ELIGERE: a Fuzzy AHP Distributed Software Platform for Group Decision Making in Engineering Design

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***Abstract*—This paper presents ELIGERE, a new open−source distributed software platform for group decision making in engineering design. It is based on the fuzzy analytical hierarchy process (fuzzy AHP), a multiple criteria decision making method used in group selection processes to rank a discrete set of alternatives with respect to some evaluation criteria. ELIGERE is built following the paradigm of distributed cyber−physical systems. It provides several features of interest in group decision making problems: a web−application where experts express their opinion on the alternatives using the natural language, a fuzzy AHP calculation module for transforming qualitative into quantitative data, a database for collecting both the experts' answers and the results of the calculations. The resulting software platform is: distributed, interactive, multi−platform, multi−language and open−source.**

ELIGERE is a flexible cyber−physical information system useful in various multiple criteria decision making problems: in this paper we highlight its key concepts and illustrate its potential through a case study, *i.e.*, the optimum selection of design alternatives in a robotic product design.

***Index Terms*—Multiple criteria decision making, fuzzy sets, fuzzy AHP, distributed information systems, product design, robotics.**

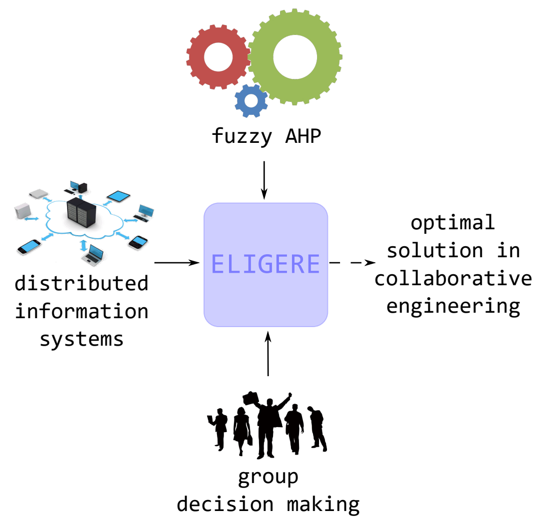

Fig. 1: The ELIGERE framework for group decision making in collaborative engineering.

I. Introduction

Group decision making (GDM) problems consist in finding the best alternative from a set of feasible alternatives $A = \{A_1, A_2, \ldots, A_m\}$ according to the preferences provided by a group of experts $E = \{E_1, E_2, \ldots, E_r\}$ [1]. In many cases, these problems are complicated by the presence of different evaluation criteria, which sometimes make the experts unable to assess accurately all the aspects of the candidate alternatives. In this case we refer to as multiple criteria decision making (MCDM) problems [2]. Many complex decision making situations arise from the life-cycle of every system, in particular in engineering design [3]. For instance, in product design and development [4], the most critical decision making step is represented by *concept selection* [5], in which many factors, of technical and economic nature, need to be taken into account for the selection of the optimum design solution. In [6] has been proven that 75% of the cost of a product is due to the design phase, and 80% of it to the conceptual design process, so erroneous design solutions need to be minimized. Hence, multiple criteria group decision making techniques might contribute to the development of a successful product [7]. Generally, the phase of concept selection requires a participative review session wherein experts from different backgrounds express their opinion (usually through a questionnaire) regarding the design alternatives, in agreement with a certain evaluation method. However, the setup of the session, the collection of the data from experts and their subsequent elaboration, can be very time consuming, slowing down the overall design process, thus increasing the *time−to−market* of new products' release.

This paper presents ELIGERE[1], a fuzzy AHP software platform for group decision making (Figure 1). ELIGERE allows: (i) showing the different alternatives via a web−application, so that people can participate to the decision session also remotely; (ii) data collection and storing of the results in a database; (iii) instant computation of the optimal solution.

[1]`https://github.com/eligere/`

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The resulting software platform is (i) *distributed*: its components are located on networked components which communicate and coordinate their actions by passing messages; (ii) *interactive*: it collects inputs from humans and elaborate them according to a MCDM method; (iii) *multi−platform*: it has been tested under Unix and Windows operating systems; (iv) *multi−language*: its core is written in C++, while its web−based infrastructure in PHP, HTML and SQL; (v) *open−source*: it is distributed under the GNU General Purpose Licence (GPL). The main motivation behind this work is to enhance, in terms of time and experts experience, the phase of decision making in any discrete selection process, responding actively to the trend of collaborative engineering.

