A HETEROGENEOUS APPROACH FOR ENVIRONMENTAL IMPACT SIGNIFICANCE ASSESSMENT BASED ON FUZZY LINGUISTIC MODELS

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Abstract:

Classical methods for Environmental Impact Significance Assessment are not efficient on handle heterogeneous information and they obtain numerical outputs of low interpretability. In this contribution we propose a novel heterogeneous approach for EISA based on fuzzy linguistic models. It provides a flexible evaluation framework in which experts can supply their preferences using different domains and applies an aggregation process based on 2-tuples linguistic computational model to obtain interpretable significance values.

Keywords:

Fuzzy linguistic model; Decision analysis; Impact assessment

1 Introduction

The rational use of natural resources demands more suitable studies on how environmental factors are impacted by human actions. Such studies are generally performed following two different perspectives. The first one is based on significance and uses the experts' judgements while the second one is based on the magnitude and attempts to quantify environmental quality changes. Our interest in this contribution is focused on the former perspective called Environmental Impact Significance Assessment (EISA) which is the process for determining the importance of the project's impacts over the affected environmental factors, considering subjective judgements provided in a qualitative or quantitative way.

In classical EISA methods [2],[6],[7],[10] criteria are assessed using numerical scales and their results are also numbers difficult to understand. They are not efficient in managing suitably heterogenous information and handling properly the uncertainties and vagueness' of such information.

To overcome such limitations in this contribution we propose a new approach for EISA, which provides, based on the decision analysis structure [1], a flexible heterogeneous evaluation framework and it is capable of gathering heterogeneous preferences taking into account the uncertainty of EISA, the qualitative or quantitative essence of criteria and the experience of the experts. The experts' preferences are modeled by means of linguistic information which implies processes of computing with words (CWW) [9], [14] which are accomplished using the 2-tuple linguistic representation and computational models [3], [4], [5], [8].

The rest of the paper is organized as follows. Section 2 reviews the EISA problem and traditional methods emphasizing on their limitations which motivate the definition of the new EISA approach presented in section 3. Section 4 shows an example and section 5 concludes the paper.

2 The EISA problem: classical solving methods

Determining the significance of environmental impacts may be modeled as a Multi-Criteria Decision Making (MCDM) problem [12] in which a project or a set of alternative projects are evaluated and ranking according to the following elements:

- A set of actions $A = \{a_1, ..., a_j\}$ to be executed.
- A set of affected environmental factors $F = \{f_1, ..., f_m\}$.
- A set of impacts.
- A set of criteria $C = \{c_1, ..., c_h\}$ characterizing impacts.
- One expert or more $E = \{e_1, ..., e_k\}$ providing preferences.

A critical issue in EISA is *maximizing assessment accuracy while simultaneously ensuring that the results obtained remain understandable* however traditional EISA methods [2],[6],[7],[10] exhibit the following limitations in achieving this purpose:

1. They are not flexible since the experts are constrained to use numerical scales although criteria exhibit diverse na-

978-1-4799-0260-6/13/$31.00 ©2013 IEEE

ture and might be evaluated using different expression domains.

2. They obtain numerical outputs of low interpretability due to quantitative results not always represents qualitative information accurately.

3. They are consequently unable to handle properly the uncertainties and vagueness' of impact significance assessment.

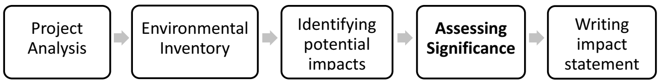

Figure 1. A general procedure for EISA

Figure 1 delineates the general procedure for EISA. Our aim in this contribution is to improve the **Assessing Significance** stage as the core for successful final evaluations of proposals. To accomplish this objective and overcome limitations mentioned above, we introduce in the next section a new EISA heterogeneous approach where the environmental experts' preferences are modeled by means of linguistic information.

3 A heterogeneous approach for EISA based on fuzzy linguistic models

The flowchart for **Assessing Significance** in the approach, based on the classical decision analysis scheme [1], consists of the three phases exhibited in Figure 2 and explained in the subsequent subsections.

