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AHPSort: an AHP based method for sorting problems

Alessio Ishizaka[a1], Craig Pearman[a], Philippe Nemery[b]

[a]*University of Portsmouth, Portsmouth Business School, Richmond Building,*

PO1 3ED Portsmouth, United Kingdom

Alessio.Ishizaka@port.ac.uk
craigpearman@hotmail.co.uk

[b]*Smart-Picker, Rue Du Trône 180, 1050 Brussels, Belgium*

pnemery@gmail.com

Abstract: Six problem formulations exist in multi-criteria decision analysis (MCDA): choice, sorting, ranking, description, elimination and design problems. The Analytic Hierachy Process (AHP) is a useful and widespread method for solving choice and ranking problems. However, it is not adapted for sorting problems. Moreover, another practical limitation of AHP is that a high number of alternatives implies a large number of comparisons. This paper presents AHPSort, a new variant of the AHP, used for the sorting of alternatives into predefined ordered categories. Furthermore, AHPSort requires far less comparisons than AHP, which facilitates decision making within large scale problems. In this paper, a real case study for supplier selection is used to illustrate our approach. First, the candidates are sorted with AHPSort within two classes: accepted and rejected suppliers. Then, a single supplier is selected with AHP among the accepted suppliers.

Keywords: AHP, AHPSort, MCDA, sorting, supplier selection, outsourcing

1. Introduction

Multi-criteria decision Analysis (MCDA) is a discipline that helps decision-makers to make decisions when several conflicting criteria need to be evaluated. When facing a decision problem, the first task of a decision-maker is to identify the type of problem. Roy (1981) has described four problem formulations within the MCDA context:

a) Choice problem ($P \cdot \alpha$): The goal is to select a single best action or to reduce the group of actions to a subset of equivalent or incomparable actions.

b) Sorting problem ($P \cdot \beta$): Actions are sorted into ordered predefined categories. These methods are useful for a repetitive and/or automatic use. It can also be used for screening in order to reduce the number of actions to consider.

c) Ranking problem ($P \cdot \gamma$): Actions are ordered in a decreasing preference. The order can be complete or partial if we consider incomparable actions.

[1] corresponding author

d) Description problem (P · δ): The goal is to help the description of actions and their consequences.

Additional problem formulations have also been proposed:

e) Elimination problem: Bana e Costa (1996) has proposed the elimination problem, which is a particular case of the sorting problem where only two classes are defined (accepted and eliminated).

f) Design problem: The goal is to identify or create a new action, which will meet the goals and aspirations of the decision-maker (Keeney 1992).

The Analytic Hierarchy Process (AHP) is one of these MCDA methods (Saaty 1977, Saaty 1980). It has been developed for ranking problems and occasionally for choice problems. Whilst other MCDA methods have evolved in order to be applied in sorting problems (Table 1), there has yet to be an AHP version conceived for sorting problems.

Table 1: MCDA problems and methods

Choice Problems	**Ranking problems**	**Sorting problems**	**Description problems**
PROMETHEE (Brans and Vincke 1985)	PROMETHEE (Brans and Vincke 1985)	FlowSort (Nemery and Lamboray 2008)	GAIA (Brans and Mareschal 1994)
ELECTRE I (Roy 1968)	ELECTRE III (Roy 1978, Roy *et al.* 1986)	ELECTRE-Tri (Yu 1992b, Yu 1992a, Mousseau and Slowinski 2000)	
UTA (Jacquet-Lagreze and Siskos 1982)	UTA (Jacquet-Lagreze and Siskos 1982)	UTADIS (Jacquet-Lagrèze 1995)	
AHP (Saaty 1977, Saaty 1980, Ishizaka and Labib 2011)	AHP (Saaty 1977, Saaty 1980, Ishizaka and Labib 2011)	**AHPSort**	

According to Vetschera et al. (2010), p.1 “sorting is significantly different from ranking or choice and therefore requires the use of specific methods”. If we agree with the first part of this sentence, we believe that ranking methods can be adapted with appropriate modifications to sorting methods rather than requiring complete redevelopment (Guitouni *et al.* 1999, Nemery 2008). Preliminary research on AHPSort, a new variant of AHP for sorting problems, have been briefly presented by the authors in recent conferences (Ishizaka and Pearman 2010, Ishizaka and Pearman 2011). This paper extends these presentations with a full description of the method and an application using a real case study.

