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A state-of-the-art survey & testbed of fuzzy AHP (FAHP) applications

Sylvain Kubler[a,*], Jérémy Robert[a], William Derigent[b,c], Alexandre Voisin[b,c], Yves Le Traon[a]

[a] University of Luxembourg, Interdisciplinary Centre for Security, Reliability & Trust, 4 rue Alphonse Weicker L-2721 Luxembourg, Europe
[b] Université de Lorraine, CRAN, UMR 7039, 2 Avenue de la forêt de Haye, Vandoeuvre-lès-Nancy Cedex, 54516, France
[c] CNRS, CRAN, UMR 7039, France

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ABSTRACT

As a practical popular methodology for dealing with fuzziness and uncertainty in Multiple Criteria Decision-Making (MCDM), Fuzzy AHP (FAHP) has been applied to a wide range of applications. As of the time of writing there is no state of the art survey of FAHP, we carry out a literature review of 190 application papers (i.e., applied research papers), published between 2004 and 2016, by classifying them on the basis of the area of application, the identified theme, the year of publication, and so forth. The identified themes and application areas have been chosen based upon the latest state-of-the-art survey of AHP conducted by [Vaidya, O., & Kumar, S. (2006). Analytic hierarchy process: An overview of applications. European Journal of operational research, 169(1), 1–29.]. To help readers extract quick and meaningful information, the reviewed papers are summarized in various tabular formats and charts. Unlike previous literature surveys, results and findings are made available through an online (and free) testbed, which can serve as a ready reference for those who wish to apply, modify or extend FAHP in various applications areas. This online testbed makes also available one or more fuzzy pairwise comparison matrices (FPCMs) from all the reviewed papers (255 matrices in total).

In terms of results and findings, this survey shows that: (i) FAHP is used primarily in the Manufacturing, Industry and Government sectors; (ii) Asia is the torchbearer in this field, where FAHP is mostly applied in the theme areas of Selection and Evaluation; (iii) a significant amount of research papers (43% of the reviewed literature) combine FAHP with other tools, particularly with TOPSIS, QFD and ANP (AHP's variant); (iv) Chang's extent analysis method, which is used for FPCMs' weight derivation in FAHP, is still the most popular method in spite of a number of criticisms in recent years (considered in 57% of the reviewed literature).

1. Introduction

Multiple criteria decision-making (MCDM) methods are frequently used to solve real world problems with multiple, conflicting, and incommensurate criteria and/or objectives. Hwang and Yoon (1981) have classified the MCDM methods into two categories: multi-attribute decision-making (MADM) and multi-objective decision-making (MODM). MADM techniques, unlike MODM, heavily involves human participation and judgments. Research on human judgments and decision making shows that the human brain is able to consider only a limited amount of information at any one time (Simpson, 1996), which makes it unreliable to take decisions when facing complex problems. Analytic Hierarchy Process (AHP), initially introduced by Saaty (1980), is by now one of the most widely applied MADM techniques, whose main strength lies in its impartial and logical grading system (reducing personal biases and allowing for comparing dissimilar alternatives), but also in its flexibility to be integrated with various techniques like Linear Programming, Quality Function Deployment, Fuzzy Logic, *etc.* (Saaty & Vargas, 2001; Vaidya & Kumar, 2006). This enables users to extract benefits from all the combined methods and achieve the desired goal in a better way.

As a practical popular methodology for dealing with fuzziness and uncertainty, the Fuzzy Logic combined with AHP, more commonly known as Fuzzy AHP or FAHP (van Laarhoven & Pedrycz, 1983), has found huge applications in recent years. According to a recent survey on Fuzzy MCDM techniques (Mardani, Jusoh, & Zavadskas, 2015), FAHP is the second most widely used technique in a stand-alone mode (just after AHP). Since, as of this writing, no state-of-the-art survey of FAHP has been issued – *the latest survey being dedicated to AHP and dating back to 2006* (Vaidya & Kumar, 2006) – this article looks into the research papers with a view to understand the spread of FAHP in different fields. Based

* Corresponding author.
E-mail addresses: sylvain.kubler@uni.lu (S. Kubler), jeremy.robert@uni.lu (J. Robert), william.derigent@univ-lorraine.fr (W. Derigent), alexandre.voisin@univ-lorraine.fr (A. Voisin), yves.letraon@uni.lu (Y. Le Traon).

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on a classification scheme, a reference repository has been established, including around 200 international journal papers (starting from 2004). Papers have been classified based on various dimension s, including the year of publication, application area, identified theme, authors' nationality, *etc.* This survey goes along with an online and free testbed[1] that makes the results and findings of this study available, as well as one or more fuzzy pairwise comparison matrices (FPCMs) from all reviewed papers. For the anecdote, the genesis of this state-of-the-art survey started from a personal motivation around the study and development of new consistency indexes for FPCMs' weight derivation, which is still a sensitive issue in the FAHP literature. In this context, we started the collection of FPCMs from scientific articles, which has led to the achievement of this survey. We believe that this online testbed will serve as a ready reference for those who wish to apply, modify or extend FAHP in various application domains, including scientists (e.g., for benchmarking purposes), reviewers and journal editors (e.g., to evaluate the relevance of future research papers), and other categories of practitioners.

The proposed state-of the-art survey is structured as follows: Section 2 discusses to what extent MADM techniques are important to overcome complex real-life problems involving different categories of stakeholders, in various sectors. Section 2 also discusses in greater detail how FAHP stands with regard to existing MCDM techniques, and what are the basic principles underlying (F)AHP. Section 3 details the research methodology considered to collect, classify and analyze the journal papers. Section 4 provides the breakdown of the literature review. Section 5 offers a comprehensive summary of the survey outcomes, graphical representations, and concluding remarks. Section 6 presents the online FAHP/FPCMs testbed; conclusion and research directions follow.

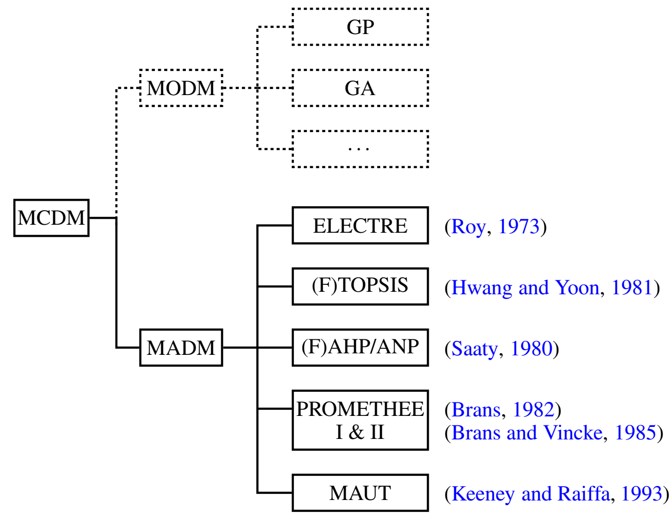
2. Background

Section 2.1 discusses why MADM techniques are widely applied to various sectors today, along with a general overview of how FAHP stands with regard to existing MCDM techniques. Following this introduction, the theories/principles underlying AHP and FAHP are respectively presented in Sections 2.2 and 2.3.

2.1. MCDM landscape

As previously stated, MCDM techniques can be classified into two categories: MODM and MADM, as illustrated in Fig. 1's taxonomy. Although this paper focuses on MADM, and particularly FAHP, it should be noted that MODM has been widely studied by means of mathematical programming methods with well-formulated theoretical frameworks, using techniques such as GA (Genetic Algorithms), GP (Goal Programming), and so on (Insua & French, 1991; Marler & Arora, 2004). MODM methods have decision variable values that are determined in a continuous or integer domain with either an infinitive or a large number of alternative choices, the best of which should satisfy the decision-maker constraints and preference priorities. MADM methods, on the other hand, have been used to solve problems with discrete decision spaces and a predetermined or a limited number of alternative choices. The MADM solution process requires inter and intra-attribute comparisons and involves human participation (expert knowledge, judgments...).

The most well known and applied MADM techniques are listed in the MCDM taxonomy, including (F)AHP/ANP, TOPSIS, ELECTRE, MAUT, and PROMETHEE I & II (papers referenced in Fig. 1 refers



MAUT – *Multi-Attribute Utility Theory*
ELECTRE, TOPSIS, PROMETHEE – *see Table 1*

Fig. 1. The MCDM classification used in this study.

the founder of the corresponding technique. All these techniques have the common objective to help decision-makers to deal with complex – *evaluation, selection, prioritisation...* – problems by imposing a disciplined methodology. Any of these techniques follows the following steps:

1. *Identifying objectives:* good decisions need clear objectives, which should be (to the extent possible) specific, measurable, agreed and realistic;
2. *Identifying options for achieving the objectives:* once the objectives are defined, the next stage is to identify options that may contribute to the achievement of these objectives;
3. *Identifying the criteria to be used to compare the options:* the next stage is to decide on how to compare different options' contribution to meeting the objectives. This requires the selection of criteria to reflect performance in meeting the objectives, meaning that it must be possible to assess (at least in a qualitative manner) how well a particular option is expected to perform in relation to each criterion;
4. *Analysis of the options:* the next stage in the process is analysis, which requires mechanisms to properly aggregate the different performance scores resulting from step 3, and rank the options accordingly (i.e., in terms of relevance with regard to the main objectives);
5. *Making choices:* The final stage of the decision making process is the actual choice of option(s). This can be seen as a separate stage because none of the available techniques can incorporate, into the formal analysis, every judgment. At this stage it may be decided that a further option should be considered and the analysis revisited;
6. *Feedback:* Good decision making requires a continuous reassessment of choices made in the past. Strategies for learning from potential mistakes in a more formal and systematic way should be implemented for enhanced future decision-making.

In the following two sections, we present in greater detail how these different steps are fulfilled using AHP and FAHP respectively. It should also be noted that, even if a distinction between MCDM and MADM can be made, the rest of this article uses both terms interchangeably.

[1] http://fahptestbed.sntiotlab.lu/

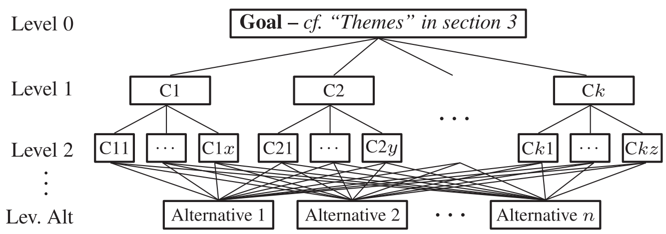


Fig. 2. Generic AHP hierarchy structure.

2.2. AHP principles

The widespread recognition and use of AHP in the literature is mainly due to its simplicity, whether regarding the definition of the MCDM problem or the different calculation stages imposed by the technique. AHP can be declined in seven stages (Vaidya & Kumar, 2006), which cover steps 1 to 5 of the generic sequence described in the previous section:

1. State the problem;
2. Broaden the objectives of the problem or consider all actors, objectives and its outcome;
3. Identify the criteria that influence the behavior;
4. Structure the problem in a hierarchy of different levels (similar to the one given in Fig. 2), including the Goal, Criteria, potential Sub-criteria and Alternatives;
5. Compare each element in the corresponding level and calibrate them on the numerical scale. This requires $\frac{n(n-1)}{2}$ pairwise comparisons, where $\mathcal{N} = [1, .., n]$ is the set of elements with the considerations that diagonal elements are equal to 1 and the other elements are the reciprocals of the earlier comparisons;
6. Perform calculations to find the maximum eigen value, consistency index (CI), consistency ratio (CR), and normalized values for each item;
7. If the maximum eigen value, CI, and CR are satisfactory, then decision is taken based on the normalized values; else the procedure is repeated till these values lies in a desired range.

Let A be a pairwise comparison matrix as formalized in Eq. 1, where a_{ij} $(i, j \in \mathcal{N})$ is supposed to reflect how many more times item/criterion i is preferred to item/criterion j.

$$A_{n\times n} = (a_{ij})_{n\times n} = \begin{array}{c} \\ 1 \\ 2 \\ \vdots \\ n \end{array} \begin{array}{c} \begin{array}{cccc} 1 & 2 & \dots & n \end{array} \\ \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} \end{array} \tag{1}$$

Pairwise comparison matrices require to satisfy the following rules:

- *homogeneity*: the pairwise comparison A is meaningful only if the elements are comparable. Constructing a hierarchy of objectives helps to arrange elements in clusters and to compare like with like;
- *reciprocal*:

$$a_{ij} = a_{ji}^{-1}; \quad \forall i, j \in \mathcal{N} \tag{2}$$

- *transitivity*:

$$\underset{\forall i,k\in\mathcal{N}|i\neq k;\, j\in\mathcal{N}-\{i,k\}}{a_{ik} = a_{ij} \times a_{jk}} \tag{3}$$

The satisfaction of the last two rules plays a significant role in AHP to guarantee the relevance/consistency of the expert judgment. To this end, Saaty introduced the consistency index (CI) so as to be able to measure to what extent a pairwise comparison matrix fulfills these two rules.

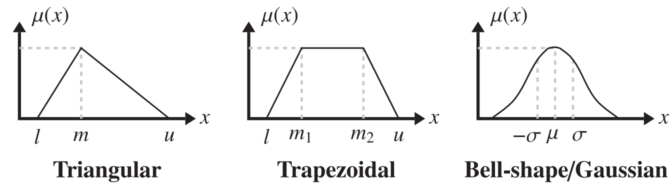


Fig. 3. Traditional membership functions used in FAHP.

2.3. FAHP principles

Different from classical set theory, fuzzy set theory permits the gradual assessment of the membership of elements in relation to a set (described using a membership function). Fuzzy sets have found their theoretical origins and applications in electrical engineering. Zadeh (1965) is the father of the fuzzy set theory, having done most of the mathematical groundwork to formalize and handle more efficiently the imprecision of human reasoning. This was in 1971 when he published his article, "Quantitative fuzzy semantics" Zadeh (1971).

van Laarhoven and Pedrycz (1983) propose, in 1983, the first FAHP method by using triangular fuzzy numbers (*cf.* Fig. 3) in the pairwise comparison matrix. In later years, many other methods were proposed, using various types of fuzzy numbers such as the Trapezoidal membership function (Buckley, 1985; Chen & Chen, 2007; Onar, Büyüközkan, Öztayşi, & Kahraman, 2016; Pan, 2008; Zheng, Zhu, Tian, Chen, & Sun, 2012) or the Bell-shape/Gaussian membership function (see Fig. 3) that is less commonly used (Büyüközkan & Feyzioğlu, 2004; Paul, 2015; Yuen, 2012). A FPCM can be expressed as in Eq. (4), where $\tilde{a}_{ij}$ $(i, j \in \mathcal{N})$ is supposed to reflect how many more times criterion i is preferred to criterion j with a certain level of uncertainty and/or vagueness. While in a classical set a_{ij}, an element belongs entirely or not to a_{ij}, in a fuzzy set $\tilde{a}_{ij}$, an element has a degree of membership that can be denoted by $\mu(x) \rightarrow [0, 1]$. The kernel of a fuzzy set $\tilde{a}_{ij}$ is defined as the set of elements whose membership degree is equal to 1 (see e.g. $x = m$ in the triangular fuzzy set example in Fig. 3), and the support of $\tilde{a}_{ij}$ is defined as the set of elements whose membership degree is different from 0 (i.e., $\forall x \in\ ]l, u[$ in the triangular and trapezoidal fuzzy set example).

$$\tilde{A}_{n\times n} = (\tilde{a}_{ij})_{n\times n} = \begin{array}{c} \\ 1 \\ 2 \\ \vdots \\ n \end{array} \begin{array}{c} \begin{array}{cccc} 1 & 2 & \dots & n \end{array} \\ \begin{bmatrix} \tilde{a}_{11} & \tilde{a}_{12} & \dots & \tilde{a}_{1n} \\ \tilde{a}_{21} & \tilde{a}_{22} & \dots & \tilde{a}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \dots & \tilde{a}_{nn} \end{bmatrix} \end{array} \tag{4}$$

A number of methods have been developed to handle FPCMs' weight derivation. van Laarhoven and Pedrycz (1983) suggested a fuzzy logarithmic least squares method to obtain triangular fuzzy weights from a FPCM. Buckley (1985) utilized the geometric mean method to calculate fuzzy weights. Chang (1996) proposed the extent analysis method, which derives crisp weights from a FPCM. Csutora and Buckley (2001) came up with a Lambda-Max method, which is the direct fuzzification of the λ_{max} method, while Mikhailov (2003) rather developed a FPP method. Among these approaches, the Chang's extent analysis method is perhaps the most popular one, the main reason lying behind the simplicity of implementation, although a significant number of research papers have demonstrated that it suffers from theoretical pitfalls (Wang & Elhag, 2006; Wang, Luo, & Hua, 2008; Zhü, 2014). Criticisms point out the fact that the weights determined by the analysis method

Table 1
Acronyms used in the article.