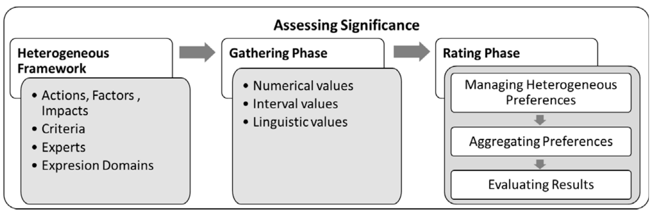

Figure 2. The heterogeneous EISA approach

3.1 Heterogeneous framework

Let $A = \{a_1, ..., a_j\}$ be the set of actions to be accomplished during the project, $F = \{f_1, ..., f_m\}$ the set of identified environmental factors which significance is given by the weighting vector $W^f = \{w_1^f, ..., w_m^f\}, w_i^f \in [0, 1]$ with $\sum_{i=1}^{m} w_i^f = 1$.

Every environmental impact is represented by means of the pair $(f_i \sim a_j)$ containing the action which causes the impact and the affected environmental factor.

Additionally let $E = \{e_1, ..., e_k\}$ the set of experts assessing the environmental impacts according to the set of criteria $C = \{c_1, ..., c_h\}$ which weights are given by the vector $W^c = \{w_1^c, ..., w_h^c\}, w_i^c \in [0, 1]$ with $\sum_{i=1}^{h} w_i^c = 1$.

Since criteria represent different dimensions of the impacts, they may conflict with each other [13] originating the division of C into two subsets: C^1 with benefit criteria and C^2 with cost criteria. Furthermore $C = C^1 \cup C^2$ and $C^1 \cap C^2 = \phi$ where ϕ is an empty set.

Let $U = \{u_{11}, u_{12}, ..., u_{m(n-1)}, u_{mn}\}$, $u_{ij} \in \{-1, 1\}$ be the vector for representing the *nature*, where -1 represents a negative impact and 1 the positive one.

The preferences provided by expert $e_k \in E$ about the impact of action $a_j \in A$ over factor $f_i \in F$ according to the criteria $c_h \in C$ is represented by x_{ij}^{hk}. They will be assessed using values within domains belonging to $O = \{N, V, L\}$:

1. *N* (Numerical Domain): $x_{ij}^{hk} = v_{ij}^{hk} \in R^+$ being R^+ the set of non-negative real numbers.

2. *V* (Interval-valued Domain): $x_{ij}^{hk} = [a_{ij}^{hk}, b_{ij}^{hk}]$ with $a_{ij}^{hk}, b_{ij}^{hk} \in R^+$ and $a_{ij}^{hk} \le b_{ij}^{hk}$.

3. *L* (Linguistic Domain): $x_{ij}^{hk} = s_{ij}^{hk} \in S, S = \{s_0, ...s_g\}$ being $g + 1$ the cardinality of the linguistic term set S.

3.2 Gathering Phase

Each expert provides his/her preferences about impacts $(f_i \sim a_j)$ by means of assessment vectors: $\{x_{ij}^{1k}, ..., x_{ij}^{qk}\}$.

3.3 Rating Phase

The rating phase generates an interpretable global significance full-value of the project. To accomplish this purpose, we follow the three steps presented in Figure 2.

3.3.1 Managing heterogeneous preferences

The aim of managing the heterogeneous preferences is to accurately obtain handleable values for later aggregation. From the gathered information x_{ij}^{hk} we first obtain normalized values $\bar{x}_{ij}^{hk}$ and then unified linguistic 2-tuples values $\hat{x}_{ij}^{hk}$.

i) Normalizing the heterogeneous preferences

In this step, in one hand we obtain values in $[0, 1]$ and on the other hand we manage the cost/benefits criteria conflicts, using equations defined below.

- For $x_{ij}^{hk} \in N$:

$$\bar{x}_{ij}^{hk} = \begin{cases} x_{ij}^{hk}/y_i & \text{if} \quad c_h \in C^1 \\ 1 - x_{ij}^{hk}/y_i & \text{if} \quad c_h \in C^2 \end{cases} \tag{1}$$

where $y_i = max\{x_{ij}^{h1}, ..., x_{ij}^{hk}\}$.

- For $x_{ij}^{hk} \in V$:

$$\bar{x}_{ij}^{hk} = \begin{cases} [a_{ij}^{hk}/y_i, b_{ij}^{hk}/y_i] & \text{if} \quad c_h \in C^1 \\ [1 - b_{ij}^{hk}/y_i, 1 - a_{ij}^{hk}/y_i] & \text{if} \quad c_h \in C^2 \end{cases} \tag{2}$$

where $y_i = max\{b_{ij}^{h1}, ..., x_{ij}^{hk}\}$.