The paper is organized as follows. In the remaining part of this section we provide the related works in MCDM methods in engineering design, focusing on fuzzy AHP. In Section II we present the theory behind the core of the software, whose architecture and implementation are explained in Section III. Section IV aims at testing and validating ELIGERE through an illustrative example, *i.e.*, the optimum selection of an ultrasonic sensors' frame for mobile robots. Comparisons with classical AHP method is presented. Section V concludes the paper and discusses future works.

A. Related works

MCDM methods help the decision making process in presence of multiple, usually conflicting criteria [8]. Among these methods, the Analytical Hierarchy Process (AHP) introduced by Saaty in [9] is an extremely elegant approach for addressing problems wherein the set of decision alternatives relies in a discrete space [10]. It decomposes a complex problem into a hierarchical structure of objectives, criteria, sub-criteria and alternatives. A scale of relative importance allow representing, in the form of a pairwise comparison, the expert verbal judgments, which are quantified using crisp numbers within the $1-9$ scale [11]. However, in some realistic situations, a crisp value might be unable to express the comparison judgment of the decision makers. To overcome this limitation, the fuzzy set theory [12] was introduced to enhance AHP, resulting in the formal methodology known as fuzzy AHP (FAHP). Fuzzy interfaces, which transform linguistic variables in fuzzy numbers, are used to avoid the uncertainty brought by numerical voting: FAHP improves the level of confidence of decision makers in giving interval judgments rather than fixed value judgments. The first study on FAHP was done by Van Laarhoven and Pedrycz in [13], where the authors used triangular fuzzy numbers to express each pairwise comparison judgment and a logarithmic least squares method to derive fuzzy weights and fuzzy performance scores. Boender *et al.* in [14] came up with weights which are optimal with respect to the considered logarithmic regression function. Chang introduced the extent analysis method in the context of triangular fuzzy numbers [15]. Several works make use of FAHP in different scenarios: economics [16], finance [17], logistic and management science [18], engineering design [7].

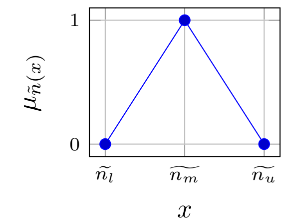


Fig. 2: Membership function of a triangular fuzzy number.

ELIGERE uses FAHP as group decision method for collaborative design. With respect to the *state−of−the−art*, the FAHP procedure implemented in ELIGERE uses a different fuzzy conversion scale and exploits a computationally efficient algorithm to compute the comparison matrix (see Section II). From the distributed point of view, ELIGERE has been built according to MVC architecture [19]. Following the open−source paradigm in software development, it implements an Apache HTTP Server [20] and a MySQL relational database [21]. The strength of these choices is evident in the resulting simplicity of the distributed system, as well as in its modularity and reliability. To the best of our knowledge, it is the first software available for group decision making with the above described features.

II. Fuzzy AHP

In this section we describe the FAHP procedure implemented in ELIGERE. Triangular fuzzy numbers evaluate the preferences of the decision makers regarding one criterion or alternative over another (*fuzzification*). The preferences of all decision makers are collected in a fuzzy comparison matrix. In order to obtain a crisp priority vector from a triangular fuzzy comparison matrix (*defuzzification*) we use the extent analysis method proposed by Chang in [15].

Before explaining the procedure, we provide some definitions and nomenclature.

Definition 1: $\tilde{n} \in F(\mathbb{R})$ is a fuzzy number with membership function $\mu_{\tilde{n}}(x) : \mathbb{R} \to [0, 1]$ if:

1) $\exists\, x_0 \in \mathbb{R}$ s.t. $\mu_{\tilde{n}}(x_0) = 1$
2) $\forall\, \alpha \in [0, 1]$,
   $A_\alpha = [x, \mu_{A_\alpha}(x) \geq \alpha]$ is a closed interval

where $F(\mathbb{R})$ represents all fuzzy sets, and $\mathbb{R}$ is the set of real numbers.

