w_2 & \cdots & w_2/w_n\\ \vdots & \vdots & \ddots & \vdots\\ w_n/w_1 & w_n/w_2 & \cdots & w_n/w_n\end{bmatrix}\begin{bmatrix}w_1\\ w_2\\ \vdots\\ w_n\end{bmatrix}=n\begin{bmatrix}w_1\\ w_2\\ \vdots\\ w_n\end{bmatrix} \tag{26}$$

This Eq. (27) $A\cdot w = n\cdot w$ is equivalent to: $(A - n\cdot I)\cdot w = 0$

According to Saaty (2008) this has a non-zero solution if n is an eigenvalue of A. However, since A has a rank one because every row is a constant multiple of the first row, all its eigenvalues are equal to zero except one. Furthermore, as, the solution **w** is any column of **A,** this leads to various solutions that differ by a multiplicative constant. Thus, to make **w** unique, we normalize it as follow:

$$w_i=\frac{\sum_{k=1}^{n}\bar{a}_{ik}}{n} \quad \text{where} \quad \bar{a}_{ij}=\frac{a_{ij}}{\sum_{k=1}^{n}a_{kj}} \tag{27}$$

Step 2: Aggregating final weights

After computing all pairwise comparison matrices, we compute the final weight of an elementary criterion by multiplying its weight by the weight of parent criterion following a bottom-up approach till reaching the first macro criterion.

Step 3: Checking the consistency

Some inconsistencies could arise during pairwise comparison. We will so compute a consistency index as follows:

- Compute the eigenvalue λ_{max} of each matrix by solving equation $A\cdot\mathbf{w} = \lambda_{max}\cdot\mathbf{w}$, where w is the eigenvector;
- Compute the consistency index for each matrix of order n where $CI = \frac{\lambda max - n}{n-1}$;
- Finally the consistency ratio is computed as $CR = CI/RI$, where RI is a known random consistency index depending upon the order of the matrix (Table 19).

The matrix is said to be consistent if CI or CR is less than 10%. Thus, if CR is more than this acceptable threshold, the evaluation process should be reviewed.

A.4. Scoring method: the adjusted fuzzy TOPSIS

The main difference between the adjusted Fuzzy TOPSIS and the classical concerns the distance and closeness index computation, which become Fuzzy in the adjusted version of Fuzzy TOPSIS.

Step 1–4: Similar to the classical Fuzzy distance
Step 5: Computation of the Fuzzy distance between each alternative and the ideal solution

The elementary Fuzzy distance between each alternatives and ideal solutions is computed based on formula (2). Then the aggregated Fuzzy distance is calculated using formulae (6), (28) and (29).

$$\tilde{d}_i^{+}=\sum_{j=1}^{n}\tilde{d}\,(\tilde{x}_{ij},\tilde{x}_j^{+}),\quad i=1,2,..,m \tag{28}$$

$$\tilde{d}_i^{-}=\sum_{j=1}^{n}\tilde{d}\,(\tilde{x}_{ij},\tilde{x}_j^{-}),\quad i=1,2,..,m \tag{29}$$

Step 6: Determination of the Fuzzy closeness index

The Fuzzy closeness index is then computed using formulae (6), (9), (12) and (24). The optimistic ranking is based on the rightmost point of the α-cut $\widetilde{CI}_i^{+}$ (33) the while the pessimistic ranking is made upon the leftmost point of the α-cut $\widetilde{CI}_i^{-}$ (34).

$$\widetilde{CI}_i=\frac{\tilde{d}_i^{-}}{\tilde{d}_i^{-}+\tilde{d}_i^{+}},\quad i=1,2,..,m \tag{30}$$

$$Sup\widetilde{CI}_i=Sup_{0\le\alpha\le1}[\widetilde{CI}_i]_\alpha,\quad i=1,2,..,m \tag{31}$$

$$Inf\widetilde{CI}_i=Inf_{0\le\alpha\le1}[\widetilde{CI}_i]_\alpha,\quad i=1,2,..,m \tag{32}$$

$$\check{CI}_i^{+} = \widetilde{SupCIN}_i = \frac{\widetilde{SupCI}_i}{Max(\widetilde{SupCI}_i)}, \quad i = 1, 2, .., m \tag{33}$$

$$\check{CI}_i^{-} = \widetilde{InfCIN}_i = \frac{\widetilde{InfCI}_i}{Max(\widetilde{InfCI}_i)}, \quad i = 1, 2, .., m \tag{34}$$