(AN)FIS	(Adaptive Neuro)-Fuzzy Inference System
ANP	Analytic Network Process
BSC	Balanced ScoreCard
COPRAS	Complex Proportional Assessment
DEA	Data Envelopment Analysis
Delphi	Data Envelopment Analysis
DEMATEL	Decision-making trial & evaluation laboratory
ELECTRE	ELimination et Choix
FA/FR	Fuzzy Arithmetic/Replicated
FMEA	Failure mode and effects analysis
GA	Genetic Algorithm
GRA	Grey Relation Analysis
(L)FPP	(Logarithmic) Fuzzy Preference Programming
LP	Linear Programming
Max-Min	Max-Min approach
MRA	Multiple Regression Analysis
(MS)GP	(Multi-Segment) Goal Programming
NN	Neural Networks
PROMETHEE	Preference Ranking Organisation Method for Enrichment Evaluations
QFD	Quality Function Deployment
RS-FAHP	Regime Switching FAHP
SWOT	Strengths, Weaknesses, Opportunities, Threats
(F)TOPSIS	(Fuzzy) Technique for Order of Preference by Similarity to Ideal Solution
TRIZ	Theory of Inventive Problem Solving
VIKOR	VlseKriterijumska Optimizacija | Kompromisno Resenje

do not represent the relative importance of decision criteria or alternatives at all, which may lead to problems such as poor robustness, unreasonable priorities and information loss. As of the time of writing there is no study that provides quantifiable information about the proportion of papers that made use (and still make use) of this analysis method when applying FAHP, we carry out (in Section 5) such an analysis based on the corpus of reviewed papers.

3. Research methodology

In our study, we collected articles that have been published in popular scientific journals and provided the most important information to practitioners and researchers who investigate FAHP-related issues. To this end, an extensive search was carried out to find FAHP[2] in titles, abstracts, keywords, and research methodologies of the papers. Our study attempts to document the high interest in FAHP, and provides a state-of-the-art review of the literature on the basis of various classification dimensions. In an effort to align our results to those reported in previous state-of the-art surveys of (F)AHP, we chose the dimensions defined in (Vaidya & Kumar, 2006), namely:

- **Year:** year of publication;
- **Application area:** chosen areas are *a.* Personal, *b.* Social, *c.* Manufacturing *d.* Political, *e.* Engineering, *f.* Education, *g.* Industry, *h.* Government, and *i.* Others (e.g., sports, farming...);
- **Theme:** chosen themes are *a.* Selection, *b.* Evaluation, *c.* Benefit-Cost analysis, *d.* Resource allocations, *e.* Priority, and *f.* Decision-making;
- **Other tools used:** list of tools – *as listed in Table 1* – combined with FAHP (if any);
- **Journal:** name of the scientific journal in which the paper was published;
- **Country:** country where the study was being conducted. If not mentioned, country of the first author is considered.

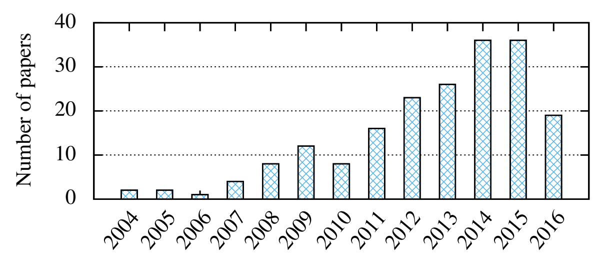


Fig. 4. Number of papers reviewed (in this survey) per year.

For this review, an article is taken into consideration if it discusses thoroughly the application and development of FAHP[3]. Furthermore, in an effort to design an heterogeneous testbed, i.e. integrating a rich set of FPCMs (i.e., sizes varying from $\tilde{A}_{2\times2}$ to $\tilde{A}_{20\times20}$), some extra papers were also selected for review. Along the same line, our review focused only on papers that make use of triangular fuzzy sets in FPCMs, which is the most commonly used membership form in the FAHP literature.

During the review process, we targeted six main library databases that cover most of the FAHP applications, namely: ScienceDirect (64% of the 190 reviewed papers), Springer (14%), Taylor & Francis (10%), Emerald (3%), IEEE (2%) and Hindawi Publishing Corporation (2%). Items such as doctoral dissertations, master's theses, textbooks, conference proceeding papers, and unpublished papers were ignored. Some of the journals cited in this review are: *Expert Systems with Applications, European Journal of Operational Research, The International Journal of Advanced Manufacturing Technology, Applied soft computing, Computers & Industrial Engineering, Journal of Intelligent Manufacturing, International Journal of Production Research, Safety Science, etc.*, but a more detailed analysis is presented later on. We focused on papers published over the last decade (starting from 2004). Due to the high number of papers published every year, we applied the following rule: *"the more recent the year, the higher the number of paper reviewed"*, so as to guarantee relevant and up-to-date findings/remarks about the FAHP usage. Fig. 4 gives valuable information regarding the num-

[2] Terms used for the search: "Fuzzy Analytic Hierarchy Process", "Fuzzy AHP", "FAHP"

[3] In other words, this survey is primarily focusing on applied research papers rather than on "theoretical" papers.

ber of papers, over the years, that are reviewed and discussed in this study[4].

4. Survey results

The structure of this section is built based on the chosen "Themes", i.e. all reviewed papers that make use of FAHP for Selection purposes are presented in Section 4.1, for Evaluation purposes in Section 4.2, and so on. In each of these sections, papers are summarized in tabular formats considering the following dimensions: *Application area, Other tool(s) used, Year* and *Specific objective* (specific to the problem addressed in each paper). A unique identifier is also attributed to each paper in the these tables (column named "N°"), which will be used in the Section 5 (entitled "Observations and concluding remarks") for summary and graphical representation purposes.

4.1. Selection

All reviewed papers falling within the scope of "Selection" are listed in Table 2. In the following, in order to discuss each paper's content, we tried to the extent possible to discuss groups of papers addressing a same or similar objective, e.g. the next paragraph presents papers that make use of FAHP for ERP (Enterprise Resource Planning) system selection, one of the subsequent paragraphs rather discusses papers dealing with Shipping management problems, and so on. Overall, seven groups/paragraphs compose this section, respectively focusing on: (i) ERP system selection; (ii) Supplier selection; (iii) Robot/Machine selection; (iv) Maintenance management; (v) Location selection; (vi) Shipping & Port facility management; (vii) Other applications.

ERP system selection: An ERP system is a package of business software that combines a number of modular software implementations to meet all the requirements of a firm (Yusuf, Gunasekaran, & Abthorpe, 2004). Generally speaking, it is the knowledge framework of a firm that automates and combines whole business tasks like purchase, sales, inventory control, human resource, production planning and finance. As explained in (Efe, 2016), any ERP software in market cannot fully meet the needs and expectations of companies, because every company runs its business with different strategies and goals. Thus, to increase the chance of success, management must choose an appropriate software that most closely suits its requirements. To help experts in this selection process, Cebeci (2009); Efe (2016); Kilic, Zaim, and Delen (2014) designed and proposed different FAHP-based models, which all have common and separate (or specific) criteria. Common criteria among the three models are e.g. User friendliness, Compatibility, Cost, Reputation, while separate criteria are e.g. Licensing in (Kilic et al., 2014), R&D capabilities in (Cebeci, 2009) and Supporting data files in (Efe, 2016). Given the fact that each ERP system implementation is specific to the business sector, customisation may be required to achieve the right fit of the ERP system to the organization's needs. In this respect, Sarfaraz, Jenab, and D'Souza (2012) have applied FAHP to a framework that helps managers to understand and select the best customisation options among multiple alternatives. Durán (2011) develops a framework for the selection of a Computerized Maintenance Management System (CMMS) that has a smaller scope than ERP systems, as it essentially focuses on maintenance activities rather than on all business tasks.

Supplier selection: As evidenced in Table 2, FAHP has been most commonly used for supply chain management and outsourcing applications. Supplier selection decisions are thorny by the fact that huge number of criteria should be taken into account, which often goes along with imprecise and/or uncertain information, either from the elicitation process of expert judgments or from the measurement process of system parameters. In (Kilincci & Onal, 2011), FAHP is applied for supplier selection in a washing machine factory that supplies a huge number of raw materials. By combining attributes both determined by experts and used in the literature, three family of attributes were identified: supplier, product performance, and service performance criteria. Although the proposed model is applied to the washing machine factory, the set of criteria are generic enough for being applied to many other application areas. Other studies rather define criteria that are very specific to a domain, for example Mohammady and Amid (2011) who focus on supplier selection in virtual enterprises, therefore paying much attention to agility, interoperability and modularity concepts/criteria; Önüt, Kara, and Işik (2009); Uygun, Kaçamak, and Kahraman (2015); Yu, Kuo, and Dat (2014) who integrate telecommunication and networking-related criteria; or still Chen and Hung (2010) who integrate pharmaceutical-related criteria to support manufacturers in R&D outsourcing activities. Zeydan, Çolpan, and Çobanoğlu (2011) develop a methodology that enables OEM (Original Equipment Manufacturing) to evaluate – *e.g. on a yearly basis* – the performance of suppliers and to decide whether they should be selected/re-engaged in new projects. Considering that the most important evaluation item for the OEM is Quality Management System Audit, the methodology essentially focuses on quality-related criteria. Kubat and Yuce (2012) proposes a slightly different framework that combines FAHP with GA in order to determine the best set of suppliers for each part of the order. Other studies (Shaw, Shankar, Yadav, & S., 2012; Wang Chen, Chou, Luu, & Yu, 2016) report and claim that the organizations are today ready to cease business with suppliers who would fail in managing environmental impacts (e.g., capacity of the supplier to use recycled/nontoxic materials, green packaging and technologies…) and, as a result, present FAHP models that turn such environmental impacts into hierarchical criteria structures. In (Lima Junior, Osiro, & Carpinetti, 2014), the goal is not to develop a supplier selection model as such, but rather to carry out a comparative study between FAHP and FTOPSIS. Results show that both methods are performant to supporting group decision-making, even though FTOPSIS seems more reliable in regard to changes of alternatives and criteria. Given the large number of papers that focus on supplier selection models (14 papers in total in Table 2), we analyzed them so as to identify the most commonly used criteria among these papers; results are the following:

1. *Quality (considered in 92% of the 14 papers):* product performance, quality assurance and control procedures, quality improvement, *etc.*;
2. *Innovativeness (85%):* capacity to launch new products and technologies;
3. *Flexibility/Technical Ability (78%):* product volume changes and time/cost required to add new products to the existing production;
4. *Lead & Delivery time (78%):* between placement of an order and delivery of the product;
5. *Financial status (78%):* economical stability;
6. *Cost (71%):* product price, logistics cost, *etc.*;
7. *Reputation/Relationship (71%):* communication openness, customer satisfaction, *etc.*;
8. followed by ($<$ 40%) *Managerial, Geographical location, Follow-up* and *Environmental* criteria.

Robot/Machine selection: The recent advancement in automation field has lead to increased usage of machine tools, robots, and other smart technologies. Within this context, company's competitiveness in terms of the productivity of its facilities, and

[4] Less papers are reviewed in 2016 compared with the previous years due to submission date of this paper (submitted in June 2016).

Table 2
References on the topic of 'Selection'.

N°	Authors	Application Areas	Specific Objective	Other tool(s) used
S1	RazaviToosi and Samani (2016)	Government	Water management strategies	TOPSIS, Max-Min
S2	Wang Chen et al. (2016)	Manufacturing	Green Supplier Selection	TOPSIS
S3	Efe (2016)	Industry	ERP system selection	TOPSIS
S4	Lee and Chou (2016)	Industry	Sustainable development	TOPSIS, Delphi
S5	Leong, Raymond, Kathleen, and Chew (2016)	Industry	Industrial plants	-
S6	Prakash and Barua (2016)	Manufacturing	Reverse logistic partner	TOPSIS
S7	Azadeh and Zadeh (2016)	Manufacturing	Maintenance policy selection	FTOPSIS
S8	Shafiee (2015)	Social	Risks in offshore wind farms	ANP
S8	Budak and Ustundag (2015)	Social	Real-time location systems	-
S10	Uğurlu (2015)	Others	Oceangoing watchkeeping officers	-
S11	Kumar, Shankar, and Debnath (2015)	Industry	Telecom sector	DEA
S12	Uygun et al. (2015)	Industry	Outsourcing provider selection	ANP, DEMATEL
S13	Beskese et al. (2015)	Government	Landfill site selection	TOPSIS
S14	Parameshwaran et al. (2015b)	Industry	Robot selection	Delphi, VIKOR
S15	Nguyen et al. (2014)	Manufacturing	Machine tools	ANP, GRA
S16	Satir (2014)	Social	Ballast water treatment	-
S17	Yu et al. (2014)	Industry	Vendor/Supplier selection model	-
S18	Bilişik et al. (2014)	Government	Garage locations	-
S19	Demirtaş et al. (2014)	Engineering	Technology selection	ANP
S20	Kahraman et al. (2014)	Political	Health research investment	-
S21	Kumru and Humru (2014)	Manufacturing	3D machine selection	ANP
S22	Ghoseiri and Lessan (2014)	Social	Waste disposal site selection	ELECTRE
S23	Lima Junior et al. (2014)	Manufacturing	Supplier selection	TOPSIS
S24	Kabir and Sumi (2014)	Social	Power substation locations	PROMETHEE
S25	Kilic et al. (2014)	Industry	ERP systems	TOPSIS
S26	Ballı and Korukoğlu (2014)	Others	Basketball candidates	TOPSIS
S27	Pang and Bai (2013)	Manufacturing	Supplier selection	ANP
S28	Mirhedayatian et al. (2013)	Engineering	Tunnel ventilation system	DEA
S29	Kengpol et al. (2013)	Government	Power plant locations	TOPSIS
S30	Isalou et al. (2013)	Government	Landfill site selection	ANP
S31	Alcan, Balin, and Başlıgil (2013)	Social	Energy management systems	TOPSIS
S32	Roshandel, Miri-Nargesi, and Hatami-Shirkouhi (2013)	Manufacturing	Supplier selection in detergent industry	FTOPSIS
S33	Ishizaka and Nguyen (2013)	Others	Bank account selection	-
S34	Demirel et al. (2012)	Political	Agricultural strategies	ANP
S35	Taha and Rostam (2012)	Manufacturing	Machine tool selection	PROMETHEE
S36	Nazari et al. (2012)	Social	Landfill sites	-
S37	Nguyen and Gordon-Brown (2012)	Education	Constrained analysis	FA/FR
S38	Kubat and Yuce (2012)	Industry	Supplier selection model	GA
S39	Mentes and Helvacioglu (2012)	Others	Mooring systems	TOPSIS
S40	Shaw et al. (2012)	Manufacturing	Low carbon suppliers	LP
S41	Fouladgar et al. (2012)	Manufacturing	Maintenance management	COPRAS
S42	Choudhary and Shankar (2012)	Government	Power plant locations	TOPSIS
S43	Yazdani-Chamzini and Yakhchali (2012)	Engineering	Machine selection	TOPSIS
S44	Sarfaraz et al. (2012)	Industry	ERP implementation	-
S45	Yücenur, Vayvay, and Demirel (2011)	Industry	Supplier selection model	ANP
S46	Liao (2011)	Industry	Market strategy selection	MSGP
S47	Mohammady and Amid (2011)	Manufacturing	Modular virtual enterprise	VIKOR
S48	Taha and Rostam (2011)	Manufacturing	Machine tool selection	NN
S49	Zeydan et al. (2011)	Manufacturing	Supplier selection	TOPSIS, DEA
S50	Durán (2011)	Manufacturing	CMMS management	-
S51	Kilincci and Onal (2011)	Manufacturing	Supplier selection	-
S52	Golestanifar et al. (2011)	Engineering	Tunnel excavation method	TOPSIS
S53	Önüt et al. (2010)	Engineering	Shopping center sites	TOPSIS
S54	Chen and Hung (2010)	Personal	Outsourcing manufacturing partners	TOPSIS
S55	Celik et al. (2009)	Personal	Shipping registry alternatives	-
S56	Cebeci (2009)	Industry	ERP systems	BSC, SWOT
S57	Vahidnia et al. (2009)	Social	Hospital sites	-
S58	Önüt et al. (2009)	Manufacturing	Telecommunication suppliers	ANP, TOPSIS
S59	Önüt, Kara, and Efendigil (2008)	Manufacturing	Machine tool selection	TOPSIS
S60	Durán and Aguilo (2008)	Manufacturing	Machine tools	-
S61	Chan, Kumar, Tiwari, Lau, and Choy (2008)	Industry	Global supplier selection -	
S62	Wang et al. (2007)	Manufacturing	Maintenance management strategies	-
S63	Tolga, Demircan, and Kahraman (2005)	Others	Operating system selection	-
S64	Enea and Piazza (2004)	Others	Project selection	-