The AHP has an impressive record of success, as evidenced in several papers (Zahedi 1986, Golden *et al.* 1989, Shim 1989, Vargas 1990, Saaty and Forman 1992, Forman and Gass 2001, Kumar and Vaidya 2006, Omkarprasad and Sushil 2006, Ho 2008, Liberatore and Nydick 2008, Sipahi and Timor 2010). The core ingredient of the AHP is the pair-wise evaluation of alternatives and criteria, which offers a more precise result than a direct evaluation as within traditional weighted sum (Millet 1997, Saaty 2005, Saaty 2006a, Saaty 2006b, Whitaker 2007). However, the pair-wise technique has the drawback of an increased demand of evaluations from the decision-maker, which limits the practical application of AHP to only problems with a low number of alternatives. This will be corroborated in our literature review.

Several methods have been proposed to tackle this limitation of the AHP method, however each has its own restrictions. Our proposed method, AHPSort, can also be used for screening and sorting but also for ranking as it provides a score for each alternative. One particular advantage of the AHPSort method is that it requires far less pair-wise comparisons, giving the method a more realistic practical application.

AHPSort has been applied in this paper using in a real case study for supplier selection. The objective was to improve the current selection system, whilst also complying with the legal framework already in place.

This paper will first offer a literature review on the ways to reduce the number of pair-wise comparison in AHP. The next section will describe AHPSort and finally the case study validating the method is presented.

2. Literature review

In AHP, comparisons between criteria or alternatives are gathered in comparison matrices. The number of comparisons required to calculate priorities for a matrix of n elements is:

$$\frac{n^2 - n}{2} \qquad (1)$$

As the number of comparisons increases quadratically with the number of alternatives, the practical use of AHP becomes difficult for large problems. Saaty suggests an upper limit of 7±2 alternatives (Saaty and Ozdemir 2003). In order to verify this empirical limit, we looked at supplier selection problems solved by AHP. We selected this application because supplier selection is seen as an extremely important decision for companies (e.g. see recent surveys (Lieb and Bentz 2005, Lieb and Bentz 2006, Lieb and Butner 2007)) and AHP has been one of the methods widely used to support this process (de Boer *et al.* 2001, Aissaoui *et al.* 2007, El-Sawalhi *et al.* 2007). This paper also intends to use the supplier selection problem as the context for our case study.

In the described applications (Table 2), AHP has been seen as a very powerful method because it allows structuring the problem in a hierarchy, it encompasses a consistency check and the decision-maker can focuses on a comparison of only two criteria/alternatives at the time, of which can be tangible or intangible factors. However, the supplier selection exercises solved with AHP have implicated only a small number of alternatives, predominately three. In the case of large number of suppliers, authors

(Muralidharan *et al.* 2002, Liu and Hai 2005) adopt a mixed procedure: pair-wise comparisons for criteria and direct evaluation, on a Likert scale, for suppliers appraisal.

Table 2: Applications of suppliers' selection with the AHP

Number of suppliers	Articles	Nbre articles
not communicated	(Yahya and Kingsman 1999, Barbarosoglu and Yazgac 2000, Udo 2000, Yang and Huang 2000, Cebi and Bayraktar 2003, El-Sawalhi *et al.* 2007)	6
2	(Barbarosoglu and Yazgac 1997, Handfield *et al.* 2002)	2
3	(Narasimhan 1983, Partovi *et al.* 1990, Akarte *et al.* 2001, Tam and Tummala 2001, Bhutta and Huq 2002, Handfield *et al.* 2002, Mikhailov 2002, Kahraman *et al.* 2003, Chan and Chan 2004, Wang *et al.* 2004, Bayazit *et al.* 2006, Yang and Chen 2006, Chan and Kumar 2007, Chen and Huang 2007, Levary 2007, Ounnar *et al.* 2007, Pearson *et al.* 2007, Sevkli *et al.* 2007, Chan *et al.* 2008, Levary 2008, Sevkli *et al.* 2008, Chen and Hung 2010, Labib 2011)	20
4	(Nydick and Hill 1992, Ghodsypour and O'Brien 1998, Barbarosoglu and Yazgac 2000, Chan 2003, Liu and Hai 2005, Xia and Wu 2007, Enyinda *et al.* 2010)	6
5	(Barbarosoglu and Yazgac 2000, Chakraborty *et al.* 2005, Wang and Yang 2007, Schoenherr *et al.* 2008, Ting and Cho 2008, Yu and Tsai 2008, Lee 2009, Chamodrakas *et al.* 2010)	5
6	(Hemaida and Schmits 2006, Percin 2006)	1
7	(Barbarosoglu and Yazgac 2000)	1
8	(Kokangul and Susuz 2009)	1
Likert scale	(Muralidharan *et al.* 2002, Liu and Hai 2005)	2