Definition 2: $\tilde{n} \in F(\mathbb{R})$ is a triangular fuzzy number (TFN) if its membership function $\mu_{\tilde{n}}(x) : \mathbb{R} \to [0, 1]$ is equal to:

$$\mu_{\tilde{n}}(x) = \begin{cases} \frac{x}{\tilde{n}_m - \tilde{n}_l} - \frac{\tilde{n}_l}{\tilde{n}_m - \tilde{n}_l} & x \in [\tilde{n}_l, \tilde{n}_m], \\ \frac{x}{\tilde{n}_m - \tilde{n}_u} - \frac{\tilde{n}_u}{\tilde{n}_m - \tilde{n}_u} & x \in [\tilde{n}_m, \tilde{n}_u], \\ 0 & \text{otherwise.} \end{cases} \tag{1}$$

The general triangular fuzzy number $\tilde{n}$ is denoted by $(\tilde{n}_l, \tilde{n}_m, \tilde{n}_u)$, where $\tilde{n}_l \leq \tilde{n}_m \leq \tilde{n}_u$ are respectively the lower, the medium and the upper value (see Fig. 2). In the following we indicate a fuzzy number without the $\widetilde{(\cdot)}$.

The FAHP assessment procedure is reported as follows.

TABLE I: Proposed triangular fuzzy conversion scale.

Symbol	Fuzzy scale	Fuzzy reciprocal scale
=	$(\frac{2}{3}, 1, \frac{3}{2})$	$(\frac{2}{3}, 1, \frac{3}{2})$
+	$(1, \frac{3}{2}, 2)$	$(\frac{1}{2}, \frac{2}{3}, 1)$
++	$(\frac{3}{2}, 2, \frac{5}{2})$	$(\frac{2}{5}, \frac{1}{2}, \frac{2}{3})$
+++	$(2, \frac{5}{2}, 3)$	$(\frac{1}{3}, \frac{2}{5}, \frac{1}{2})$

A. *Hierarchical structure of the problem*

The general problem is decomposed into the following hierarchical structure (Fig. 3):

- Goal to be obtained
- Quantitative and qualitative criteria
- Alternatives

The goal is generally the choice of the optimal solution. The optimal solution is selected among a finite number of alternatives, with respect to a finite number of evaluation criteria.

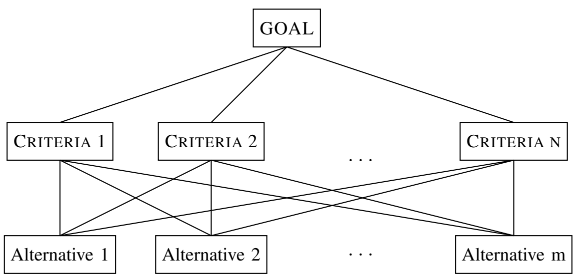


Fig. 3: Simplified hierarchical structure of FAHP

B. *Fuzzy conversion scale*

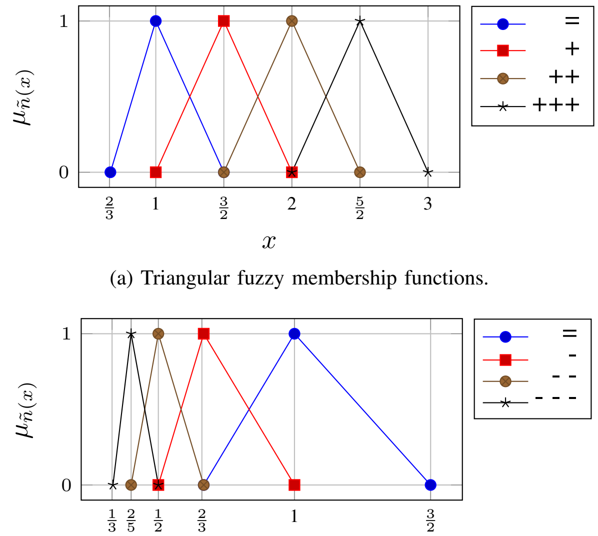
The translation of verbal judgment into triangular fuzzy numbers is provided by an appropriate fuzzy conversion scale. Starting from the scale reported in Chang's work [15], we propose to use the scale reported in TABLE I, which uses four levels instead of five and replaces the verbal judgments with more readable symbols. The corresponding membership functions are shown in Fig. 4.