quality of its products, is adversely affected by improper selection of equipment. Several studies applied FAHP to support decision makers in selecting the most appropriate technologies considering multiple conflicting qualitative and quantitative criteria. Nguyen, Dawal, Nukman, and Aoyama (2014) built a fuzzy MCDM model for machine tool selection by combining FANP to handle imprecise/uncertain information from expert judgments, with GRA (Grey Relation Analysis) to calculate the weighted priorities of the machine alternatives. Demirtaş, Özgürler, Özgürler, and Güneri (2014); Kumru and Humru (2014) also develop a FANP-based selection model, respectively for 3D coordinate-measuring machine (3D CMM) selection and *e*-purse smart card technology selection. Parameshwaran, Kumar, and Saravanakumar (2015b) propose a four-step approach respectively using (i) the Fuzzy Delphi method for identifying critical factors, (ii) FAHP for calculating the criteria weights, (iii) FTOPSIS and Fuzzy VIKOR for evaluating alternatives with respect to criteria, and (iv) the Brown and Gibson Model for obtaining the aggregated robot selection index. Lee and Chou (2016) follow a similar approach (except the fourth step) to help assessing and selecting relevant emerging 3D integrated circuit technologies. As part of a decision support system for machine tool selection in a flexible manufacturing cell, Taha and Rostam (2011); 2012) propose two distinct frameworks, combining FAHP with NN in the first framework and FAHP with PROMETHEE in the second one, although both frameworks consider the same set of criteria. FAHP is also applied to the tunnelling sector, for example by Golestanifar, Goshtasbi, Jafarian, and Adnani (2011); Yazdani-Chamzini and Yakhchali (2012) for boring and excavation machine selection, and by Mirhedayatian, Jelodar, Adnani, Akbarnejad, and Saen (2013) for ventilation system selection.

Maintenance management: Equipment maintenance cost is one of the main expenditure items for earthmoving operations that can reach up to 60% of operational costs Fouladgar, Yazdani-Chamzini, Lashgari, Zavadskas, and Turskis (2012). Although intensive research has been carried out on maintenance strategy selection, there is still a need to adapt the approach to the machine type, environment, maintenance strategies, and so on. To this end, (Fouladgar et al., 2012) combine FAHP and COPRAS for selecting the optimal maintenance strategy, whose evaluation considers cost, accessibility, risk and added value criteria. Azadeh and Zadeh (2016) take into account 15 criteria from the literature, some being crisp values obtained from simulation, some expressed in linguistic terms (in the form of triangular fuzzy numbers) based on experts' opinions. Wang, Chu, and Wu (2007) focus on the selection of maintenance strategies in a power plant, where the predictive maintenance strategy alternative appears to be the most suitable for boilers.

Location selection: In some application sectors, the choice of the location for deploying a system may impact on the system performance and environment. For example, in the energy sector, the location of the power plant affects the amount of generated energy, power plant's productivity, cost of power generation and transmission, economical development and environment. In this particular context, several research works have proposed FAHP-based location selection frameworks for thermal power plants (Choudhary & Shankar, 2012), solar power plants (Kengpol, Rontlaong, & Tuominen, 2013), and high voltage lines (Kabir & Sumi, 2014). Another highly sensitive sector, from both a social and governmental policy perspective, is the management of landfill sites. Several studies have been looking at FAHP for solving this MCDM problem such as (Beskese, Demir, Ozcan, & Okten, 2015; Ghoseiri & Lessan, 2014; Isalou, Zamani, Shahmoradi, & Alizadeh, 2013; Nazari, Salarirad, & Bazzazi, 2012), in which a wide range of factors have been considered such as social, geological, economic, technical, but also political and government positions. Speaking of government, Bilişik, Demirtaş, Tuzkaya, and Baraçlı (2014); Önüt, Efendigil, and Soner Kara (2010) apply FAHP to help the Turkish (Istanbul) government to choose the best location, respectively for a public bus garage and shopping center. Vahidnia, Alesheikh, and Alimohammadi (2009) apply FAHP for selecting the optimum site for hospital construction in Tehran's city, while Budak and Ustundag (2015) apply it for selecting the best real-time location system – *considering UHF RFID, Active RFID and Infrared technologies as alternatives* – for a hospital in order to efficiently track assets, people and workflows.

Shipping & Port facility management: FAHP has been applied to the shipping and port facility management sectors, too. For example, Uğurlu (2015) proposes a framework that enables oceangoing watchkeeping officers to choose the best ship depending on their contract, working condition, and ship & company-related criteria. Mentes and Helvacioglu (2012) are dealing with mooring systems, which are associated with high level uncertainties and risks during tanker loading and unloading operations (companies spending a lot of money and time to repair or rebuild the facilities). The goal of their study is to propose an effective decision-making tool at the initial design stage of the spread mooring system. In (Satir, 2014), the goal is to deal with ballast water systems that are part of ships for improving propulsion and stability (instead of rocks), but which unfortunately and inevitably leads to the introduction of nonnative organisms into the port of discharge. To reduce this risk, the authors investigate and develop a FAHP-based approach to select the best ballast water treatment system. Celik, Deha, and Ozok (2009) develop a framework for selecting a suitable shipping registry alternative for the existing fleet or new building ships, which is one of the most critical process for ship management companies in terms of administrative and operational considerations.

Other applications: Table 2 report other papers that make use of FAHP for selection purposes in other application areas, e.g. for health research investment (Kahraman, Süder, & Kaya, 2014), agricultural and offshore wind farm strategy selection (Demirel, Yčenur, Demirel, & Muşdal, 2012; Shafiee, 2015), basketball candidate selection (Ballı & Korukoğlu, 2014) or still bank account selection purposes (Ishizaka & Nguyen, 2013).

4.2. Evaluation

Based on the reviewed papers reported in Table 3, eight groups of papers (paragraphs) compose this section, respectively focusing on: (i) Education; (ii) Environment & Sustainability; (iii) Healthcare; (iv) Banking; (v) Project management; (vi) Shipping; (vii) Government prospection; and (viii) Other applications.

Education: The quality of education is always considered as an important factor in the development of any nation, that must commit to continuous quality improvement to benefit students. Some socio-economic studies propose to use FAHP in order to evaluate the teaching education system and its institutions, such as in (Das, Sarkar, & Ray, 2012; 2015) where FAHP is used (in conjunction with COPRAS) to measure the performance of Indian technical institutions. The authors argue that COPRAS has several advantages over other MCDM methods, mentioning its simplicity, high possibility of graphical interpretation, better computational time performance, *etc.* Some research works address the problem of teaching quality evaluation by introducing performance indexes, e.g. Chen, Hsieh, and Do (2015) propose to employ FAHP combined with group-decision making mechanisms to derive a teaching performance index system, while Lin (2010) develop a FAHP-based evaluation model to mesure the quality of course websites. From another perspective, a teaching institution should take care of the future of students. Having this in mind, Akkaya, Turanoğlu, and Öztaş (2015) use FAHP to evaluate the best industrial sectors that should be recommended to students.

Environment & Sustainability: Papers have been classified in two sub-groups: (a) Evaluation for green industry and (b) Evaluation of sustainability. Group (a) refers to companies that take place in the green market and seek profits. As a result, papers falling in this category propose models reducing risks and uncertainty in this emerging market; Mangla, Kumar, and Barua (2015) propose a flexible decision modeling capable of evaluating the risks in the green supply chain. At a more concrete level, the authors use FAHP to determine the priority of the identified risks and IRP (Interpretive Ranking Process) to test the ranking resulting from FAHP. Lee, Mogi, Kim, and Gim (2008b) develop a FAHP model dedicated to the hydrogen technology. Papers of Group (b) propose tools to evaluate the sustainability of products, processes, or even companies as a whole (i.e., considering the global product lifecycle, including manufacturing, distribution, usage and recycling processes). In (Sabaghi, Mascle, Baptiste, & Rostamzadeh, 2016), a sustainability index is determined thanks to a hierarchical structure based on three major criteria: environmental, economic and social

Table 3
References on the topic of 'Evaluation'.

N°	Authors	Application areas	Specific objective	Other tool(s) used
E1	Sabaghi et al. (2016)	Industry	Sustainable development	-
E2	Meiboudi et al. (2016)	Social	Green schools	-
E3	Zare et al. (2016)	Industry	Industrial waste management	GP
E4	Chang et al. (2016)	Government	Safety and health management	VIKOR, ANP
E5	Chen et al. (2015)	Education	Teaching performance	-
E6	Singh et al. (2015)	Manufacturing	Sustainability evaluation of SMEs	-
E7	Wang et al. (2015)	Others	Ship maneuverability	ANP
E8	Das, Sarkar, and Ray (2015)	Education	Technical education system evaluation	-
E9	Lupo (2015)	Social	International airport quality	ELECTRE
E10	Wang (2015b)	Manufacturing	Green operations initiatives	Delphi, TOPSIS
E11	Pak et al. (2015)	Engineering	Port safety evaluation	-
E12	Akkaya et al. (2015)	Education	Industrial sector prospection	-
E13	Kececi et al. (2015)	Engineering	Ship officer performance	-
E14	Chang et al. (2015)	Others	*e*-book business model	VIKOR, TOPSIS, GRA
E15	Mangla et al. (2015)	Manufacturing	Risks in green supply chain	-
E16	Yeap et al. (2014)	Personal	Web technology	-
E17	Mandic et al. (2014)	Government	Serbian banks	TOPSIS
E18	Jothimani et al. (2014)	Manufacturing	Supply chain performance	TOPSIS
E19	Kabak et al. (2014)	Social	Building energy performance	ANP
E20	Rostamzadeh et al. (2014)	Government	Entrepreneurial activity	VIKOR, TOPSIS
E21	Routroy and Pradhan (2013)	Manufacturing	Success supplier development factors	-
E22	Chan et al. (2013)	Engineering	Green product designs	-
E23	Cho and Lee (2013)	Industry	Commercialization	-
E24	Aghdaie, Zolfani, and Zavadskas (2013)	Industry	Market segments	COPRAS
E25	Lupo (2013)	Education	Education quality measurement	-
E26	Ertay, Kahraman, and Kaya (2013)	Government	Renewable energy evaluation	-
E27	Moalagh and Ravasan (2013)	Manufacturing	ERP post-implementation success	ANP
E28	Rezaei et al. (2013)	Industry	Entrepreneurship orientation	FPP
E29	Cho et al. (2012)	Industry	Supply chain performance	-
E30	Zolfani et al. (2012)	Government	ICT centers	TOPSIS, GRA
E31	Ip et al. (2012)	Personal	Hotel websites	-
E32	Chou, Sun, and Yen (2012)	Industry	Human resource evaluation	DEMATEL
E33	Büyüközkan and Çifçi (2012)	Industry	Healthcare performance	FTOPSIS
E34	Das et al. (2012)	Political	Performance of technical institutions	COPRAS
E35	Ju et al. (2012)	Social	Emergency management	-
E36	Isaai et al. (2011)	Social	Train scheduling	-
E37	Büyüközkan et al. (2011)	Social	Healthcare quality	-
E38	Lin (2010)	Education	Website quality	-
E39	Yüksel and Dağdeviren (2010)	Manufacturing	Balanced Scorecard	ANP
E40	Tseng et al. (2009)	Manufacturing	Wire board manufacturers	-
E41	Ertuğrul and Karakaşoğlu (2009)	Government	Cement firms	TOPSIS
E42	Seçme et al. (2009)	Government	Turkish banking sector	TOPSIS
E43	Gumus (2009)	Waste transportation firms	TOPSIS	
E44	Lee et al. (2008b)	Political	Hydrogen technology competitiveness	-
E45	Jaganathan et al. (2007)	Manufacturing	New technologies	-

sustainability. Chan, Wang, White, and Yip (2013) define a methodology to select the best green product design, where it is argued that FAHP can remedy the disadvantages of actual tools performing LCA (Life Cycle Assessment), which are often time-consuming. Sustainability evaluation can also be applied for industrial waste management purposes. A poor control of this management can deeply affect human health and/or environment, which is why some studies try to properly evaluate hazardous waste transportation firms (Gumus, 2009; Zare, Nouri, Abdoli, Atabi, & Alavi, 2016). Wang (2015b) tackles the problem of green initiatives performance measurement and build a decision support tool to help industrial practitioners to evaluate various green operations initiatives. The mathematical modeling of the proposed approach combine three techniques: Fuzzy Delphi (used for the criteria identification), FAHP (for criteria weight calculation) and TOPSIS (for the alternative green initiative evaluation). Finally, sustainability evaluation can also be used to guide the company strategic decisions related to gaz emissions and energy management. In order to evaluate the effectiveness of a manufacturing SME's sustainability policy, Singh, Olugu, Musa, and Mahat (2015) propose a FAHP-based evaluation method to compute a global sustainability score (aggregating financial and non-financial indicators). In the domain of printed wire board, Tseng, Lin, and Chiu (2009) investigate criteria and attributes that determine a successful adoption and implementation of a cleaner production, whose results show that a good adoption and implementation of a cleaner production is highly correlated to a good management leadership with an adapted strategic plan. It is worth noting that industries are not the only one s concerned by sustainability, green school initiatives are also undertaken as in (Meiboudi, Lahijanian, Shobeiri, Jozi, & Azizinezhad, 2016) where FAHP is applied to evaluate school's sustainability practices.