The high number of papers enumerated in Table 2 indicates that the AHP has been successfully applied widely for supplier selection problems but is inappropriate when the number of candidates is high. This is becoming more apparent given the development of the e-tender process.

Some methods have already been developed to reduce the number of necessary pair-wise comparisons:

- To only partially complete the comparison matrix and to deduce the other comparisons by transitivity (Harker 1987a, Harker 1987b). The idea is to halt completion of the matrix, when the derived priorities no longer change, and as such that additional comparisons become superfluous. The main disadvantage of this method however is that this ultimately relies on the initially selected comparisons from which the deductions are made.

- To use clusters and pivots (Shen *et al.* 1992, Ishizaka 2012). Objects are divided into several ordered clusters such that two adjacent clusters have one common object: the pivot. Then, pair-wise comparisons are performed for each cluster and priorities are calculated. Finally, the global priorities are derived by using the pivot to link priorities of each cluster. This method is appropriate for problems with a reasonable number of alternatives. For a large number of alternatives, the number of required comparisons is still high.

- To make comparisons for a node that has a high weight and froze node with a very low weight (Millet and Harker 1990). The intention is to provide pair-wise comparisons of alternatives in regards to criteria that have an overall high impact on the final priorities, due to their overwhelming weight. However, it is not warranted that criteria with low weights have also a low discriminating power. Weights are only one component of the differentiation, indeed they must be multiplied by the performance of the alternatives on this criterion. A high difference of performances can be also highly discriminating even with a low weight of the criterion.

In this section, we have seen that AHP is often used in literature for supplier selection problems but is limited to a low number of alternatives. Some techniques have been proposed to reduce the number of comparisons, but none of them are fully satisfactory. In the next section, we will introduce the AHPSort, a new adaptation of the AHP for sorting. This method can furthermore be used in the ranking context of a large number of alternatives.

3. AHPSort

Sorting methods are used to assign alternatives to predefined groups. The groups are defined in an ordinal way based on decision-maker's preferences. This means that classes are ordered from the most to the least preferred. This is the major difference with classification, where groups are nominal (Zopounidis and Doumpos 2002). This section presents AHPSort, a variant of the AHP for sorting alternatives.

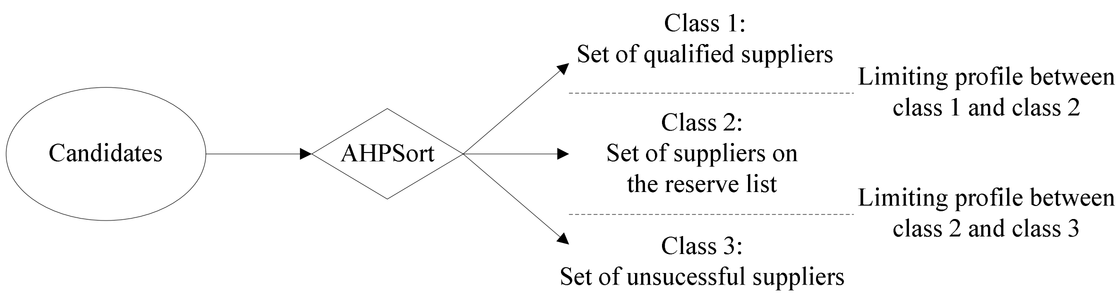

Figure 1: AHPSort for the sorting process

AHPSort is based on eight steps:

A) Problem definition

1) Define the goal, criteria c_j, $j = 1,\ldots, m$ and alternatives a_k k = 1,…, l of the problem.