C. *Comparison matrix*

Let us consider r decision makers and n criteria to be evaluated. To make a pairwise comparison about criteria, $n\,(n-1)\,/2$ questions are submitted to experts. Let us indicate with f_{ij} the TFN associated with the $i-th$ answer of the $j-th$ interviewed ($i = 1, ..., n\,(n-1)\,/2$; $j = 1, ..., r$). In order to collect all the answers and build the pairwise comparison matrix, let us fill two fuzzy vectors $\boldsymbol{p}$ and $\boldsymbol{q}$, whose generic fuzzy elements p_i and q_i are given by

$$p_i = \frac{\sum_{j=1}^{r} f_{ij}}{r} \tag{2}$$

$$q_i = (p_i)^{-1}. \tag{3}$$



(a) Triangular fuzzy membership functions.

(b) Triangular fuzzy reciprocal membership functions.

Fig. 4: Fuzzy set scale

The sum between fuzzy numbers is obtained by adding the respective components. The three components of q_i are $(1/p_{iu}, 1/p_{im}, 1/p_{il})$, being (p_{il}, p_{im}, p_{iu}) the components of p_i. Using $\boldsymbol{p}$ and $\boldsymbol{q}$ we fill the pairwise comparison matrix $\boldsymbol{C}$ according to the following proposed general algorithm

$$c_{i,j} = \begin{cases} p_{i,j-1+i\cdot\frac{i-1}{2}+i\cdot(n-i-1)} & \text{if } j < i \\ (1,1,1) & \text{if } j = i \\ q_{i,i-1+j\cdot\frac{j-1}{2}+j\cdot(n-j-1)} & \text{if } j > i \end{cases} \tag{4}$$

Note that each element $c_{i,j}$ of the $n \times n$ fuzzy matrix $\boldsymbol{C}$ is still a triangular fuzzy number, even if generally not symmetric. To be lighter on symbolism, the lower, the medium and the upper part of $c_{i,j}$ will be indicated in the following as (l_{ij}, m_{ij}, u_{ij}).

D. *Extent analysis*

The defuzzification process consists of the following four steps.

a) Fuzzy synthetic extent value: the fuzzy synthetic extent value s_i associated with the $i-$th object (in this case, the $i-$th criterion) is calculated as

$$s_i = \sum_{j=1}^{n} c_{i,j} \odot \left[\sum_{i=1}^{n} \sum_{j=1}^{n} c_{i,j} \right]^{-1} \tag{5}$$

where the first sum refers to the fuzzy sum of the $c_{i,j}$ elements of the $i-th$ row of $\boldsymbol{C}$ (see Eq. 6 and 7), while the second double sum is calculated according to (8) and (9). The product between fuzzy numbers, indicated with $\odot$, is obtained by multiplying the respective components.

$$\sum_{j=1}^{n} c_{i,j} = \left(\sum_{j=1}^{n} l_{ij}, \sum_{j=1}^{n} m_{ij}, \sum_{j=1}^{n} u_{ij} \right) \tag{6}$$

$$\begin{cases}\sum_{j=1}^{n} l_{ij} = l_i \\ \sum_{j=1}^{n} m_{ij} = m_i \\ \sum_{j=1}^{n} u_{ij} = u_i\end{cases} \tag{7}$$

$$\sum_{i=1}^{n}\sum_{j=1}^{n} c_{i,j} = \left(\sum_{i=1}^{n}\sum_{j=1}^{n} l_{ij}, \sum_{i=1}^{n}\sum_{j=1}^{n} m_{ij}, \sum_{i=1}^{n}\sum_{j=1}^{n} u_{ij}\right) \tag{8}$$

$$\begin{cases}\sum_{i=1}^{n}\sum_{j=1}^{n} l_{ij} = l \\ \sum_{i=1}^{n}\sum_{j=1}^{n} m_{ij} = m \\ \sum_{i=1}^{n}\sum_{j=1}^{n} u_{ij} = u\end{cases} \tag{9}$$

Through simple passages, (5) turns into

$$s_i = (l_i, m_i, u_i) \odot (l, m, u)^{-1} = \left(\frac{l_i}{u}, \frac{m_i}{m}, \frac{u_i}{l}\right) \tag{10}$$

b) Comparison between two fuzzy numbers: to compare two fuzzy numbers s_1 and s_2 we need to calculate the degree of possibility V of a fuzzy number to be greater than the other, and vice versa, as follows

$$\begin{cases} V(s_1 \geq s_2) = 1 & \text{if } s_{1m} \geq s_{2m} \\ V(s_2 \geq s_1) = \dfrac{s_{1l} - s_{2u}}{(s_{2m} - s_{2u}) - (s_{1m} - s_{1l})} & \text{otherwise} \end{cases} \tag{11}$$