Healthcare: FAHP evaluation is also applied to the service sector, especially for healthcare, where managers need to demonstrate how efficient and customer-focused their services are. Büyüközkan, Çifçi, and Güleryüz (2011) develop an evaluation framework to find out the best healthcare service quality performance among various hospital alternatives, with respect to tangible criteria such as the level of facilities/equipment, hospital appearance, hygiene, responsiveness, reliability, assurance, empathy and professionalism. The findings of this study show that empathy and professionalism are the two most important dimensions. The same authors extended their methodology in a later study Büyüközkan and Çifçi (2012) – *dedicated to the electronic service quality of hospital websites* – by adding a sensitivity analysis step. Indeed, because the priorities are highly dependent on subjective judgments of the decision makers, the stability of the final ranking under small variations of the principal weights should be checked out. Emergency situations are frequent in hospitals and must be properly tackled. In this respect, Ju, Wang, and Liu (2012) propose a FAHP-based evaluation index system of the emergency response capability, using 2-tuple linguistic variables that significantly simplify the decision makers' understanding of the computed scores. The two previous studies point out that the hospital service quality highly depends on the motivation and skills of the assigned human resources. In the same vein, Chang, Lin, and Wu (2016) carried out a study on 334 781 job openings that required certificates for occupational safety and health management, therefore proposing a tool to evaluate the certificate market. This tool combines FANP to obtained the causalities among the main criteria and calculate the relative weights, and VIKOR to rank the alternatives and select the best certificates. The results help to better understand the current state of the certificate market, and suggest a ranking between certificates that could be useful for teaching institutions or hiring managers.

Banking: There is an increasing need for measuring performance in the financial service sector, especially when it comes to banking activities. Evaluation is still of essential importance to creditors, investors and other interested parties. To this end, Seçme, Bayrakdaroğlu, and Kahraman (2009) propose a model that facilitates such an assessment, whose case study focuses on Turkish banks. Mandic, Delibasic, Knezevic, and Benkovic (2014) develops an analogous process considering Serbian banks. Although similarities can be observed in both hierarchical structures, the number of levels is different and specific domain-related criteria are introduced; Mandic et al. (2014) focusing more on financial parameters (equity, portfolio, cash...), and Seçme et al. (2009) on non-financial parameters (service delivery or productivity).

Shipping: There are many factors affecting navigational safety in ports, including weather, channel characteristics and vessel types. Pak, Yeo, Oh, and Yang (2015) have identified and selected several port safety factors from the literature, which have been turned into a FAHP structure in order to evaluate and rank the safety levels (from a captain's perspective) of five ports in Korea. In (Kececi, Bayraktar, & Arslan, 2015), the main objective is to evaluate the crew's performance, and particularly ship officers. It can be noted that 60% of the criteria (21 out of 34) are generic enough to be applied to other sectors (e.g., motivation, decisiveness, leadership...), while the remaining criteria are very specific to the shipping sector (e.g., adaptation on sealife, adaptation to International safety management codes...). In (Wang, Liu, & Cai, 2015), a novel rating-based FANP model is proposed to evaluate the ship maneuverability and the improvement of the American Bureau of Shipping (ABS) maneuverability standards.

Government prospection: For governmental investment guidance, it is important to measure the degree in which a firm is entrepreneurial. Rezaei, Ortt, and Scholten (2013) describe an approach to measure such an entrepreneurship orientation considering three key dimensions: innovativeness, risk-taking and proactiveness. The results show that the 'proactiveness' is the most important dimension in the entrepreneurship orientation-construct, followed by 'innovativeness' and risk-taking. Rostamzadeh, Ismail, and Bodaghi Khajeh Noubar (2014) propose a similar entrepreneurship measurement model by adding two new dimensions: (i) competitiveness - aggressiveness, and (ii) autonomy. The proposed model is applied to rank 30 SEMs in Malaysia, where the government has created an enormous amount of funding towards the promotion of entrepreneurship. Turkey's cement industry is one of the largest in the world and, similarly, it is an important issue for investors, creditors and governments to evaluate the performance of cement firms. To this end, Ertuğrul and Karakaşoğlu (2009) develop an appropriate evaluation model based on financial tables. Zolfani, Sedaghat, and Zavadskas (2012) report the findings of a governmental project that consisted to equip, between 2005 and 2010, more than 10 000 villages in Iran with rural information and communicative technology offices (Rural Telecenters). FAHP was applied to evaluate and compare the achievements (if any) of these offices in terms of virtual government services, social and cultural services.

Supply Chain management: A supply chain is a network of facilities and distribution options that performs the functions of procurement of materials, transformation of these materials into intermediate and finished products, and the distribution of these finished products to customers. To optimize their benefits, manufacturing organisations often make complex supply chain decisions, e.g. regarding the choice of development strategies (Routroy & Pradhan, 2013; Yüksel & Dağdeviren, 2010) or the acquisition of new manufacturing technologies (Jaganathan, Erinjeri, & Ker, 2007). Yüksel and Dağdeviren (2010) use a FANP technique to implement the Balanced Scorecard (BSC) model, which helps to determine business performance considering both the financial and non-financial indicators. Because manufacturing companies move towards downsizing and outsourcing, they depend more on the suppliers to deliver quality product/service on time. When a supplier capability is not up to the company's expectation, this one can decide to improve the supplier capability and create a win-win environment (commonly referred to as "supplier development"). Within this context, Routroy and Pradhan (2013) propose a FAHP-based approach to identify and evaluate the critical success factors responsible for supplier development in a manufacturing supply chain environment. The authors identify 13 factors, where the most critical ones – *considering a specific use case* – appear to be the "long term strategic goal" and "proximity to manufacturing base". Jaganathan et al. (2007) design a group decision support system to evaluate new manufacturing technologies based on FAHP. The conclusion of this paper is twofold: (i) this article advocates the use of a necessary contradictory test to check the fuzzy user preferences; (ii) based on the case study's findings, FPP seems to be preferred to LP to solve multi-level muti-person FAHP problems. Cho, Lee, Ahn, and Hwang (2012) carried out an extensive study on the performance metrics that are proposed for the service supply chain performance evaluation, each metric referring to a specific level of the CIM pyramid (i.e., at the strategic, tactical or operational levels). The authors define a hierarchical structure with the different metrics as leaves and apply FAHP to obtain the metric weights. The case study considers a hotel's supply chain, whose results show that the customer service is the area impacting the most on the supply chain performance. Jothimani, Sarmah, and Gunasekaran (2014) address the problem of supply chain performance measurement for third party logistics (3PL), which is growing around the world as shippers are more and more outsourcing logistical activities. Moalagh and Ravasan (2013) propose a FANP framework to perform a success assessment at the post-implementation stage of an ERP project for evaluating how much the system has succeeded in achieving its predetermined objectives.

Table 3 report s other papers that make use of FAHP for evaluation purposes in other application areas, e.g. for intelligent timetable evaluation (Isaai, Kanani, Tootoonchi, & Afzali, 2011), airport service quality assessment (Lupo, 2015), website quality and *e*-book business model evaluation (Chang, Tsai, & Chang, 2015; Ip, Law, & Lee, 2012; Yeap, Ignatius, & Ramayah, 2014), and for building energy performance assessment (Kabak, Köse, Kırılmaz, & Burmaoğlu, 2014).

4.3. Decision-making

Based on the reviewed papers reported in Table 4, six groups of papers (paragraphs) compose this section, respectively focusing on: (i) Production & Company performance; (ii) Risk management; (iii) Environment & Sustainability; and (iv) Other applications.

Table 4
References on the topic of 'Decision-making'.

N°	Authors	Application areas	Specific objective	Other tool(s) used
M1	Shaverdi et al. (2016)	Industry	Petrochemical company performance	TOPSIS
M2	Le et al. (2016)	Others	Load shedding in power systems	-
M3	Rodríguez et al. (2016)	Others	Risk in IT projects	FIS
M4	Wang et al. (2016)	Industry	Safety evaluation of coal mine	LFPP
M5	Andrić and Lu (2016)	Engineering	Risk assessment of bridges	-
M6	Yu et al. (2015)	Industry	Service Quality	ANP
M7	Mosadeghi, Warnken, Tomlinson, and Mirfenderesk (2015)	Political	Urban land-use planning	-
M8	Nezarat et al. (2015)	Engineering	Geological risks in tunneling	-
M9	Boutkhoum et al. (2015)	Industry	Green Logistics	-
M10	Yazdani-Chamzini (2014)	Industry	Equipment handling	FTOPSIS
M11	Najafi, Karimpour, and Ghaderi (2014)	Social	Mineral prospectivity mapping	-
M12	Kaya and Kahraman (2014)	Social	Smart building	TOPSIS
M13	Deng et al. (2014)	Government	Sustainable energy	-
M14	Chen et al. (2014b)	Government	Tourist activities	Delphi
M15	Mavi (2014)	Political	Entrepreneurial university	TOPSIS
M16	Radivojevic and Gajovic (2014)	Manufacturing	Risk modeling	-
M17	Carnero (2014)	Manufacturing	Maintenance management	-
M18	Taylan et al. (2014)	Industry	Risk assessment	TOPSIS
M19	Chou et al. (2013)	Industry	Bidding strategy	MRA
M20	Pooyandeh and Marceau (2013)	Social	Stakeholders' negotiation support	-
M21	Kahraman et al. (2013)	Government	Government investment policy	TOPSIS
M22	Ren et al. (2013)	Political	Biomass-based technology assessment	-
M23	Zou and Li (2010)	Engineering	Risk analysis	-
M24	Sun (2010)	Industry	Service quality	TOPSIS
M25	Chang, Wu, Lin, Chen, (2008))	Industry	Silicon wafer slicing quality	-

Production & Company performance: In an increasingly competitive marketplace, organizations have recognized benchmarking as being of strategic importance in the drive for better performance. To apply competitive and generic maintenance benchmarking in small and medium enterprises, Carnero (2014) develops and presents a two-step approach that combines FAHP (to assign weightings to the decision criteria) with Monte Carlo simulations (to obtain the utility in maintenance of each area of activity). This approach is applied to and validated for three distinct use cases, respectively in the context of a pharmaceutical company, a manufacturer of building materials, and a sports center. Shaverdi, Ramezani, Tahmasebi, and Rostamy (2016) propose a novel performance evaluation model that helps decision makers to measure the performance of petrochemical firms. According to the authors, the novelty of this approach lies in the fact that modern financial measures are taken into account in addition of traditional ones. Chang, Wu, Lin, Chen, (2008)) present a FAHP-based algorithm to determine manufacturing quality in silicon wafer that help decision-makers (e.g., engineers) to identify the worst performing machines in terms of precision. This helps them to rapidly adjust the manufacturing system to eliminate problematic phenomena, increase slicing quality as well as the process capability. Yu, Keng, and Chen (2015) present a framework for the measurement of service quality in the banking sector, whose prime objective is to help bank managers to improve one or more service areas. In practice, service areas are integrated to the framework through the criteria hierarchy where either FANP is applied (for dependent criteria) or FAHP (otherwise).

Risk management: Risk management is the process of identifying, quantifying, and managing the risks that an organization faces, which include strategic, operational, financial failures, market disruptions, and so forth. Risk management involves identifying the types of risk exposure within the organization, measuring those potential risks, proposing means to hedge, insure or mitigate some of these risks. Several papers reported in Table 4 have developed risk management decision support tools using FAHP. Radivojevic and Gajovic (2014) present a description of the main characteristics of supply chains and a model for risk assessment based on the experience and knowledge of experts from insurance companies that are professionally engaged in such risk-related exercises. The whole approach is integrated into a decision support systems for ranking supply chain risk categories, which can be of great benefit to managers in the decision making process for risk mitigation. Zou and Li (2010) develop a comprehensive risk checklist associated with subway projects, which is further translated into a risks hierarchy structure. FAHP is then applied for assessing the risks at the early stage of a subway line construction project. Andrić and Lu (2016); Nezarat, Sereshki, and Ataei (2015); Wang, Wang, and Qi (2016) also focus on underground construction project risks, in distinct sectors (tunneling, bridge construction, coal mine), but more from a safety standpoint considering geological risks and hazards. Chou, Pham, and Wang (2013); Taylan, Bafail, Abdulaal, and Kabli (2014) implement FAHP for construction project management under incomplete and uncertain situations, although the objective of these two papers is slightly different. Taylan et al. (2014) study 30 construction projects with respect to five main criteria (time, cost, quality, safety and environment), while Chou et al. (2013) rather propose an assessment model that quantifies project risks and, accordingly, calculate a range of viable bids. Rodríguez, Ortega, and Concepción (2016) develop a new FAHP-based model for the evaluation of risks in IT projects. This new model benefits from the combination of FIS (Fuzzy Inference System) and a modified FAHP, helping to incorporate a more intuitive model that not only facilitates risk assessment and its consistency, but provides, in each case, a better understanding of how project risk level is related to its risk factors.

Environment & Sustainability: The development of decision-making support systems for enhanced environmental performance is also an important field of application. Boutkhoum, Hanine, Tikniouine, and Agouti (2015) propose a decision-making approach combining FAHP within the online analytical processing (OLAP) data cube model to help decision-makers to select a good itinerary for transporting (dangerous) goods. The evaluation takes into account environmental criteria (risk of pollution, noise, and explosion hazards of chemicals in the civil area), social, (e.g., pollution impact) as well as economic criteria (e.g., transportation cost).

Deng, Xu, Liu, and Mancl (2014) introduce a decision support tool that, based on characteristics of different biogas plants and geographic regions, can effectively provide decision support (e.g., for governments) to develop sustainable biogas strategies. Because the biomass feedstocks that can be used to produce biogas are diverse, Ren, Fedele, Mason, Manzardo, and Scipioni (2013) develop a sustainability assessment model (including economic, environmental, technological and socio-political criteria) to rank biomass-based technologies for hydrogen production. From a land management perspective, decision making can be of great help to effectively manage land development plans, but only if the perspectives of concerned stakeholders are taken into consideration. In this respect, Pooyandeh and Marceau (2013) develop a web-based system that help land stakeholders to negotiate and reach an agreement based on the examination of multiple alternatives. A bottom-up modeling approach using FAHP is developed in an effort to facilitate learning among stakeholders (by sharing and validating their understanding of the situation) and reach a consensus. Mavi (2014) is looking at the phenomenon of entrepreneurial universities, which has received considerable attention over the last decades. In this context, the author presents an original FAHP-based study highlighting the importance to take into account environmental factors that highly condition the development of entrepreneurial universities with the teaching, research, and entrepreneurial missions that they pursue.

Other applications: In a context where governments are placing increasing emphasis on promoting tourist activities, Chen, Yu, Tsui, and Lee (2014b) present a two-step design method for international hotel atmosphere evaluation. The first phase makes use of Delphi to collect information and knowledge for establishing the FAHP hierarchy. The second phase implements FAHP to integrate experts' knowledge, calculate the criteria priorities, and obtain the final evaluation of the international hotel's atmosphere. Hotel managers (or any other hotel's stakeholder) can therefore use the proposed tool to make decisions out of the final ranking for enhanced hotel atmosphere design. Other papers reported in Table 4 develop decision-making systems for very different purposes than the ones previously discussed, such as (Kahraman, Suder, & Cebi, 2013) who use FAHP as a government investment decision support tool in higher education, or (Le, Quyen, & Nguyen, 2016) who use it for load shedding decision support.