- For $x_{ij}^{hk} \in S$:

$$\bar{x}_{ij}^{hk} = \begin{cases} s_{ij}^{hk} & \text{if} \quad c_h \in C^1 \\ Neg(s_{ij}^{hk}) & \text{if} \quad c_h \in C^2 \end{cases} \tag{3}$$

where Neg is the negation operator such that $Neg(s_i) = s_{g-i}$.

ii) Unifying the heterogeneous preferences

For unifying the heterogeneous preferences we consider the method proposed in [5]. Firstly the Basic Linguistic Term Set (BLTS) $\hat{S} = \{\hat{s}_0, \hat{s}_1, ..., \hat{s}_g\}$ is selected (see [5] for details).

We shall then transform each value into a fuzzy set using the corresponding transformation function:

- For $\bar{x}_{ij}^{hk} \in [0,1]$, $T_{N\hat{S}} : [0,1] \to F(\hat{S})$ is defined as:

$$T_{N\hat{S}}(\bar{x}_{ij}^{hk}) = \sum_{i=1}^{g} (\hat{s}_i/\lambda_i), \tag{4}$$

where $\lambda_i = \mu_{\hat{s}_i}(\bar{x}_{ij}^{hk}) \in [0,1]$ is the membership degree of $\bar{x}_{ij}^{hk}$ to $\hat{s}_i \in \hat{S}$:

$$\mu_{\hat{s}_i}(\bar{x}_{ij}^{hk}) = \begin{cases} 0, & \text{if} \quad \bar{x}_{ij}^{hk} \ni \text{Support}\mu_{\hat{s}_i}(x) \\ \frac{\bar{x}_{ij}^{hk} - a_i}{b_i - a_i} & \text{if} \quad a_i \leq \bar{x}_{ij}^{hk} \leq b_i \\ 1 & \text{if} \quad b_i \leq \bar{x}_{ij}^{hk} \leq d_i \\ \frac{c_i - \bar{x}_{ij}^{hk}}{c_i - d_i} & \text{if} \quad d_i \leq \bar{x}_{ij}^{hk} \leq c_i \end{cases} \tag{5}$$

- For $\bar{x}_{ij}^{hk} \in [\bar{i}, \underline{i}]$ being $[\bar{i}, \underline{i}]$ an interval on $[0,1]$, $T_{I\hat{S}} : [\bar{i}, \underline{i}] \to F(\hat{S})$ is defined as:

$$T_{I\hat{S}}(\bar{x}_{ij}^{hk}) = \sum_{i=1}^{g} (\hat{s}_i/\lambda_i), \tag{6}$$

where $\lambda_i = max_y min\{\mu_I(y), \mu_{\hat{s}_j}(y)\}$, $y \in [0,1]$ and

$$\mu_I(y) = \begin{cases} 0 & \text{if} \quad y < d \\ 1 & \text{if} \quad d \leq y \leq e \\ 0 & \text{if} \quad y > e \end{cases} \tag{7}$$

- For $\bar{x}_{ij}^{hk} \in S$ with $S = \{s_j, j = 1, ..., h\}$ and $h \leq g$, $T_{S\hat{S}} : S \to F(\hat{S})$ is defined as:

$$T_{S\hat{S}}(\bar{x}_{ij}^{hk}) = \sum_{i=1}^{g} (\hat{s}_i/\lambda_i), \tag{8}$$

where $\lambda_i = max_y min\{\mu_{s_j}(y), \mu_{\hat{s}_j}(y)\}$

Afterwards we shall transform the fuzzy sets into linguistic 2-tuples over the BLTS using the function $\chi : F(\hat{S}) \to \tilde{S}$ defined as:

$$\chi(\lambda_0, \lambda_1, ..., \lambda_g) = \triangle\left(\frac{\sum_{j=0}^{g} j\lambda_j}{\sum_{j=0}^{g} \lambda_j}\right) \tag{9}$$

The 2-tuple model [3] represents the linguistic information by means of a 2-tuple (s_i, α) where $s_i \in S = \{s_0, ..., s_g\}$ is the linguistic term and α is the symbolic translation.

The associated 2-tuple is $\hat{S} = S \times [-0.5, 0.5)$ and the bijective function $\triangle : [0, g] \to \hat{S}$ is defined as:

$$\triangle(\beta) = \begin{cases} s_i, & i = round(\beta) \\ \alpha = \beta - i, & \alpha \in [-0.5, 0.5) \end{cases} \tag{10}$$

where $round$ assigns to β the integer number $i \in \{0, 1, ..., g\}$ closest to β.