2) Define the classes $C_i, i=1,\ldots,n$, where n is the number of classes. The classes can be ordered and have a label (e.g. excellent, good, medium, bad)

3) Define the profiles of each class. This can be done with local limiting profiles lp_{ij}, which indicates the minimum performance needed on each criterion j to belong to a class C_i, or with local central profiles cp_{ij}, which is given by a typical example of an element belonging to the class C_i on the criterion j. We need $j \cdot n$-1 limiting profiles or $j \cdot n$ central profiles to define each class.

B) Evaluations

4) Evaluate pair-wise the importance of the criteria c_j and derive their **weight** w_j with the eigenvalue method of the AHP.

$$\mathbf{A} \cdot \mathbf{p} = \lambda \cdot \mathbf{p} \qquad (2)$$

where A is the comparison matrix

p is the priorities/weight vector

λ is the maximal eigenvalue

5) Compare in a pair-wise comparison matrix a single alternative a_k with each limiting profiles lp_{ij} or central profile cp_{ij} for each criterion j.

6) From the comparison matrices, derive the local priority p_{kj} for the alternative a_k and the local priority p_{ij} of the limiting profiles lp_{ij} or central limiting profiles cp_{ij} with the eigenvalue method (2).

C) Assignment to classes

7) Aggregate the weighted local priorities, which provide a global priority p_k for the alternative k (3) and a global priority lp_i for the limiting profile or cp_i for the central profiles (4).

$$p_k = \sum_{j=1}^{m} p_{kj} \cdot w_j \qquad (3)$$

$$lp_i \text{ or } cp_i = \sum_{j=1}^{m} p_{ij} \cdot w_j \qquad (4)$$

The comparison of p_k with lp_i or cp_i is used to assign the alternative a_k to a class Ci.

a) limiting profiles:

If limiting profiles has been defined, the alternative a_k is assigned to the class C_i which has the lp_i just below the global priority p_k (Figure 2).

$$p_k \geq lp_1 \quad \Rightarrow \quad a_k \in C_1$$

$lp_2 \leq p_k < lp_1 \Rightarrow \quad a_k \in C_2$ (5)

…

$p_k < lp_{n-1} \quad \Rightarrow \quad a_k \in C_n$

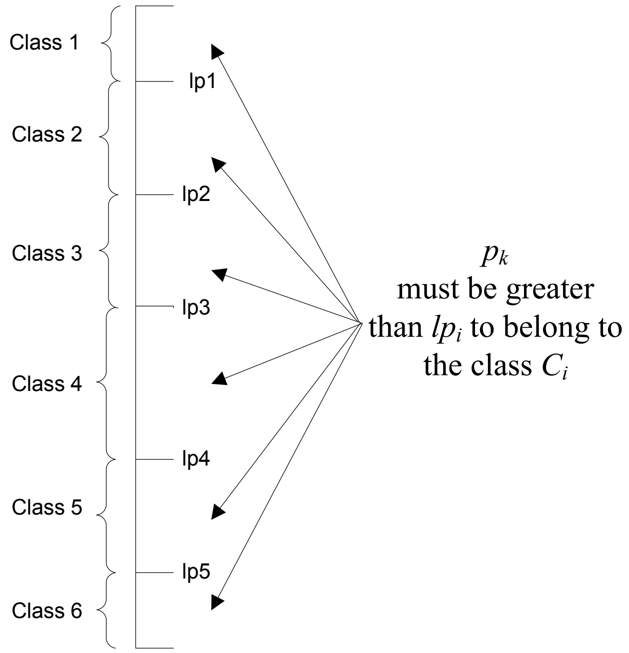

Figure 2: Sorting with limiting profiles

b) Central profiles:

If the decision-maker has difficulties to define a limiting profile, he can define a typical example of a class: the central profiles cp_i. The limiting profiles are deduced by $(cp_i + cp_{i+1})/2$. The alternative a_k is assigned to the class C_i which has the nearest central profile cp_i to p_k (Figure 3). In the case of equal distance between two central profiles, the optimistic assignment vision allocates a_k to the upper class, whilst the pessimistic assignment vision allocates a_k to the lower class.