A.5. Distance between two fuzzy numbers (Jahantigh et al., 2014)

Let us consider two generalized fuzzy numbers $\widetilde{A}_1(a_1, b_1, \beta_1, \gamma_1, \omega_1)$ and $\widetilde{A}_2(a_2, b_2, \beta_2, \gamma_2, \omega_2)$. Their corresponding α-cut are denoted by $[\widetilde{A}_1]_\alpha = [\widetilde{A}_1^L(\alpha), \widetilde{A}_1^R(\alpha)]$ and $[\widetilde{A}_2]_\alpha = [\widetilde{A}_2^L(\alpha), \widetilde{A}_2^R(\alpha)]$ for all $\alpha \in [0, 1]$.

According to Jahantigh et al. (2014), the crisp distance between two generalized fuzzy numbers $\widetilde{A}_1$ and $\widetilde{A}_2$ is defined as follows:

$$\text{If } w = \min(\omega_1, \omega_2) > \frac{1}{2} \quad d(\widetilde{A}_1, \widetilde{A}_2) = \left| \begin{array}{l} \int_0^{\frac{1}{2}} (1-\alpha)(\widetilde{A}_1^R(\alpha) - \widetilde{A}_2^R(\alpha)) + \alpha(\widetilde{A}_1^L(\alpha) - \widetilde{A}_2^L(\alpha))d\alpha \\ + \int_{\frac{1}{2}}^{w} \alpha(\widetilde{A}_1^R(\alpha) - \widetilde{A}_2^R(\alpha)) + (1-\alpha)(\widetilde{A}_1^L(\alpha) - \widetilde{A}_2^L(\alpha))d\alpha \end{array} \right| + \left|\int_w^{w'} \alpha(R(\alpha) - L(\alpha))d\alpha\right| \tag{35}$$

$$\text{If } w = \min(\omega_1, \omega_2) < \frac{1}{2} \quad d(\widetilde{A}_1, \widetilde{A}_2) = \left|\int_0^{w} (1-\alpha)(\widetilde{A}_1^R(\alpha) - \widetilde{A}_2^R(\alpha)) + \alpha(\widetilde{A}_1^L(\alpha) - \widetilde{A}_2^L(\alpha))d\alpha\right| + \left|\int_w^{w'} \alpha(R(\alpha) - L(\alpha))d\alpha\right| \tag{36}$$

where:

$w' = \max(\omega_1, \omega_2)$

$$R(\alpha) = \begin{cases} \widetilde{A}_1^R(\alpha) \text{ for } w' = \omega_1 \\ \widetilde{A}_2^R(\alpha) \text{ for } w' = \omega_2 \end{cases} \tag{37}$$

$$L(\alpha) = \begin{cases} \widetilde{A}_1^L(\alpha) \text{ for } w' = \omega_1 \\ \widetilde{A}_2^L(\alpha) \text{ for } w' = \omega_2 \end{cases} \tag{38}$$

A.6. The generalized Hausdorff metric

Let F^g be the family of all generalized fuzzy numbers and K a set of compact subset of R^2 and A and B are two subsets of R^2. The Hausdorff metric on H: $K \times K \to [0, \infty)$ defined by Voxman (1998) is:

$$H(A, B) = \max\{\sup_{b \in B} d_E(b, A), \sup_{a \in A} d_E(a, B)\} \tag{39}$$

where d_E is the usual Euclidean metric for R^2

The generalized Hausdorff metric d_∞^R on $F^g \times F^g$ is defined by:

$$d_\infty^R(\widetilde{A}_1, \widetilde{A}_2) = \sup_{0 \leqslant \alpha < w} (H([\widetilde{A}_1]_\alpha, [\widetilde{A}_2]_\alpha)\} + \beta \sup_{w \leqslant \alpha < w'} |R(\alpha) + L(\alpha)| \tag{40}$$

where: $\beta = \begin{cases} 1 \text{ for } w' \neq \omega_1 \\ 0 \text{ for } w' = \omega_2 \end{cases}$

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