Summarizing, the normalized heterogeneous preferences are unified into linguistic 2-tuples as:

$$\hat{x}_{ij}^{hk} = \begin{cases} \chi(T_{N\hat{S}}(\bar{x}_{ij}^{hk})) & \text{if} \quad \bar{x}_{ij}^{hk} \in N \\ \chi(T_{V\hat{S}}(\bar{x}_{ij}^{hk})) & \text{if} \quad \bar{x}_{ij}^{hk} \in V \\ \chi(T_{S\hat{S}}(\bar{x}_{ij}^{hk})) & \text{if} \quad \bar{x}_{ij}^{hk} \in S \end{cases} \tag{11}$$

3.3.2 Aggregating Preferences

After obtaining 2-tuple assessments, it is required to generate the significance values by means of the following steps: i) Computing collective criteria values, ii) Computing impacts' significance, iii) Adjusting significance and iv) Computing final significance values.

This phase is supported on the aggregation operators for linguistic 2-tuple detailed in [3]:

- The arithmetic mean $M : \hat{S}^m \to \hat{S}$ defined as:

$$M((s_1, \alpha_1), ..., (s_m, \alpha_m)) = \triangle\left(\frac{1}{n} \sum_{i=1}^{m} \triangle^{-1}((s_i, \alpha_i))\right) \tag{12}$$

- The weighted average $\bar{W} : \hat{S}^m \to \hat{S}$ defined as:

$$\bar{W}((s_1, \alpha_1), ..., (s_m, \alpha_m)) = \triangle\left(\sum_{i=1}^{m} w_i \triangle^{-1}((s_i, \alpha_i))\right) \tag{13}$$

i) Computing collective criteria values

The assessment of all experts about each criterion for the impact cause by each action over each factor, is denoted as I_{ij}^h and it is computed using the 2-tuple mean:

$$I_{ij}^h = M(\hat{x}_{ij}^{h1}, ..., \hat{x}_{ij}^{hk}) \tag{14}$$

ii) Computing impacts' significance

The significance of each impact is denoted as I_{ij} and is computed using the 2-tuple weighted average operator with W^f as:

$$I_{ij} = \bar{W}(I_{ij}^1, ..., I_{ij}^h) \tag{15}$$

iii) Adjusting significance

An I_{ij} linguistic value does not comprise itself if the impact will be positive or negative. To represent the nature of an impact, we propose to proceed in similar way to a Linguistic Hierarchy (LH) building process [4]. A LH is the union of all levels $t : LH = \bigcup_t l(t, n(t))$, where each level t of a LH corresponds to a linguistic term set with a granularity of uncertainty of $n(t)$ denoted as: $S^{n(t)} = \{s_0^{n(t)}, ..., s_{n(t)-1}^{n(t)}\}$.

To solve our problem, a two-level LH should be generated, with the BLTS at level 1 and an Adjusted Linguistic Term Set (ALTS) at level 2 generated as $l(t, n(t)) \to l(t+1, 2.n(t)-1)$. Once we have the ALTS at level 2, to obtain its semantic we define a ϑ transformation function:

Definition 2. Let $LH = \bigcup_t l(t, n(t))$ whose term sets are

l(1, n(t)) BLTS

l(2, 2.n(t)-1) ALTS

and let us consider the 2-tuple linguistic representation. The transformation function from BLTS to ALTS is defined as:

$$\vartheta : l(1, n(t)) \to l(2, 2 \cdot n(t) - 1))$$

$$\vartheta((s_i, \alpha)) = \begin{cases} \triangle^{-1}(\triangle(s_i, \alpha) + \frac{g-1}{2}) & if \quad u = 1 \\ \triangle^{-1}(\frac{g-1}{2} - \triangle(s_i, \alpha)) & if \quad u = -1 \end{cases} \tag{16}$$

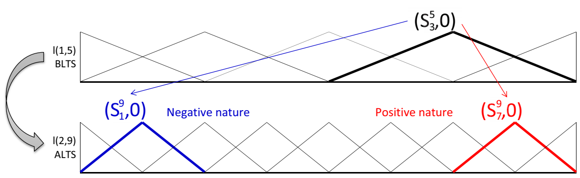

Figure 3. Example of ϑ performance

Figure 3 gives an example on how the ϑ function operates. Finally we can adjust all I_{ij} values through:

$$I'_{ij} = \vartheta(I_{ij}) \tag{17}$$

iv) Computing final significance values

We shall generate final indicators: Factor's Significance (FI_i), Action's Significance (AI_j), Action's Weighted Significance (WI_j) and Global Significance (PI); using the respective equation.