The pairwise comparison of n fuzzy synthetic extent values leads to $2n$ crisp values $V(s_i \geq s_j)$.

c) Comparison between one fuzzy number and a set of fuzzy numbers: the comparison between each fuzzy number s_i and all the others s_k, with $k = 1, ..., n$ and $k \neq i$, is achieved using Eq. 12, which allows obtaining n values of comparison.

$$\begin{aligned} &V(s_i \geq s_1, s_2, \ldots, s_n) = \\ &= V[(s_i \geq s_1) \cdot (s_i \geq s_2) \cdot \ldots \cdot (s_i \geq s_n)] = \\ &= \min V(s_i \geq s_1, s_2, \ldots, s_n) \end{aligned} \tag{12}$$

d) Weighted vector: Let us indicate each previous comparison value with $d'(a_i)$ as

$$d'(a_i) = \min V(s_i \geq s_k), \;\; i = 1, ..., n, \;\; k = 1, ..., n, \;\; k \neq i \tag{13}$$

We collect all the $d'(a_i)$ values in a weighted vector as

$$\boldsymbol{W}' = [d'(a_1), d'(a_2), ..., d'(a_n)]^T \tag{14}$$

Normalizing (14) we obtain

$$\boldsymbol{W} = [d(a_1), d(a_2), ..., d(a_n)]^T \tag{15}$$

which represents the normalized weighted vector for the criteria. The same procedure is replicated for the alternatives.

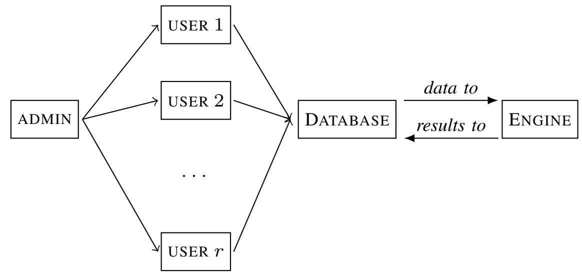


Fig. 5: ELIGERE conceptual workflow

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III. ELIGERE Architecture and Implementation

In this section we describe the architecture and the main components of ELIGERE.

ELIGERE is based on the analytical assessment of questionnaires submitted via a web−interface to a panel of experts. The fuzzy set theory allows the translation of their linguistic judgments in quantitative data processed by a proper algorithm to rank first the criteria (preference section) and after the alternatives (suitability section). ELIGERE conceptual workflow is depicted in Fig. 5 and briefly explained in the following.

1 The *admin* generates the questionnaire using an automatic form which allows uploading the criteria and the alternatives as well as images, videos or 3D files as support.
2 The *users* fill the questionnaire on their own browser observing the link, the name and password provided by the admin. When her/he submits the questionnaire, the answers are uploaded on the database.
3 The computational module queries the database and when the data are available, they are processed according to the implemented FAHP. After the calculations, the final results (the weight of the criteria, the weight of the alternatives with respect to each criterion, the final best alternative) are uploaded on the database.

The conceptual workflow was translated into the architecture depicted in Fig. 6. Since the architecture was developed using MVC pattern, ELIGERE articulates in presentation, business and data access layer. The framework is a modular collection of a series of components which exchange messages on the network using the TCP/IP and HTTP protocols. In the following we describe its main components: the *FAHP engine*, the *dynamic web application* and the *relational database*.

A. FAHP engine

ELIGERE engine contains the main logic of the software, the FAHP procedure described in Sect. II. Developed in C++ programming language, it provides the data processing based on the expert judgments. The connection between the engine and the SQL server database is made possible through a MySQL function. Once that connection is established, FAHP engine and database exchange informations through TCP/IP protocol. FAHP engine and GUI (Graphical User Interface) engine are built respectively upon Eigen and Q_t libraries.