4.4. Benefit-cost

A decision on whether or not to undertake a project usually requires investigating the *pros* (benefits) and *cons* (costs) of the project, and an attempt to express those in monetary terms. This is commonly known as benefit-cost analysis (BCA), sometimes called cost-benefit analysis (CBA). It is nonetheless difficult to express benefits and costs in monetary terms, especially when some of the benefits or costs are intangible such as "improved accuracy" or "learning efforts". (F)AHP has been advocated as a potential decision support technique where the benefit or cost aspects act as criteria and the projects as alternatives (similar to the "make-buy" decision process). Although Wijnmalen (2007) warns that the usual multiplicative synthesis of alternative priorities for benefits, opportunities, costs and risks (also known as the BOCR model) obtained from separate (F)AHP/ANP can be ambiguous, a few scholars have nevertheless considered such techniques to develop various types of Benefit-Cost frameworks, as evidenced in Table 5.

Anagnostopoulos and Petalas (2011) develop a FAHP-based BCA approach to determine how profitable distinct irrigation projects are. To this end, two distinct criteria hierarchies are constructed: one identifying the benefits and another the costs. Each alternative thus obtains two scores that are divided by each other ($\frac{\text{benefit score}}{\text{cost score}}$) in order to obtain the alternative's profit level. Following a different approach, Thengane, Hoadley, Bhattacharya, Mitra, and Bandyopadhyay (2014) present a FAHP-based BCA approach relying on a unique criteria hierarchy, whose goal is to assess in terms of BCA eight of the most common hydrogen production technologies. Five environmental criteria selected under the benefits category are considered, namely: greenhouse gas emissions, raw material/utilities consumption, energy efficiency, scalability, and finally waste disposal/atmospheric emissions. The results obtained for benefits category are then plotted against the normalized equivalent annual costs of each technology in order to identify the most beneficial one. Lee (2009) also relies on a unique criteria hierarchy but rather using the BOCR model, meaning that B.O.C.R are defined as four distinct criteria at "Level 1" of the hierarchy (*cf.* Fig. 2), thus enabling the selection of suppliers with the consideration of benefits, opportunities, costs and risks. The same authors (Lee, Chen, & Chang, 2008a) construct a similar approach for evaluating an IT department in the manufacturing industry in Taiwan, even though "Level 1" of the hierarchy is slightly different relying on the BSC model[5] and related criteria: (i) financial, (ii) customer, (iii) internal business process, and (iv) learning and growth criteria. From the same perspective, Wu, Tzeng, and Chen (2009) propose a three-step approach combining BSC with FAHP and three other MCDM analytical tools (SAW, TOPSIS, and VIKOR) in order to rank the banking performance and improve the gaps with three banks as an empirical example. Perçin (2008) introduces a new/hybrid FTOPSIS approach to evaluate the most suitable business process outsourcing decision. The approach is original as it uses the FAHP hierarchy structure, but not the pairwise comparison process.

4.5. Development

The collection, analysis and transfer of accurate customer needs and requirements throughout the product and process development play a crucial role to deliver market-disrupting products and services. As is shown in Table 6, QFD is often combined with FAHP for dealing with product design and customer requirements. QFD is a cross-functional planning tool used to ensure that the customers'voice is heard throughout the R&D, engineering, and manufacturing stages of the product. QFD originated in the late 1960*s* in Japan from the work of Akao (1990). Using it, the development team can systematically specify the customer's requirements and evaluates each proposed product so as to identify the degree to which it meets the set of requirements. (F)AHP is usually used to 'feed' the House of Quality (HoQ), which displays the relationships between the customer requirements (also called the WHATs) and the technical requirements/characteristics (also called the HOWs). Fig. 5 shows a traditional HoQ (WHATs, HOWs...). There are in fact two distinct ways to combine (F)AHP with HoQ matrices in the literature, namely:

(a) FAHP applied to determine the importance of the WHATs (i.e., to prioritize the customer requirements), as depicted through symbol ❖ in Fig. 5;
(b) FAHP applied to determine the degrees of the relationship between the HOWs and a WHAT, as illustrated through symbol ♣ in Fig. 5.

The first combination (❖) is the most commonly applied in the literature, e.g. applied in (Chen & Weng, 2006) for enhanced logistic service operations, in (Nepal, Yadav, & Murat, 2010) for automotive product development, in (Bereketli & Genevois, 2013; Chowdhury & Quaddus, 2016) for sustainable service design, in (Alinezad, Seif, & Esfandiari, 2013) for pharmaceutical vendor selection, and

[5] The financial performance perspective of BSC provides the natural connection with cost/benefit analyses.

Table 5
References on the topic of 'Benefit-Cost'.

N	Authors	Application areas	Specific objective	Other tool(s) used
B1	Thengane et al. (2014)	Government	Hydrogen source assessment	LFPP
B2	Anagnostopoulos and Petalas (2011)	Government	Irrigation projects	-
B3	Lee (2009)	Industry	Supplier selection model	BSC
B4	Wu et al. (2009)	Others	Banking performance	BSC, TOPSIS, VIKOR
B5	Perçin (2008)	Manufacturing	Business process outsourcing	FTOPSIS
B6	Lee et al. (2008a)	Manufacturing	IT department performance	-

Table 6
References on the topic of 'Development'.

N°	Authors	Application areas	Specific objective	Other tool(s) used
D1	Chowdhury and Quaddus (2016)	Industry	Sustainable service design	QFD
D2	Parameshwaran et al. (2015a)	Engineering	Mechatronic products	Delphi, QFD, FMEA, ANP
D3	Wang (2015a)	Industry	Business-intelligence systems	QFD, Delphi, DEMATEL
D4	Wang et al. (2014)	Industry	Green product development	TOPSIS
D5	Tan et al. (2014)	Engineering	Process engineering	-
D6	Roy et al. (2014)	Engineering	Machine development	QFD
D7	Roghanian and Alipour (2014)	Engineering	Lean production	QFD, PROMETHEE
D8	Bereketli and Genevois (2013)	Engineering	Sustainable product development	QFD
D9	Alinezad et al. (2013)	Industry	Pharmaceutical supplier selection	QFD
D10	Paksoy et al. (2012)	Manufacturing	Distribution channel design	FTOPSIS
D11	Nepal et al. (2010)	Engineering	Automotive products	QFD
D12	Li and Huang (2009)	Engineering	Manufacturing system design	TRIZ
D13	Büyüközkan, Feyzioğlu, and Ruan (2007)	Others	Multiple preference formats	QFD
D14	Chen and Weng (2006)	Industry	Customer service assessment	QFD, MSGP
D15	Ayag (2005)	Engineering	Product design	-
D16	Kwong and Bai (2003)	Engineering	Customer requirements	QFD

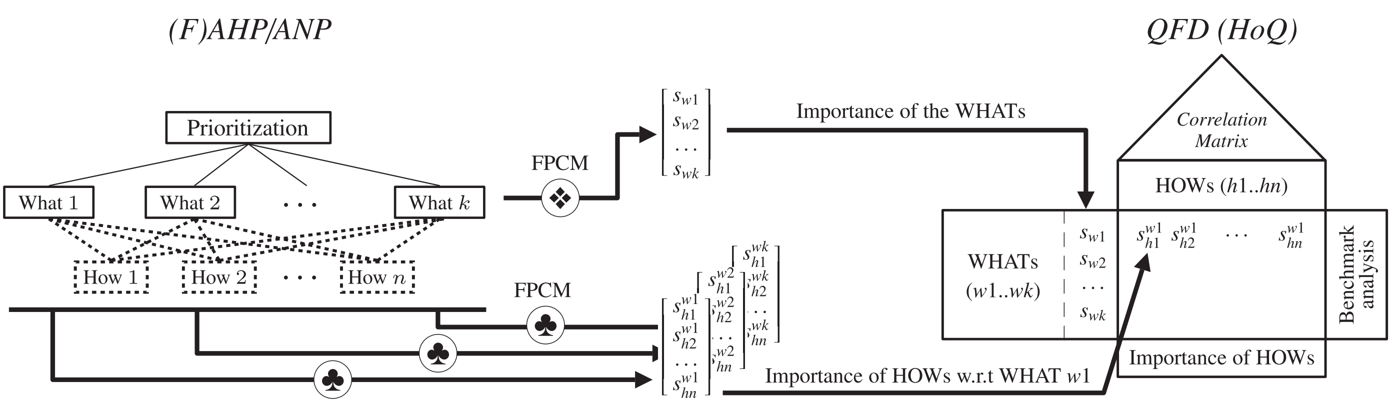


Fig. 5. House of Quality (HoQ) in QFD: design & concepts.

so on (Kwong & Bai, 2003; Roy, Ray, & Pradhan, 2014). The second type of combination (♣) has been applied e.g. for lean production purposes in (Roghanian & Alipour, 2014) and for mechatronics-based product development in (Parameshwaran, Baskar, & Karthik, 2015a). Wang (2015a) propose a more complex engineering framework using FAHP to determine the relative importance of the WHATs (i.e., combination ❖), while using DEMATEL to determine the degrees of the relationship between the HOWs and a WHAT (i.e., combination ♣).

As reported in Table 6, other studies have been using FAHP for product development and innovation without necessarily combining it with QFD. Ayag (2005) presents a FAHP-based methodology whose goal is to reduce a set of conceptual design alternatives. This methodology can be used, for example, by a product or project engineer in real-life manufacturing systems. Tan, Aviso, Huelgas, and Promentilla (2014) develop a similar methodology for process engineering decision-making problems, which is applied to and validated for three distinct case studies, namely for the ranking of (i) different types of chloralkali electrolytic cells, (ii) Co2 capture techniques in cement plants, and (iii) wastewater treatment options for municipalities. Wang, Chan, and Li (2014) implement FAHP, or the Chang's extent analysis to be more precise, from a Life Cycle Assessment perspective at the design phase for green product development. To this end, the different phases of a product life cycle (i.e., material selection, manufacturing, distribution, installation, usage, end-of-life) are considered as criteria at "Level 1" of the hierarchy. Paksoy, Pehlivan, and Kahraman (2012) focus on distribution channel design that takes place after the product design process, the overall goal being to evaluate and select the best organization strategy model (among five) for vegetable oil distribution channel management. Li and Huang (2009) present a framework that combines TRIZ and FAHP for innovative design of automated manufacturing systems. TRIZ is applied for breaking up the complex design problem into a contradiction matrix as well as incentive principles, while FAHP is employed as a decision support tool to facilitate the selection and evaluation of innovative designs in the presence of intangible attributes and uncertainty.

Table 7
References on the topic of 'Priority'.

N°	Authors	Application areas	Specific objective	Other tool(s) used
P1	Macuzić et al. (2016)	Industry	Organizational resilience factors	FTOPSIS
P2	Toklu et al. (2016)	Manufacturing	Strategic action plan	SWOT, ANP
P3	Govindan et al. (2015)	Manufacturing	Green manufacturing drivers	-
P4	Bulut et al. (2015)	Engineering	Marine engine selection problem	-
P5	Jakiel and Fabianowski (2015)	Engineering	Bridge structural arrangements	-
P6	Liu et al. (2015)	Engineering	Failure mode and effects analysis	FMEA, VIKOR
P7	Wang (2015c)	Education	FAHP	-
P8	Hosseini Firouz and Ghadimi (2015)	Industry	Electric power distribution systems	-
P9	Azarnivand et al. (2015)	Social	Water and environmental management	SWOT
P10	Kabra et al. (2015)	Government	Humanitarian supply chain management	-
P11	Jaiswal, Ghosh, Lohani, and Thomas (2015)	Government	Watershed	-
P12	Ren et al. (2015)	Government	Hydrogen production technologies	TOPSIS
P13	Chang (2014)	Government	Green building project	Delphi, TOPSIS
P14	Ren and Sovacool (2014)	Social	Energy security analysis	-
P15	Kubler et al. (2013)	Manufacturing	Product Lifecycle Management	-
P16	Aryafar, Yousefi, and Ardejani (2013)	Others	Mining operations	-
P17	Calabrese et al. (2013)	Others	Intellectual capital management	-
P18	Tavana, Khalili-Damghani, and Abtahi (2013)	Industry	Advanced-technology prioritization	TOPSIS, ANP
P19	Kutlu and Ekmekçioğlu (2012)	Manufacturing	Failure mode and effects analysis	TOPSIS, FMEA
P20	Dehghanian et al. (2012)	Manufacturing	Power management	-
P21	Javanbarg et al. (2012)	Education	Optimization model	-
P22	Duru, Bulut, and Yoshida (2012)	Education	FAHP model definition	RS-FAHP
P23	Yang et al. (2011)	Political	Environmental management	-
P24	Rostamzadeh and Sofian (2011)	Manufacturing	Production performance	FTOPSIS
P25	Tadic et al. (2009)	Education	Quality goals ranking	TOPSIS
P26	Bozbura and Beskese (2007)	Others	Capital measurement	-

4.6. Priority

Based on the reviewed papers reported in Table 7, five groups of papers (paragraphs) compose this section, respectively focusing on: (i) Supply chain & Maintenance; (ii) Strategy management; (iii) Environment & Sustainability; (iv) Energy management; and (v) Other applications.

Supply chain & Maintenance: Kabra, Ramesh, and Arshinder (2015) explore and prioritize the coordination barriers in the humanitarian supply chain management, particularly in the Indian context to enhance the performance of relief operations. The approach is a three-stage process: (i) barriers to coordination are identified through a literature review; (ii) these are grouped into five categories (management, technological, cultural, people, and organizational barriers), which are then turned into a hierarchical criteria structure; (iii) barriers are finally prioritized on the basis of their severity using FAHP. It is interesting to note that FAHP is only applied for ranking these criteria/barriers in terms of priority and, as a result, no "alternatives" level is defined. Kubler, Derigent, Voisin, Rondeau, and Thomas (2013) apply FAHP for prioritizing manufacturing product-related data that needs to be embedded/stored on intelligent products, which may be useful for tracking and/or collaboration purposes throughout the product life cycle. The data prioritization process depends on a number of factors, including the life cycle phase in which the product is being handled, the downstream processes and stakeholder needs/expectations, and so on. Kutlu and Ekmekçioğlu (2012); Liu, You, You, and Shan (2015) present two distinct FAHP-based approaches for FMEA, which is a widely used engineering technique for defining, identifying and tackling known and/or potential failures and problems. In (Liu et al., 2015), a risk evaluation methodology for FMEA is developed to tackle risk factors and identify the most serious failure modes for corrective actions. In (Kutlu & Ekmekçioğlu, 2012), FAHP is combined with TOPSIS to get the scores of potential failure modes, which are then ranked to find out the most important and risky ones that should be tackled as a matter of priority. Bulut, Duru, and Kocak (2015) develop and present an innovative framework, referred to as *rotational priority investigation*, which aims to improve the applicability of the Chang's extent analysis, particularly with regard to possible rank reversal and intransitivity phenomena. The proposed framework is a post-survey treatment of rank reversal problem and is applied for a marine engine selection problem.