$p_k \geq cp_1 \quad \Rightarrow a_k \in C_1$

$cp_2 \leq p_k < cp_1$ AND $(cp_1 - p_k) < (cp_2 - p_k) \quad \Rightarrow a_k \in C_1$ (6)

$cp_2 \leq p_k < cp_1$ AND $(cp_1 - p_k) = (cp_2 - p_k) \quad \Rightarrow a_k \in C_1$ in the optimistic vision

$cp_2 \leq p_k < cp_1$ AND $(cp_1 - p_k) = (cp_2 - p_k) \quad \Rightarrow a_k \in C_2$ in the pessimistic vision

$cp_2 \leq p_k < cp_1$ AND $(cp_1 - p_k) > (cp_2 - p_k) \quad \Rightarrow a_k \in C_2$

…

$p_k < cp_n \quad \Rightarrow a_k \in C_n$

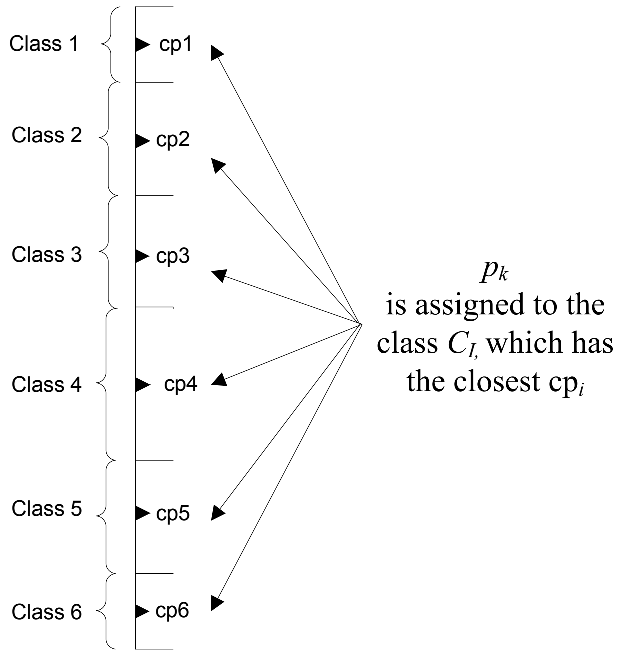

Figure 3: Sorting with central profiles

8) Repeat process 5) to 8) for each alternative to be classified.

4. Case study

In order to investigate the validity of the proposed method, we describe its application in a real case study. The studied organisation operates primarily in the United Kingdom, is state owned and publically funded. The governance and public-funding nature of the organisation means the decisions made, especially in relation to suppliers and expenditures, must be of high visibility and transparency.

4.1. Problem description

The studied organisation is required by Royal Charter to formally report on its activities and performance in relation to income and expenditure. The annual report and accounts publication provides a range of stakeholders, including parliament, governmental bodies, governance organisations, customers, auditors, staff, special interest groups, the industry and the media, with a detailed account of their performance for the preceding financial year.
The organisation itself provides a diverse range of services and is supported by a number of wholly owned subsidiaries, each operating on a full commercial basis and providing services to the organisation, making this type of reporting a complex process. Any report also has to incorporate multiple sign off stages and needs to be flexible enough to accommodate a full Welsh version which can only be produced once the English version is finalised, yet is required to launch at the same time. The choice of a supplier to produce these publications is the specific organisational problem that will be analysed.

The organisation has an obligation to secure and demonstrate value and quality for stakeholders in each subsidiary and in all activities. A key contributor in demonstrating value for money is the ability to form effective and strategic supplier relationships. This involves working alongside suppliers to minimise costs, maximise innovation and to obtain maximum mutual benefits. At the forefront of this consideration is the work of the procurement department, to which the supplier selection decision is of crucial importance.
The process is facilitated by the use of a standardised software package, which is used to collate documents and as a secure area for sending and receiving documents and messages.
The studied organisation therefore requires the services of an independent design supplier to provide all design and print services required in the completion of its Annual Report and Accounts. This is the result of a formal review by the organisation, required under the EU Public Procurement Regulations.