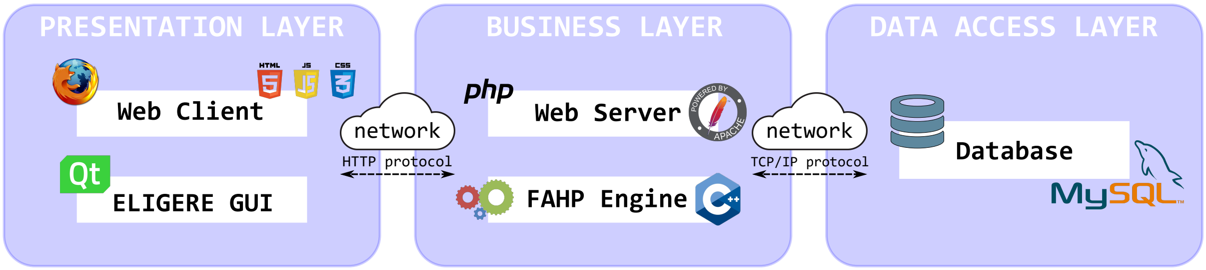

Fig. 6: ELIGERE MVC pattern architecture.

B. Dynamic web−application

ELIGERE dynamic web application allows: (1) the admin to generate and administrate the survey to users; (2) the users to fill the survey. Based on the client−server architecture, the web application articulates in web server and web clients.

Web clients: they request and visualize the web−pages of ELIGERE using classical web browser applications. Web clients exchange informations with the web server node via HTTP protocol. The communication is started by a client program which communicates with a server program for: (1) retrieving a specific survey; (2) creating a new survey if the user is an admin.

Web server: it is represented by an Apache HTTP Server. Thanks to the web Server node, ELIGERE is able to: (1) process HTTP requests from the users; (2) dynamically generate the surveys using the PHP interpreter; (3) retrieve data from database; (4) save data on database.

C. Relational Database

ELIGERE database uses MySQL server for its simplicity, security and interoperability. As every database system, it collects, stores and make available data. ELIGERE relational database (1) provides an history of past surveys; (2) collects data from the r questionnaires (one for each expert) related to the same survey; (3) provides the input data to the FAHP engine; (4) stores the output data from FAHP engine.

IV. Case Study

We validate the proposed framework in the concept selection of an ultrasonic sensors' frame for mobile robots. The considered product gives the robot the functionality of collision avoidance and environment awareness. Besides its main functionality which has to be absolutely guaranteed, some other criteria can be considered into the design process: these give, to some extent, some degrees of freedom to the designer. In this context, ELIGERE was tested with an heterogeneous team composed by seven experts in a concept selection review session where six design alternatives A_j, $j = 1, \dots, 6$ were ranked with respect to three evaluation criteria: C_1, simplicity; C_2, aesthetic design; C_3, integrability with mobile robotic platform. Results show that A_1 has been considered the optimal design solution. Fig. 7 shows the output data from ELIGERE, *i.e.* the ranking of alternatives with respect to each criterion, the ranking of criteria and the ranking of alternatives. We perform a comparison of the results with respect to the classical AHP, using the crisp scale obtained from TABLE I using only the medium values of the fuzzy numbers. The same verbal judgments quantified using crisp or fuzzy numbers leads to different results: FAHP claims A_1 to be the optimal solution, while AHP gives the same aggregate score to A_1 and A_2. Let us consider separately the sets of data, namely the sets of criteria and alternatives scores in both cases AHP and FAHP. The use of TFN results in increasing the variance defined by $\sigma^2 = \frac{1}{h-1}\sum_{k=1}^{h}(x_k - \bar{x})^2$, where h is the number of data in the set, x_k each data value, $\bar{x}$ the average value of the set. This means that, when using fuzzy values, even if the average value is the same, the differences among scores in the set of data are more evident. Moreover, as we can see in Fig. 8, this difference, interpreted here with a normalized variance, increases as the number of elements in the set increases, going from the set of criteria to the set of alternatives. Thus, we expect more differences in the results between FAHP and AHP as the number of elements in the sets increase, while an approaching of FAHP to AHP as the number of elements decrease. This encourages to use FAHP in more complex problems, with high number of criteria and alternatives.
ELIGERE has been tested on a standard machine with Intel® Core™ i7 CPU 2.67 GHz and 8 Gb RAM, running Windows 7 and Ubuntu 14, 64 bits. Once that data are available on the database, the computation of the optimal solution requires less than 1s. The other phases are operator−dipendent, and ELIGERE acts as software tool for the *admin* in setting up, managing and saving the interactive design session.