Strategy management: Strategic planning is a vital management tool for projecting the long-range business goals and is not only for big businesses, but also applicable to small businesses in spite of their limited resources. To do this effectively, organizations should determine their strengths and weaknesses, and produce appropriate action plans – *prioritized according to limited resources* – to overcome these weaknesses. In this respect, Toklu, Erdem, and Taşkin (2016) introduce a fuzzy sequential model combining SWOT and FANP to help organizations in strategic planning process, considering three distinct criteria categories: Strategic, Tactical and Operational (defined at "Level 1" of the criteria hierarchy, *cf.* Fig. 2). Tadic, Gumus, Arsovski, Aleksic, and Stefanovi (2009) focus on ranking quality goals at the process level to help quality managers to undertake certain activities with the aim of improving a process in the shortest possible period of time (goals that have the biggest influence on process efficiency must be identified). The evaluation and ranking of resilience factors has important implications for the management of any enterprise. Motivated by the lack of a unified list of all possible risks and organizational resilience factors in organizations, Macuzić, Tadić, Aleksić, and Stefanović (2016) propose a new model for the ranking of resilience factors with a focus on SMEs. Rostamzadeh and Sofian (2011) present a fuzzy decision-making approach for prioritizing effective 7Ms (Management, Manpower, Marketing, Method, Machine, Material, and Money) to improve production systems performance. Along with planning and production strategies, organizations have to implement strategies and practices to manage "Knowledge", which is a vital resource in any organization to improve quality and customer satisfaction, as well as to decrease cost in every meaning. To improve organizational and intellectual capital management practices, both Bozbura and Beskese (2007) and Calabrese, Costa, and Menichini (2013) propose a FAHP-based methodology to measure the intellectual capital with respect to three capital categories, including Human, Organizational and Relational.

Environment & Sustainability: Recent years have seen manufacturing processes understand the green issues due to the social and environmental concerns involved. The drivers of green manufacturing, however, have not been thoroughly investigated. Thus, as already discussed in previous sections/themes, several studies focused on investigating the responsibility of identifying drivers of green manufacturing. Govindan, Diabat, and Shankar (2015) identify twelve common drivers from the combined assistance of existing literature, industrial managers, and expert opinion in the relevant field (a questionnaire was circulated among 120 leading firms in South India), and then determine the ranking priority of these drivers for implementation of green actions in the manufacturing strategy. Yang, Khan, and Sadiq (2011) also focus on prioritizing environmental issues but with a focus on offshore oil and gas operations. A model used for the prioritization is a five-level hierarchy, where FIS is applied at the lower levels (4 and 5) to infer the major risk parameters. Chang (2014) develops a ranking algorithm for managing uncertainty and imprecision of green building project evaluation during the structure process. The study takes three cities in Taiwan as the green building targets, and identifies Tapei as the optimal green building city. Other studies use FAHP to prioritize the strategic alternatives for reviving water resources on the basis of sustainable development criteria (Azarnivand, Hashemi-Madani, & Banihabib, 2015). The SWOT matrix is considered to identify and structure internal strategic factors *vs.* external ones in the group decision making process.

Energy management: Enhanced environmental services involve managing energy usage and sustainability that is a complex MCDM problem as a whole, involving economic, technical, socio-political impacts, as well as different types of energy sources. For example, Ren et al. (2015) investigate hydrogen production technologies to solve the severe energy and environmental problems caused by the excessive use of fossil fuel for transportations. Based on the resulting priority sequence, *Coal gasification with CO2 capture and storage* and *Hydropower-based water electrolysis* technologies are predicted to play an important role in the future hydrogen economy of China. The same authors carried out a study on the influential factors on China's energy security, along with a prioritization of the strategic measures with respect to enhancing some of these factors (Ren & Sovacool, 2014). Maintenance plays also an important strategic and opertional role in the energy sector. In this respect, some studies have focus ed on improving maintenance strategies based on FAHP. Dehghanian, Fotuhi-Firuzabad, Bagheri-Shouraki, and Razi Kazemi (2012) investigate the key factors associated with the critical component identification in power distribution systems and, afterward, determine the most important component types. Hosseini Firouz and Ghadimi (2015) present a new model of system maintenance cost, whose maintenance cost elements are determined as functions of system reliability indices and preventive maintenance budget.

Other applications: Table 7 report additional papers that focus more on theoretical aspects, and particularly on priority derivation of triangular fuzzy preference relations (Javanbarg, Scawthorn, Kiyono, & Shahbodaghkhan, 2012; Wang, 2015c).

4.7. Resource allocation

Resource allocation plays an important role in many service or manufacturing situations. Papers making use of FAHP to solve this problem are listed in Table 8. A resource allocation problem can be stated as: an optimization problem where one seeks to allocate a limited amount of resources to a finite set of activities (Katoh & Ibaraki, 1999). The problem is usually solved using MODM techniques. In its simplest form, the problem turns in the minimization of a separable function under the constraint of the total amount of resources, as expressed in Eq. 5, with N the total amount of resources, and $f(x_j)$ the cost or reward function generated by the allocation of the amount of resources x_j to activity$_j$.

$$\text{minimize } \sum_{j=1}^{n} f(x_j) \qquad (5)$$

$$\text{subject to } \sum_{j=1}^{n} x_j = N\ ,\ \ x_j \geq 0$$

Starting from the above formalization, the problem has been generalized using non-separable function s and more complicated constraints (e.g., nested, tree, network or submodular) (Katoh & Ibaraki, 1999). Papers referenced in Table 8 apply FAHP for allocating resources in three distinct manners:

1. *for optimization purposes:* the optimization criteria have been express in the form of a criteria hierarchy, where FAHP orders the entire set of solutions. Azadeh, Nazari-Shirkouhi, Hatami-Shirkouhi, and Ansarinejad (2011) do perform such an optimization combing FAHP and TOPSIS to obtain the whole set of combinations of solutions using a simulation process;
2. *for determining criteria weights to be optimized:* afterward, an optimization procedure is performed for solving the problem. Hajipour, Niaki, Borji, and Kangi (2014) use the fuzzy weights derived from FAHP as coefficients of the criteria in a linear function to be optimized. Shahhosseini and Sebt (2011); Somsuk and Laosirihongthong (2014) use FAHP to determine the most important factors but do not detail the optimization procedure;
3. *for complexity reduction:* FAHP is used to decrease the problem by selecting a subset of either resources or activities. Lee, Mogi, and Hui (2013); Lee, Mogi, and Kim (2009); Şen and Çınar (2010) consider such an approach but, again, do not detail the optimization procedure.

Based on the reviewed papers reported in Table 8, three groups of papers (paragraphs) compose this section, respectively focusing on: (i) Human resource; (ii) Money allocation; (iii) Other resource allocation applications.

Human resources: The objective consists in allocating a set of operators to one or more operations depending, among other things, on the task requirements and operator's skills. Şen and Çınar (2010) consider multiple-skilled operators to be allocated to manufacturing operations. To this end, the authors propose a two-level hierarchy, the first level (*cf.* "Level 1" in Fig. 2) includes *Competency, Experience, Personal characteristics, Assembly capability*, and *Control capability*. FAHP is applied to determine the criteria weights, while the Max-Min approach is applied to pre-allocate a sub-set of operators to an operation. Shahhosseini and Sebt (2011) aim at selecting the best human resources for a construction project. The approach considers four classes of human resources, a criteria hierarchy being defined for each of these categories. For the four distinct FAHP hierarchies, the first level (i.e., "Level 1") includes technical, behavioral and contextual competencies. Azadeh et al. (2011) identifies the optimal scenario for allocating operators to a cellular manufacturing system. In the proposed approach, all the possible scenarios are considered as alternatives in the FAHP structure, and human resources contribute to these scenarios. To put it another way, scenario-related criteria values are computed through a simulation model whose outputs are {*Number of operators, Average lead time of demand, Average waiting time of demand, Number of completed parts, Operator utilization, Average machine utilization*}, and where FAHP is applied to rank the considered scenarios.

Money allocation: The objective consists in allocating a limited amount of money to projects or action plans. Within this con-

Table 8
References on the topic of 'Resource Allocation'.

N°	Authors	Application areas	Specific objective	Other tool(s) used
R1	Hajipour et al. (2014)	Industry	Investment allocation	-
R2	Somsuk and Laosirihongthong (2014)	Government	Incubator resource management	-
R3	Lee et al. (2013)	Government	Energy reduction	-
R4	Kannan et al. (2013)	Manufacturing	Order allocation in green supply chain	LP, TOPSIS
R5	Shahhosseini and Sebt (2011)	Others	Human resource allocation	ANFIS
R6	Azadeh et al. (2011)	Manufacturing	Operators' assignment	TOPSIS
R7	Şen and Çınar (2010)	Manufacturing	Pre-allocation of operators	Max-Min
R8	Lee et al. (2009)	Government	Energy technology development	-

text, Lee et al. (2013, 2009) are seeking to allocate money resources to the best R&D energy projects. Both papers consider the same energy-related problem (the authors being the same), where FAHP is applied to classify the best projects. High level criteria are considered in both studies such as economical spin-off, commercial potential, inner capacity and technical spin-off. The authors, nonetheless, go a step further in (Lee et al., 2013) since they combine FAHP with a DEA analysis, which helps to include a quantitative economic viewpoint. However, one can argue that both studies do not provide a complete resource allocation framework since the money allocation phase is not fully addressed (or at least presented) in their studies. To promote the success of University business incubators, Somsuk and Laosirihongthong (2014) propose to identify the most important factors to concentrate their efforts and resources accordingly. However, as previously, the authors do not address the allocation stage. Finally, Hajipour et al. (2014) help to allocate financial resources according to a quality action plan. To this end, FAHP and BSC are used respectively to compute the weights of the quality costs (corresponding to the problem variables) and to take into consideration shareholders' opinions. The allocation phase is performed as a constrained optimization.

Others: Table 8 reports another paper, namely (Kannan, Khodaverdi, Olfat, Jafarian, & Diabat, 2013), which deals with green supplier selection and order quantity allocation. The best suppliers are ranked and selected using FAHP based on environmental and economic criteria, which is followed by a fuzzy multiple-objective linear programming stage to determine the order quantity of each selected supplier.

5. Observations and concluding remarks

In an effort to provide a clear and comprehensive summary of the survey outcomes, Sections 5.1 to 5.6 present graphical and tabular representations, syntheses and discussions of the FAHP method as a developed decision making tool. Whenever possible, the survey outcomes are compared with findings and predictions from past MCDM-related surveys such as (Vaidya & Kumar, 2006) (AHP-related survey), (Mardani et al., 2015) (Fuzzy MCDM-related survey) and (Behzadian, Khanmohammadi Otaghsara, Yazdani, & Ignatius, 2012) (TOPSIS-related survey).

5.1. Distribution of papers arranged: Theme-wise & application area-wise

Figs. 6(a) and 6(b) provide a percentage distribution of the 190 reviewed papers respectively arranged *Theme*-wise and *Application area*-wise (values in brackets corresponding to the number of papers per category). It can be observed that FAHP is being predominantly used in the theme area of Selection and Evaluation, which is a similar finding to Vaidya's survey. As far as the area of application is concerned, most of the times FAHP has been used in *Manufacturing, Industry* and *Government* categories. This finding differs significantly from Vaidya's survey since AHP was primarily used (back to 2006) in Engineering, Personal and Social categories. A plausible explanation of this difference could be attributed to the combination of AHP with the fuzzy logic, which is a theory widely applied within manufacturing and industrial applications. To support this statement, let us quote (Karwowski & Evans, 1986) who enumerate three reasons for this:

1. In manufacturing process, machine control and product quality management, the information required to formulate a model's objective, decision variables, constraints, and parameters may be vague or not precisely measurable;
2. Imprecision and vagueness are inherent to the decision maker's mental model;
3. Imprecision and vagueness as a result of personal bias and subjective opinion may further dampen the quality and quantity of available information.

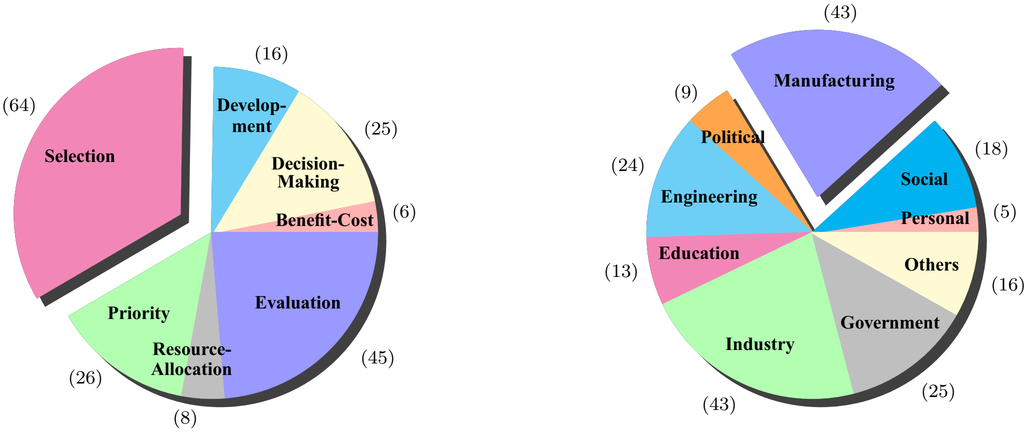
It should be added that, in manufacturing and industrial settings, a wide range of stakeholders and experts are involved throughout the product life cycle, from the beginning-of-life of the product involving designers, marketers, manufacturers, distributors and dealers, through its middle-of-life involving users, repairers, up to its end-of-life, involving disposers and recyclers (Stark, 2015). This inevitably causes increased complexity in the process of elicitation of expert judgments and group-decision making, which is why fuzzy MCDM techniques are often considered and applied.

When discussing papers in Section 4 and associated tables, we tried to discuss groups of papers that have been addressing a same or similar objective (on the basis of the "Specific Objective" column). However, since it may be difficult for readers to have an at-a-glance overview of all these groups, we illustrate all this through a city-based representation in Fig. 7, which should help researchers and practitioners to easily identify FAHP studies in their area(s) of interest.

5.2. Other tool combination overview

Realizing the need to refine their results, researchers often combined FAHP with other tools, as evidenced through our state-of-the-art literature review and Tables 2 to 8. This does not mean that FAHP is no more used in a stand-alone mode. In fact, from looking at our survey results, 110 papers out of the 190 (i.e., 57%) use FAHP in a stand-alone mode. In an effort to help the reader to have an at a glance summary of how the remaining 43% (i.e., 82 papers) are combined with FAHP, Table 9 shows the references arranged in a matrix format showing the combinations of "Tools" and "Themes" to which each paper belongs. It can be observed that most of the papers fall in the combination of: (a) (F)TOPSIS and selection, (b) (F)TOPSIS and evaluation, (b) QFD and Development, and (c) ANP and selection.

Overall, this table emphasizes that FAHP as a tool comes with a natural flexibility that enables it to be combined with a wide range of techniques and for very distinct purposes. (F)TOPSIS is



(a) Theme specific distribution (b) Application area specific distribution

Fig. 6. Specific distribution of the reviewed papers arranged *Theme*-wise and *Application area*-wise (*cf.* Section 3 for more details).