$$FI_i = M(I'_{i1}, ..., I'_{in}) \tag{18}$$

$$AI_j = M(I'_{1j}, ..., I'_{mj}) \tag{19}$$

$$WI_j = \bar{W}(AI_1, ..., AI_n) \tag{20}$$

$$PI = M(I'_{11}, ..., I'_{mn}) \tag{21}$$

3.3.3 Evaluating results

To conclude, impacts, actions and factors are ranked according to their significance values. The larger the better then the more negatively affected factors and the more aggressive actions have lower significance values.

4 Illustrative example

To illustrate the EISA approach functioning, we consider a simplification of the *exploitation of a petrol station* project [11].

4.1 Heterogeneous Framework

- Actions: the operation of petrol pumps (a_1), the operation of car wash (a_2), the transport of fuels and materials (a_3) and the filling of fuel tanks (a_4).
- Environmental factors: daily sound comfort (f_1), hydrocarbons in air (f_2), public health and civic safety (f_3) and energy infrastructures (f_4).
- Criteria (according to Conesa's methodology [2]): intensity (c_1), extension (c_2), moment (c_3), persistence (c_4), reversibility (c_5), synergy (c_6), accumulation (c_7), effect (c_8), periodicity (c_9) and recoverability (c_{10}).
- Domains: criteria $c_1, c_2, c_6, c_7, c_8, c_9$ and c_{10} are assessed in the linguistic set of five terms S^5 depicted in Figure 4-a) while criteria c_3, c_4 and c_5 are assessed in R^+ representing years.

The importance units of factors, criteria's weight and the nature of each impact are respectively represented by:

$W_f = \{0.20, 0.30, 0.35, 0.15\}$,

$W_c = \{0.36, 0.24, 0.08, 0.04, 0.04, 0.04, 0.04, 0.04, 0.04, 0.08\}$,

$U = \{0, -1, -1, 0, -1, 0, 0, -1, -1, 0, 0 - 1, 1, 0, 0, 0\}$.

TABLE 1. HETEROGENEOUS PREFERENCES

Expert	Impact	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}
	$f_1 \sim a_2$	L	L	0,00	1,00	1,00	L	L	L	H	VL
	$f_1 \sim a_3$	H	VL	0,00	1,00	1,00	M	M	M	VH	VL
	$f_2 \sim a_1$	H	L	0,00	5,00	10,00	M	L	VH	L	M
e_1	$f_2 \sim a_4$	M	VL	0,10	1,00	2,00	L	VL	VL	M	H
	$f_3 \sim a_1$	H	L	0,10	0,20	10,00	M	M	VH	L	M
	$f_3 \sim a_4$	VH	L	0,00	10,00	10,00	M	M	VH	L	H
	$f_4 \sim a_1$	VL	L	1,50	10,00	10,00	VL	L	VL	L	VH
	$f_1 \sim a_2$	L	VL	0,00	0,05	1,00	VL	L	M	H	L
	$f_1 \sim a_3$	VH	VH	0,00	1,00	1,00	M	M	M	H	L
	$f_2 \sim a_1$	M	M	0,00	10,00	10,00	H	L	L	M	H
e_2	$f_2 \sim a_4$	L	L	0,10	1,00	2,00	VL	VL	L	M	M
	$f_3 \sim a_1$	H	L	0,10	0,20	10,00	M	M	VH	L	H
	$f_3 \sim a_4$	VH	VH	0,00	10,00	10,00	M	M	VH	H	VH
	$f_4 \sim a_1$	VL	L	1,00	10,00	10,00	L	VL	L	L	VH
	$f_1 \sim a_2$	M	L	0,00	0,00	1,00	VL	L	H	VH	VL
	$f_1 \sim a_3$	M	L	0,00	0,50	0,50	M	M	M	VH	VL
	$f_2 \sim a_1$	M	VL	0,00	5,00	5,00	M	M	H	M	H
e_3	$f_2 \sim a_4$	M	L	1,00	3,00	3,00	VL	L	L	M	M
	$f_3 \sim a_1$	H	L	1,00	0,20	5,00	M	M	H	M	M
	$f_3 \sim a_4$	VH	L	0,00	10,00	10,00	H	H	VH	M	M
	$f_4 \sim a_1$	L	L	2,00	8,00	5,00	L	VL	L	M	H