4.2. Description of the whole process

The actual procurement process of the case study organisations has seven stages. We have been required to maintain these stages, whilst improving its effectiveness and transparency.

a) Advertise requirements in European Journal

The case study organisation is required by E.U. legislation to follow an agreed process. The first stage is regulated in order to ensure suppliers are made aware of the tender in a fair and consistent way. This is ensured through the submission of the notice to tender in the Official Journal of the European Union (OJEU), which is an online publication of all tenders from the public sector, updated daily.
The notice to tender details an instruction to all suppliers, including dates, contacts, methods and criteria used for evaluation. It will also include an 'Invitation to tender', which outlines the specification of requirement, the service level agreement and the pricing schedule.

b) Pre-Qualification Stage

This initial selection stage intends to ensure only suppliers that can meet the financial and technical requirements progress to the evaluation stage. Assessment will, among other methods, evaluate past experience and performance in similar contracts. Other factors that are evaluated include equal opportunities in employment, environmental values and commitment, and health and safety operations. Screening criteria are listed and evaluated through a survey sent to candidates. A weighted sum is used to screen out unsuitable suppliers. A threshold of 60% is used but a maximum of eight suppliers may progress to the evaluation stage. This is not something formally communicated, but a practical facet to their process.

c) Invitation to Tender (ITT) Stage

The emphasis on this stage is to ensure all suppliers are evaluated objectively, consistently and without bias. Scenario specific criteria will be communicated and used to evaluate all suppliers. The criteria used intend to ascertain the capability, quality, innovation and creativity competencies of each supplier.

d) Evaluation of ITT Responses

The overall objective of this evaluation stage is to find the most suitable supplier for the tender. Additional methods of criteria assessment include on-site visits and reference gathering. The suppliers are ranked with a weighted sum according to their performance on the criteria.
If only one supplier is first ranked then a direct negotiation will take place rather than an evaluation. If numerous suppliers are deemed to be suitable for selection after a sensitivity analysis, then they will be invited to partake in an e-Auction in addition to the evaluation of the non-price factors. This offers the organisation a transparent process in which the participating suppliers can make competing offers, allowing the organisation to secure the best value for money.

e) E-Auction

The highest scorers of the non-price evaluation are invited in an e-Auction. The live e-Auction is typically scheduled to run 30 minutes. It is considered to be an efficient way to negotiate the price element of the contract. The organisation described this decision as part of the requirement to 'find the most economically advantageous tender'.

f) Contract

At this stage the successful tendering supplier will be informed and a 'standstill period' of ten days will be enforced. This is a contractual period that ultimately allows time for any unforeseen circumstances to be dealt with. After this expires the contract will be awarded and signed by both parties. The Official Journal of the European Union will be informed of the successful supplier and a notice will be published.

g) Debrief of results and feedback

The unsuccessful suppliers will also be notified. Each will receive individualised feedback outlining reasons for rejection and their performance in each criterion and relative to the successful supplier.

Our contributions are on the pre-qualification and the evaluation of ITT responses stages, which are based on multi-criteria bid evaluation models. Our approach will be discussed with the company when the entire process is finished.

4.3. Criteria definition

In bids evaluation, there are three types of criteria:

- *ON/OFF criteria* require that the candidate comply with thresholds of admissibility. Only candidates above all the criteria thresholds proceed to the evaluation process.
- *Screening criteria* have a similar function than ON/OFF criteria but scores can be compensated. The candidate does not need to be above all the criteria thresholds but above a global threshold.
- *Evaluation criteria* are used to rank suppliers.

In our case study, screening and evaluation criteria are used. Screening criteria determine the thresholds of admissibility to proceed to the Evaluation of ITT (section 4.4). They are not used for the final ranking in the evaluation stage because they only ensure a minimal adequacy of the supplier. Evaluation criteria are used for the final ranking (section 4.5), therefore the list of criteria are different in the two stages.