V. Conclusions

A distributed, cyber−physical framework is presented for group decision making in engineering design. It is based on the FAHP, a method for decision making in presence of multiple criteria. An illustrative example, *i.e.*, the concept selection in product design for robotics applications has been presented. A comparison with respect to classical AHP shows how the influence of uncertainty in the verbal judgments might lead to different optimal solutions. The developed framework, ELIGERE, aims at helping design teams in any selection process. It allows instant computation of the optimal solution, as well as an interactive experience for users. In the next future, we plan to integrate virtual reality capabilities in ELIGERE.

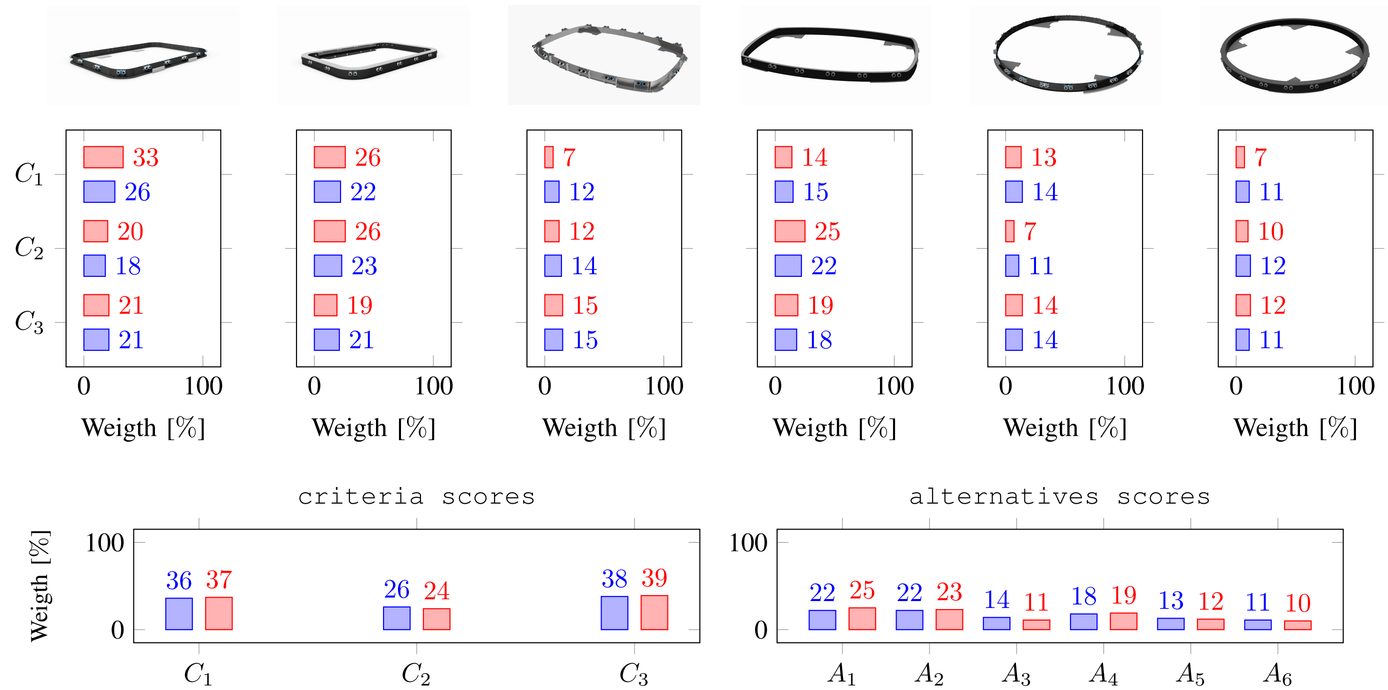

Fig. 7: ELIGERE's output. Ranking of: alternatives w.r.t. each criterion, criteria, alternatives. FAHP (red); AHP (blue).

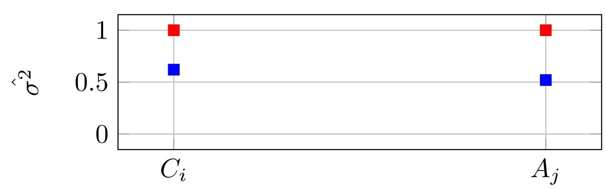

Fig. 8: Normalized variance for criteria and alternatives scores. FAHP (red); AHP (blue). Variance is normalized w.r.t. FAHP values.

The authors release ELIGERE under GNU GPL licence, as they strongly believe in the importance of open−source towards the sharing of informations in the research community.

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