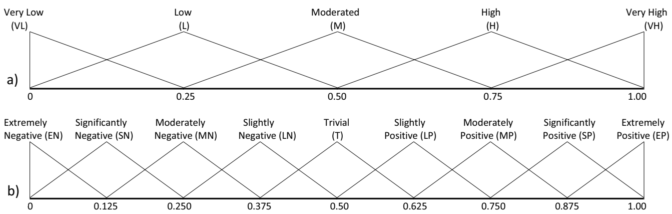

Figure 4. Linguistic Term Sets

4.2 Gathering heterogeneous preferences

The experts' gathered preferences are presented in Table 1.

4.3 Rating Phase

4.3.1 Managing heterogeneous preferences

First cost criteria c_3 and c_{10} are normalized, then all the heterogenous preferences are unified into 2-tuple into S^5.

4.3.2 Aggregating preferences

i) Computing collective criteria values

For computing collective criteria values of each impact we use equation (14).

ii) Computing impacts' significance

For computing significance for each impact we aggregate the collective criteria values through equation (15) obtaining the results on S^5 shown in Table 2, column "I_{ij} on BTLS S^5".

iii) Adjusting impacts' significance

From the BLTS S^5 at level 1 we generate the level 2 obtaining a LH whose term sets are:

BLTS: $l(1,5)$ $\{s_0^5, s_1^5, s_2^5, s_3^5, s_4^5\}$
ALTS: $l(2,9)$ $\{s_0^9, s_1^9, s_2^9, s_3^9, s_4^9, s_5^9, s_6^9, s_7^9, s_8^9\}$

The semantic of the ALTS S^9 is defined according to the significance scale in [10] as can be seen in Figure 4-b). To transform terms from S^5 to S^9 equation (17) is applied. Adjusted values are shown in Table 2, column "I'_{ij} on ATLS S^9".

iv) Computing final significance values

For computing the final significance values illustrated in Table 3, we use equations (18) to (21).

TABLE 2. IMPACTS' SIGNIFICANCE VALUES

Impact	I_{ij} on BTLS S^5	*Nature*	I'_{ij} on ATLS S^9
$f_1 \sim a_2$	(M,-0.45)	-1	(MN,0.45)
$f_1 \sim a_3$	(H,-0.49)	-1	(SN,0.49)
$f_2 \sim a_1$	(M,0.06)	-1	(MN,-0.06)
$f_2 \sim a_4$	(L,0.34)	-1	(LN,-0.34)
$f_3 \sim a_1$	(M,0.20)	-1	(MN,-0.20)
$f_3 \sim a_4$	(H,0.06)	-1	(SN,-0.06)
$f_4 \sim a_1$	(L,-0.13)	1	(LP,-0.13)

TABLE 3. FINAL SIGNIFICANCE VALUES

FI_i	f_1 (MN,-0.03)	f_2 (MN,0.30)	f_3 (SN,0.37)	f_4 (LP,-0.13)
AI_j	a_1 (LN,-0.13)	a_2 (MN,0.45)	a_3 (SN,0.49)	a_4 (MN,-0.20)
WI_j	a_1 (MN,-0.06)	a_2 (EN,0.49)	a_3 (EN,0.30)	a_4 (SN,0.13)
PI	(MN,0.31)			

4.3.3 Evaluating results

In this step, the computed significance values are ordered to output final rankings:

- Impacts' significance: $(f_4 \sim a_1) \succ (f_2 \sim a_4) \succ (f_1 \sim a_2) \succ (f_2 \sim a_1) \succ (f_3 \sim a_1) \succ (f_1 \sim a_3) \succ (f_3 \sim a_4)$.
- Factors' significance: $f_4 \succ f_2 \succ f_1 \succ f_3$.
- Actions' significance: $a_1 \succ a_2 \succ a_4 \succ a_3$.
- Weighted actions' significance: $a_1 \succ a_4 \succ a_2 \succ a_3$.

5 Conclusions

In this contribution we proposed a novel approach for EISA based on fuzzy linguistic models. It enables a flexible heterogeneous framework in which experts can provide their preferences using different domains. It also applies an accurate 2-tuple aggregation process that makes possible to obtain linguistic interpretable significance values. The functioning of the approach has been illustrated by solving an EISA problem.

Acknowledgements

This work is partially supported by the Research Project TIN-2012-31263 and ERDF.

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