4.4. Pre-qualification stage

The pre-qualification stage is a sorting exercise; therefore we apply AHPSort as described in section 3.

A) Problem definition

1) Define the problem:
In the pre-qualification stage, the company selects all suppliers which fulfil the minimal requirements for the vacancy, in order to progress to the invitation to the tender stage. Twelve companies have responded to the advertisement. Five criteria have been selected by the management of the studied company for the pre-qualification stage:

Experience: The organisation requires an established company for this contract. ‘Established’ is defined as a company that has been operating in the relevant industry for a minimum of three years. All tendering companies should have experience in annual report design and production for large companies or government departments. Report design and production should also form at least 50% of the company’s business activity and operations. Also relevant to this criterion is the requirement that the tendering company is not to have worked on annual report design or publication with a direct competitor. This is to avoid any leakage of information.

Flexibility: The case study organisation requires a flexible supplier. ‘Flexible’ is defined as offering a range of services and to be contactable at any time during the working week. The company will need to present willingness to provide weekend resource for certain key stages of the project.

Security: The tendering organisation will be required to work, with respect to its design operations, from one location. The print operations should also be undertaken at one location, but it need not be the same as the aforementioned ‘design site’. The purpose of this criterion is to ensure project control on quality, timings and physical security considerations.

Resilience: This criterion relates to the suppliers realistic potential to complete the project, without risk or flaw. The organisation will evaluate this through the analysis of the tendering organisations staff turnover and assets, among other considerations. For staff turnover, for example, an upper limit of 5% throughout the company has been initiated.

Environment: This criterion considers any environmental accreditations the tendering organisation may have.

2) Define the classes:
In the pre-qualification stage, the decision is binary: the suppliers are sorted into two categories, accepted or rejected in respect to progression to the tender stage.

3) Define the profile of each class:
The limiting profiles have been defined by the management in **Table 3**.

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Table 3: Limiting profiles

Criteria	Limiting profile
Experience	3 year in the industry 50% of the company's business for report design and production
Flexibility	Contactable at any time during working day
Security	Design and print operations performed at one location
Resilience	5% staff turnover
Environment	1 environmental accreditation

B) Evaluation

4) Criteria weights assessment

The criteria have been compared pairwise in a questionnaire (Figure 4) by the organisations procurement manager with input from other project team members. The evaluations are then entered in the Expert Choice software for calculating the criteria weights

Circle one number per row below using the scale:
1 = Equal 3 = Moderate 5 = Strong 7 = Very strong 9 = Extreme
2, 4, 6, 8 are intermediate values

Experience	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Flexibility
Experience	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	Security
Experience	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Resilience
Experience	9	**8**	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Environment
Flexibility	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	Security
Flexibility	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Resilience
Flexibility	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Environment
Security	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	Resilience
Security	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Environment
Resilience	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Environment

Figure 4: AHP questionnaire for weighting criteria

Table 4: Criterion weighting comparison

Criterion	AHP weighting
Experience	0.565
Flexibility	0.081
Security	0.234
Resilience	0.081
Environment	0.040
Inconsistency Ratio = 0.05	

The main observation to highlight with the AHP judgement of the criteria is the overwhelming value placed on experience.

5) Comparison of alternatives to limiting profile

The sorting of the twelve suppliers was obtained by comparing pair-wise each alternative to the limiting profile in a questionnaire for each criterion (appendix 1). All the candidates are compared to the limiting profile in the same table for each criterion. This is to avoid a deviation of limiting profile in the mind of the decision-maker and ensure that all candidates are compared to the same benchmark.

C) Assignment to classes

The calculation of local priorities (point 6) and its weighted aggregation (point 7) of the AHPSort methodology are done simultaneously in Expert Choice. However, as Expert Choice was not conceived primarily for sorting procedures (Ishizaka and Labib 2009), it requires that all evaluations regarding the same supplier (in appendix 1) are gathered in a separate Expert Choice file. In total, 12 files are created: one for each supplier. For example, Figure 5 displays the data of the file dealing with supplier A.