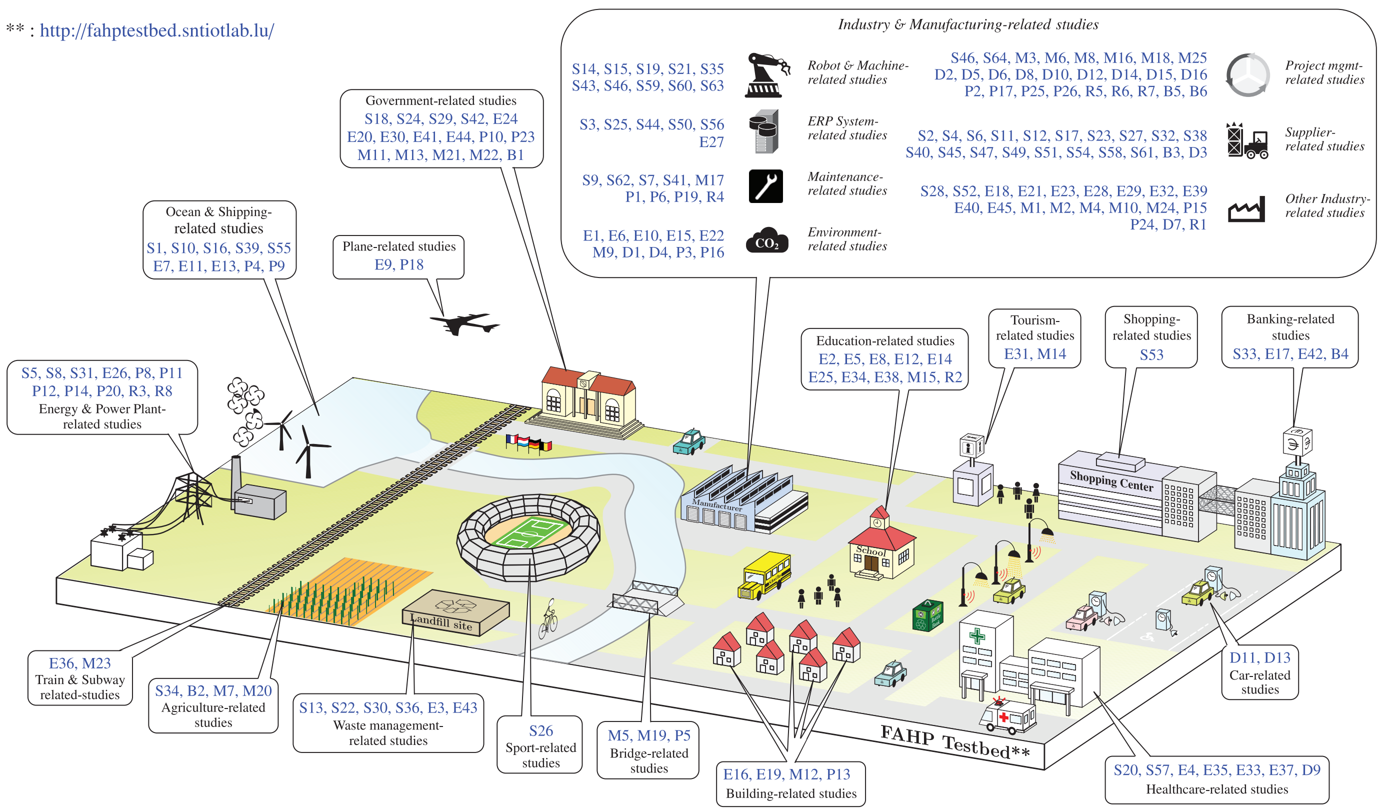


Fig. 7. Classification of the reviewed papers according to the "Specific objective" addressed in each of them.

predominantly used alongside FAHP, but other techniques are better suited to specific themes, such as GRA and COPRAS for evaluation, or still RS-FAHP, SWOT and FMEA for prioritization. In the future, it is likely that similar, but also new combination frameworks, will emerge even though it is always challenging to demonstrate that the proposed combination performs better than FAHP used in a stand-alone mode. Indeed, although some studies have carried out intensive and persuasive experiments to show the combination's benefits (Govindan et al., 2015; Hosseini Firouz & Ghadimi, 2015; Kubler et al., 2014; Lima Junior et al., 2014; RazaviToosi & Samani, 2016), a number of papers do not pay sufficient attention to this crucial aspect, especially when introducing a new or complex combination of tools that requires an even more thorough comparison analysis with the existing state-of-the art techniques, as e.g. in (Chang et al., 2015; Parameshwaran et al., 2015a; Uygun et al., 2015; Wang, 2015a; Wu et al., 2009).

5.3. Distribution of papers arranged journal-wise

Table 10 provides the list of journals ordered on the basis of the number of papers (from that journals) that have been reviewed and integrated to our state-of-the-art survey ($N = 190$, and associated percentage $\% = 100$, standing for the total number of papers). It can be noted that the majority of the papers have been published in journal specialized in intelligent and advanced manufacturing and production, which is in line with the findings previously reported (see Fig. 6(b)). Interestingly, Table 10 shows that a very significative number of papers have been published in "Expert Systems with Application". This can be partly explained by the fact

Table 9
Categorized list of references on the basis of “Other Tools” integrated with FAHP with respect to “Themes” .

	Selection	Evaluation	Benefit-cost	Res. allocation	Development	Priority	Decision-making
(AN)FIS				R5			M3
ANP	S34, S45, S27, S30, S19, S21, S15, S8, S12, S58	E39, E27, E19, E4, E7			D2	P18, P2	M6
BSC	S56		B3, B4				
COPRAS		E24, E34					S41
DEA	S49, S11					S28	
Delphi	S14, S4	E10			D3, D2	P13	M14
DEMATEL	S12	E32			D3		
ELECTRE	S22	E9					
FA/FR	S37						
FMEA					D2	P6, P19	
GA	S38						
GRA		E30, S15, E14					
(L)FPP		E28, M4	B1				
LP	S40			R4			
Max-Min	S1			R7			
MRA							M19
(MS)GP		E3	S46		D14		
NN	S48						
PROMETHEE	S35, S24						D7
QFD					D2, D3, D9, D8, D13, D11, D16, D6, D1, D14		D7
RS-FAHP						P22	
SWOT	S56					P9, P2	
(F)TOPSIS	S43, S39, S59, S31, S32, S23, S25, S26, S53, S42, S49, S54, S29, S6, S3, S4, S2, S7, S13, S1, S58	E14, E33, E43, E41, E18, E17, E42, E20, E30, E10	B4, B5	R6, R4	D4, D10	P25, P18, P13, P12, P1	S52, M21, M15, M24, M12, M18, M1, P24, M10
TRIZ					D12		
VIKOR	S14, S47	E20, E14, E4	B4			P6	

that the scope of this journal, in addition of being on intelligent systems, pays a particular attention to expert systems, i.e. research studies involving elicitation and analysis of expert opinions, judgments and practices. As a consequence, many scholars readily turn to this journal as well as theories that make it possible to (ii) handle imprecise or uncertain information (e.g., Fuzzy Logic), and (i) help to organize critical aspects of the problem in a manner similar to that used by the human brain in structuring the knowledge (i.e., in a hierarchical structure such as AHP). The column entitled “IF” in Table 10 refers to the journal’s Impact Factor based on the Thomson Reuters international citation database[6], while the last column provides a more in-depth analysis of the ‘Citation-Year ratio’. More specifically, three ratio values are given respectively referring to the minimal, average and maximal number of citations over the years regarding the set of papers – *from a given journal* – that have been integrated to our state-of-the-art survey (more details about the ratio computation can be found in Appendix A). Some interesting observations that can be made in light of both IF and “citation-year ratio” scores are that some journals such as *IIE Transactions* or *International Journal of Approximate Reasoning* released FAHP papers that attracted widespread and continuous attention (over years) since Citation-Year ratio values are quite high while their respective IFs are not that significant. Conversely, other journals such as *Safety Science* or *International Journal of Advanced Manufacturing Technology* have a respectable IF, but do not necessarily attract the attention of FAHP researchers and practitioners. Looking at the IF and “Citation-Year ratio” columns can help researchers to easily identify and (potentially) target one or more journals considering both the overall journal’s impact *vs.* interest expressed by researchers in FAHP studies published in that journal.

[6] ∅ indicates that the journal is not referenced in the database.

5.4. Distribution of papers arranged country-wise

Table 11 gives insight into the spread of FAHP usage on the basis of the country where the study has been conducted. Asia is clearly the torchbearer in this field, which confirms the predictions made by Vaidya and Kumar (2006) a decade ago; the authors confidently predicted an increasing trend of AHP applications in developing countries like India, China, *etc.*, while stressing the fact that the theme areas of Selection and Evaluation would likely play an important role in complex economic and other systems from different development perspectives. This trend has been since then confirmed by other (more recent) surveys such as (Behzadian et al., 2012; Mardani et al., 2015), whose resulting distribution by authors’ nationality brought into light that Taiwan, Turkey, Iran, China and India were the most active countries in applying MCDM and TOPSIS techniques.

5.5. Assessment on the adoption of Chang’s extent analysis

As mentioned in Section 2.3, the Chang’s extent analysis method is one of the most applied technique, despite criticisms. Indeed, a significant number of research papers have demonstrated that this method suffers from theoretical pitfalls, particularly for deriving the true weights from FPCMs. Given this fact, it is worth analyzing how spread/adopted this method is in the literature.

Table 10
Journal & Citation specific distribution.

Rank(N)	Journal name	N	%	IF	Citation-Year ratio
1	Expert Systems with Applications	41	21.0%	2.981	[0.00, 21.5, 57.4]
2	Applied Soft Computing	10	5.2%	2.857	[2.00, 15.3, 41.5]
3	Journal of Cleaner Production	7	3.6%	4.959	[0.00, 12.6, 33.7]
	International Journal of Advanced Manufacturing Technology	7	3.6%	1.568	[1.33, 5.34, 9.80]
4	Journal of Intelligent Manufacturing	6	3.1%	1.995	[2.00, 8.31, 14.0]
5	Computers & Industrial Engineering	5	2.6%	2.086	[0.00, 8.21, 23.3]
6	International Journal of Production Economics	4	2.1%	2.787	[2.00, 25.8, 52.4]
	Environmental Earth Sciences	4	2.1%	1.765	[4.33, 7.42, 11.0]
	Technological and Economic Development of Economy	4	2.1%	1.563	[2.67, 5.56, 8.25]
	International Journal of Production Research	4	2.1%	1.477	[4.17, 15.1, 44.4]
7	Renewable & Sustainable Energy Reviews	3	1.6%	6.798	[5.50, 6.39, 7.67]
	International Journal of Hydrogen Energy	3	1.6%	3.205	[3.50, 6.25, 9.00]
	European Journal of Operational Research	3	1.6%	2.679	[10.5, 16.7, 25.6]
	International Journal of Approximate Reasoning	3	1.6%	2.696	[11.0, 21.5, 35.9]
	Safety Science	3	1.6%	2.157	[0.00, 1.00, 3.00]
	Journal of Intelligent & Fuzzy Systems	3	1.6%	1.004	[2.50, 3.67, 6.00]
	Benchmarking: An International Journal	3	1.6%	∅	[0.00, 2.94, 6.33]
8	Energy	2	1.1%	4.292	[10.0, 16.8, 23.5]
	Journal of Environmental Management	2	1.1%	3.131	[2.67, 14.6, 26.6]
	Energy and Buildings	2	1.1%	2.973	[2.00, 7.75, 13.5]
	Technological Forecasting and Social Change	2	1.1%	2.678	[2.00, 7.25, 12.5]
	Applied Mathematical Modelling	2	1.1%	2.291	[4.00, 6.84, 9.67]
	Process Safety and Environmental Protection	2	1.1%	2.078	[6.20, 7.85, 9.50]
	Tunnelling and Underground Space Technology	2	1.1%	1.741	[2.00, 7.75, 13.5]
	Journal of Loss Prevention in the Process Industries	2	1.1%	1.409	[0.00, 2.63, 5.25]
	Journal of Civil Engineering and Management	2	1.1%	1.530	[6.00, 6.75, 7.50]
	IIE Transactions	2	1.1%	1.463	[13.1, 19.3, 25.5]
	Journal of Risk Research	2	1.1%	1.027	[1.50, 3.00, 4.50]
	Quality & Quantity	2	1.1%	0.867	[0.50, 2.25, 4.00]
	Mathematical Problems in Engineering	2	1.1%	0.644	[0.00, 0.00, 0.00]
	Journal of Applied Mathematics	2	1.1%	∅	[0.50, 0.50, 0.50]
9	Other Journals *(49 journals in total)*	49 × 1	49 × 0.5%	–	–
		190	100%		

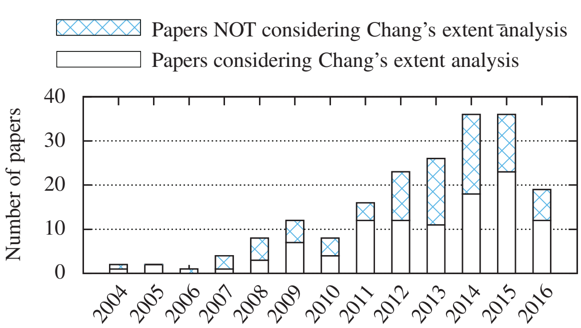


Fig. 8. Distribution of papers using Chang's extent analysis.

Fig. 8 provides such an analysis by plotting per year the number of papers – *on the basis of the corpus of reviewed papers* – that make use of the analysis method (either the whole or part of the method). This histogram clearly shows that majority of the papers (109 out of the 190, i.e. 57%) made use and still make use of this method, and this trend does not seem about to reverse despite repeated criticisms over the last decade.

5.6. Concluding remarks and forecasts

Based on this review, some brief concluding remarks could be formulated to highlight the course of future FAHP applications:

- FAHP will continue to be widely applied to the manufacturing and industrial sectors, where intelligent and smart connected systems will increasingly be adopted by big and small companies. To support this statement, we would point to disciplines, technologies and communities that exhibit rapid growth such as the Internet of Things (IoT), Cyber-Physical Systems (CPS), Industry 4.0, and Big Data (Atzori, Iera, & Morabito, 2010; Chen, Mao, & Liu, 2014a; Evans & Annunziata, 2012; McFarlane, Giannikas, Wong, & Harrison, 2013). According to the IDC prediction, the IoT market in manufacturing operations will grow from \$42.2 billion in 2014 to \$98.8 billion in 2020;
- As discussed in the previous sections, FAHP is often combine with various other techniques (in 43% of the corpus of reviewed papers), we are thus confident to say that new hybrid FAHP frameworks will continue to be designed and proposed in the coming years;
- Although sophisticated approaches for deriving weights from FPCMs have been proposed over the last decade to properly tackle consistency check and guarantee the decision making be reasonable (Krejčí, 2016; Meng & Chen, 2016; Ohnishi, Dubois, Prade, & Yamanoi, 2008; Zhü, 2014), it is likely that the Chang's extent analysis will remain popular and applied in the future for the sake of simplicity. The release of further critical studies on the method's pitfalls, as well as of novel, efficient, and (most importantly) easy-to-use methods for deriving weights from FPCMs should take over the extent analysis method in the mid-to long-term.

We feel that this review work could serve as a ready reference for those who wish to apply, modify or extend FAHP in various applications domains. To make this happen, we have developed and released an online testbed to enable researchers, reviewers and other practitioner stakeholders to access the survey results and findings, and potentially (if of interest) one or more FPCMs from the reviewed papers. This testbed is presented in greater detail in the next section.

Table 11
List of country-wise arranged reviewed papers.

Rank	Country	N	%
1	Turkey	47	25.0%
2	Iran	28	15.1%
3	Taiwan	21	10.9%
4	China	17	8.9%
5	India	14	7.3%
6	Korea	6	3.1%
	Malaysia	6	3.1%
	Canada	6	3.1%
7	UK	5	2.6%
	Italy	5	2.6%
	USA	5	2.6%
	Serbia	5	2.6%
8	Australia	3	1.6%
9	Bangladesh	2	1.0%
	Chile	2	1.0%
	Denmark	2	1.0%
	Japan	2	1.0%
	Spain	2	1.0%
	Vietnam	2	1.0%
	Thailand	2	1.0%
10	Brazil	1	0.5%
	France	1	0.5%
	Greece	1	0.5%
	Morocco	1	0.5%
	Netherlands	1	0.5%
	Philippines	1	0.5%
	Poland	1	0.5%
	Saudi Arabia	1	0.5%
		190	100%

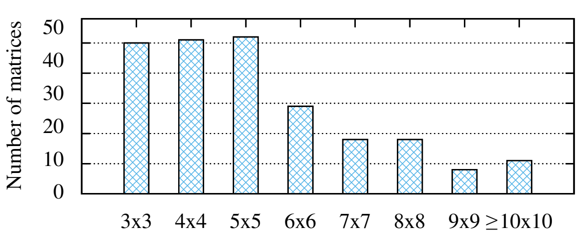


Fig. 9. Distribution of FPCMs according their size ($\tilde{A}_{n\times n}$).

6. Open FAHP/FPCMs testbed

As it has been explained in the introduction section, this state-of-the-art survey started from a personal motivation around the study of a new consistency index for FPCMs' weight derivation, for which we started the collection of FPCMs from various scientific journal papers with the objective to use them as basis of a testbed to evaluate the proposed consistency index. This gave us the idea to make all those FPCMs' available online (for free) to various communities of researchers. In total, 255 FPCMs from 180 papers (out of the 190 reviewed[7]) have been collected and made available through the online testbed. Fig. 9 gives insight into the distribution of these 255 FPCMs according to their respective size (FPCMs whose size is greater than 10×10 – *up to* 20×20 – are summed together under the $\geq 10 \times 10$ *x*-label).

Fig. 10(a) provides two screenshots of the online testbed, where we highlight (using frame and numbering annotations) its main functionalities, as discussed hereinafter:

- *FPCM-related information (see ☞ in Fig. 10(a)):* End-users can access information related to the journal paper from which the FPCM(s) has (have) been selected, along with information about the classification carried out in this survey (i.e., the identified Theme, Application area, Year of publication...). End-users have also the possibility to (i) download one or a group of FPCMs (.mat), including the related BibTeX metadata, and (ii) access the official journal paper webpage;
- *Filters for FPCMs selection (see ➾):* several filters to enable end-users to display (and potentially download) specific FPCMs according to their preferences (e.g., specific matrix size, paper's theme, year of publication...).
- *Statistics tab (see ✾):* dynamic visual graphs and pie charts to display statistics related to both (i) the whole corpus of papers and associated FPCMs (see "On all data" label in Fig. 10(a)), and (ii) the subset of papers and associated FPCMs resulting from the use of filters (see "On selected data" in Fig. 10(a)).

We believe that this online FAHP testbed can serve as a ready reference for different categories of end-users, such as *(i) researchers/scholars:* to help to identify relevant scientific papers (e.g., looking at a specific theme, application area...) when writing FAHP-related state-of-the art chapters, and (ii) to enable them to download (triangular) FPCMs when carrying out scientific analyses (e.g., for FPCMs' weight derivation method comparison studies); *(ii) reviewers and/or editors:* to help them to identify evaluating the novelty and relevance of future research papers submitted in this field.

Furthermore, we hope that this testbed will act as a dynamic platform where future research papers could be integrated (e.g., on a yearly basis), thereby providing an up-to-date overview of the FAHP state-of-the-art literature. To make this happen, Fig. 10(b) provides a high-level workflow about how end-users (authors of scientific journal papers, journal editors...) can suggest new FAHP articles (and associated FPCMs), or even benchmark studies for being integrated to the testbed[8].

7. Conclusion & research directions

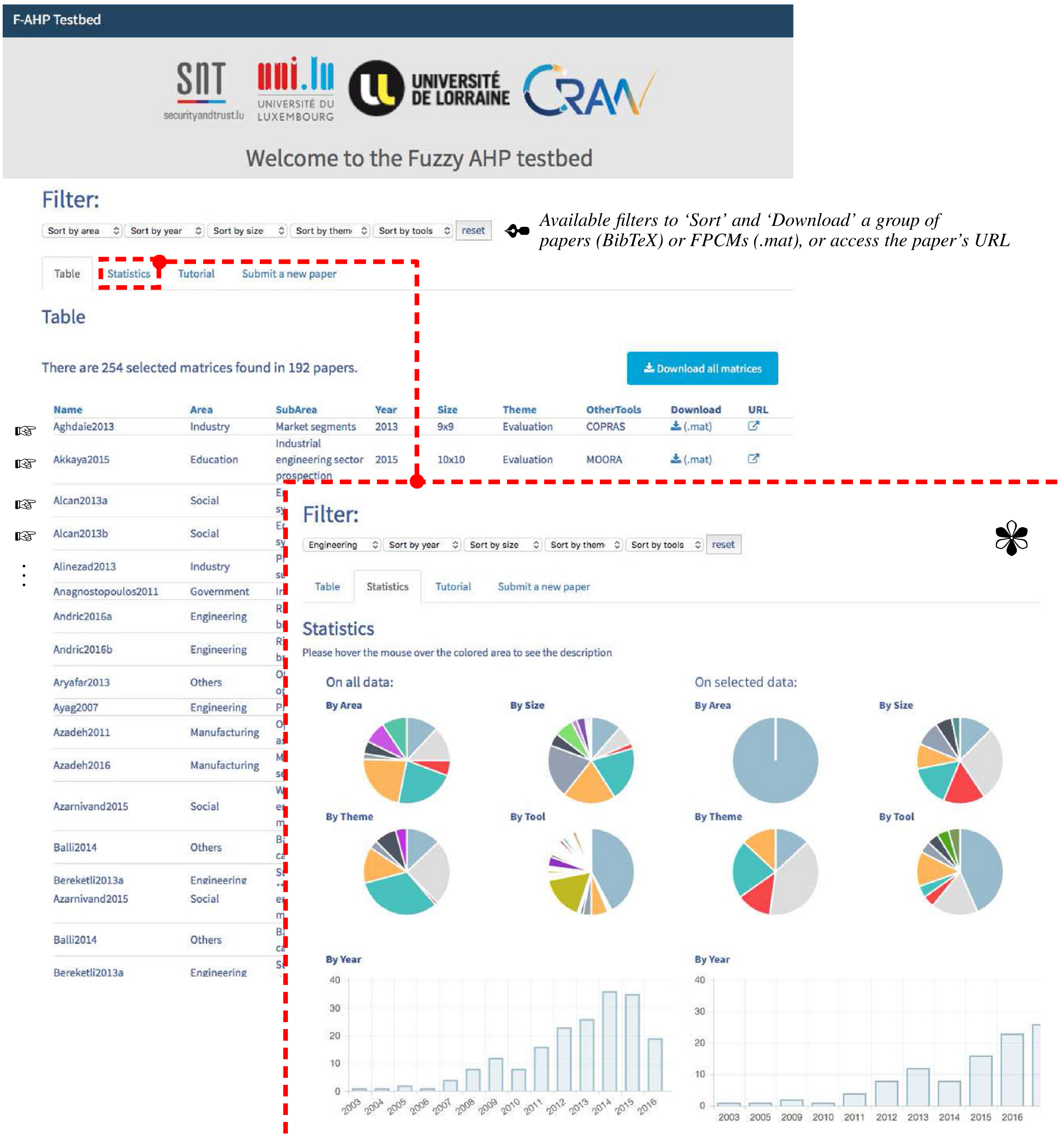
7.1. State-of the-art survey's conclusion

Because human decision-making contains fuzziness and vagueness, FAHP is often applied to tackle MCDM problems. Although a number of criticisms have been levelled against FAHP, or more specifically against scientific methods used to derive weights from fuzzy pairwise comparison matrices (FPCMs), FAHP remains very popular. Its popularity is due to its flexibility to be combined with other techniques (e.g., TOPSIS, QFD, LP...) and its simplicity of implementation. Given the high number of scientific papers applying FAHP, and as of the time of writing there is no state of the art survey of FAHP, we carry out such a literature review in this paper.

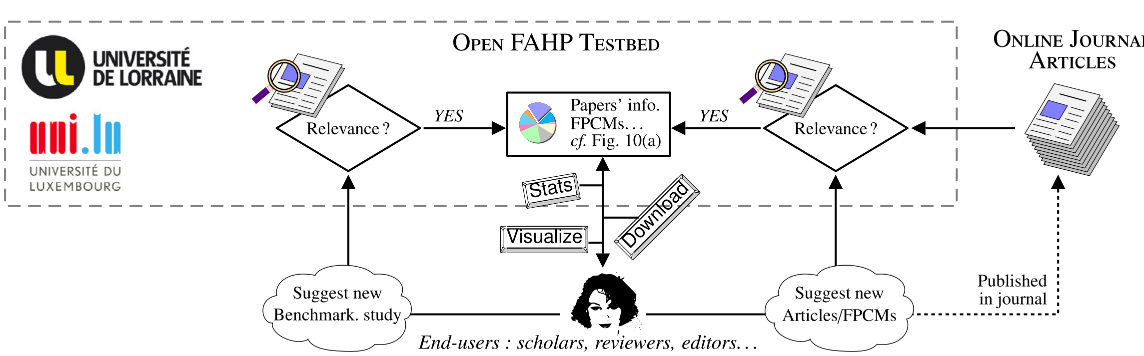
In total, 190 scientific papers published in international journals between 2004 and 2016 are reviewed, classified, and discussed. Classification has been carried out on the basis of the area of application, the identified theme, the year of publication, and so forth. The identified themes and application areas have been chosen based upon the latest state-of-the-art survey of AHP conducted by Vaidya and Kumar (2006). To help readers extract quick and meaningful information, the reviewed papers are summarized in various tabular formats and charts. Unlike previous literature surveys, results and findings are made available through an online testbed (see Fig. 10), which can serve as a ready reference for those who wish to apply, modify or extend FAHP in various applications areas. In terms of results and findings, this survey shows that: (i) FAHP is used primarily in the Manufacturing, Industry and Government sectors; (ii) Asia is the torchbearer in this field, where FAHP is mostly applied in the theme areas of Selection and Evaluation; (iii) a significant amount of research papers (43% of the reviewed literature) combine FAHP with other tools, and particularly with

[7] 10 out of the 190 papers do not introduce any FPCM.

[8] An online form is available on the proposed testbed.



(a) Screenshots of the Open Testbed and associated functionalities



(b) Workflow of the Open Testbed definition and potential extension (e.g. new FAHP papers, FPCMs & Benchmarking studies)

Fig. 10. Online Testbed making available results and findings of the state-of-the-art survey, as well as FPCMs from the reviewed papers.

TOPSIS, QFD and ANP; (iv) the Chang's extent analysis – *the most criticized FPCMs' weight derivation method* – remains very popular, considered in 57% of the reviewed papers.

Our online testbed also integrates one or more FPCMs from all the reviewed papers (a total of 255 matrices), which are available for download. Paper-related BibTeX files are also available for download, and the official journal paper webpage (URLs) is accessible. We believe that this online and free FAHP/FPCMs testbed can serve as a ready reference for different categories of end-users, such as researchers/scholars, reviewers and/or editors, *etc.*, for various reasons previously described.

7.2. Future research directions

All scientific papers reviewed in this survey can help verify that the fuzzy-based AHP approaches can take uncertainty or vague information into consideration in various application areas. Having said that, there is still a room for making improvement, some of the major research issues/directions being summarized as follows:

- For many decision theory specialists, it is not clear that fuzzy sets have ever led to a new decision paradigm. For example, Dubois (2011) argues that, in many cases, fuzzy sets have just been added to existing techniques (fuzzy AHP, fuzzy weighted averages, fuzzy extensions of ELECTRE…) with no clear benefits, especially when fuzzy information is changed (via defuzzification) into precise numbers at the preprocessing level. The difficulty to evaluate such benefits comes along with the difficulty of checking inconsistencies between comparative judgments in FPCMs. Since the transitivity and reciprocal rules cannot be easily and successfully achieved considering FPCMs (not only for arithmetic reasons but for semantic ones also), it will be interesting in future studies to carry out a thorough analysis and comparison of existing FPCMs' weight derivation methods, focusing not only on "efficiency" but also on "easy-to-use" aspects, as it is the primary reason behind Chang's extent analysis success. The online testbed can obviously benefit researchers by giving them the possibility to quickly establish benchmarks (e.g., for FPCMs' weight derivation method comparison) as they can today access (download) more than 255 FPCMs;
- Along with the challenge to properly measure/manage "consistency" in FPCMs, there is also a need for mathematical formulation to verify that FAHP can improve the solution from standard AHP. Saaty (2006) argued that there is no need to incorporate fuzzy logic in AHP as pairwise comparison matrices are "fuzzy" enough. Therefore, mathematical proofs or sensitivity analyses on the merits of using fuzzy logic in AHP are still needed, e.g. to demonstrate that the quality of the solutions obtained from FAHP are good enough in view of the additional computational effort involved;
- Another difficulty of using FAHP (or even AHP) to solve complex decision problems is to identify all associated decision criteria for a hierarchy model. Although a thorough literature review is often carried out in research papers to identify such criteria, one may wonder whether the identified criteria are "relevant" to the decision problem. Some studies propose to combine (F)AHP with pre-structured planning methods such as Delphi (to obtain the most reliable consensus of a group of experts through a series of intensive questionnaires), or SWOT (to identify internal and external factors that are favorable and unfavorable to achieve the goal of the business venture or project), but providing easy-to-use and efficient combination frameworks for solving MCDM problems is definitely a research direction.

Acknowlegement

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Appendix A. Citation-year ratio computation

The column denoted by 'Citation-Year ratio' in Table 10 refers to the minimal, average and maximal citation-year ratios of the n papers (from a given journal) that have been reviewed and integrated to our state-of-the-art survey. Concretely, these ratios are computed based on Eq. A.1, where:

- p_i refers to one paper out of the n reviewed from the corresponding journal;
- $C(\mathrm{p}_i)$ refers to the number of citations of paper p_i (based on Google Scholar);
- $Y(\mathrm{p}_i)$ to the number of years from the publication date of paper p_i to June 2016.

$$\left[\min_{\forall i\in\{1..n\}}\left(\frac{C(\mathrm{p}_i)}{Y(\mathrm{p}_i)}\right);\ \frac{\sum_{i=1}^{n}\left(\frac{C(\mathrm{p}_i)}{Y(\mathrm{p}_i)}\right)}{n};\ \max_{\forall i\in\{1..n\}}\left(\frac{C(\mathrm{p}_i)}{Y(\mathrm{p}_i)}\right)\right] \tag{A.1}$$

In an effort to facilitate the understanding, an example is detailed hereinafter considering the two papers published in *Journal of Environmental Management*, respectively in 2009 and 2013, which have been integrated to this survey. These two papers and related year of publication, as well as the number of citations, are reported in Table A.12 and used as inputs in Eq. A.2 to compute the minimal, average and maximal Citation-Year ratio values.

$$\left[\min\left(\frac{186}{7};\frac{8}{3}\right);\ \frac{\frac{186}{7}+\frac{8}{3}}{2};\ \max\left(\frac{186}{7};\frac{8}{3}\right)\right] \tag{A.2}$$

$[2,67;14.6;26.6]$

Table A.12
Papers from *Journal of Environmental Management* that have been integrated to our state-of the-art survey .

N°	Paper title	Year	Citations
1	Hospital site selection using fuzzy AHP and its derivatives	2009	186
2	A spatial web/agent-based model to support stakeholders' negotiation regarding land development	2013	8

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