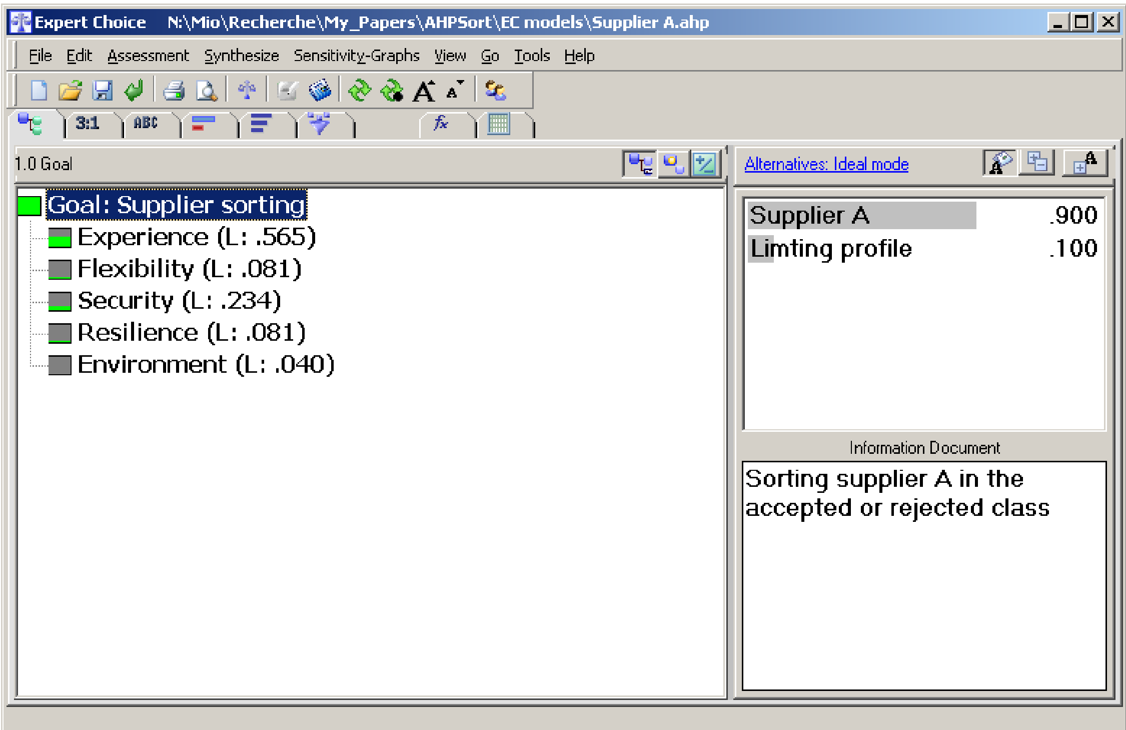

Figure 5: Sorting of supplier A with Expert Choice

Table 5: *Supplier ranking in the qualification stage*

	Experience (0.565)	Flexibility (0.081)	Security (0.234)	Resilience (0.081)	Environment (0.040)	Score limiting profile	Overall priority
Supplier A	0.9	0.9	0.9	0.9	0.9	0.100	.900
Supplier B	0.9	0.9	0.9	0.9	0.9	0.100	.900
Supplier C	0.889	0.9	0.9	0.9	0.9	0.106	.894
Supplier D	0.875	0.9	0.833	0.167	0.9	0.191	.809
Supplier E	0.833	0.875	0.875	0.167	0.833	0.209	.791
Supplier G	0.833	0.750	0.5	0.833	0.833	0.285	.715
Supplier F	0.5	0.143	0.9	0.9	0.9	0.423	.577
Supplier H	0.125	0.9	0.5	0.9	0.9	0.614	.386
Supplier I	0.2	0.125	0.8	0.167	0.167	0.668	.332
Supplier J	0.1	0.125	0.5	0.5	0.5	0.700	.300
Supplier K	0.111	0.1	0.5	0.167	0.167	0.748	.252
Supplier L	0.1	0.1	0.1	0.1	0.1	0.900	.100

The results of the entire pre-qualification stage are presented in Table 5. It is to note that the sum of the priority of the limiting profile and the alternative is always 1. When we have only two classes, the alternative is in the upper class if it has a global priority higher than 0.5. In the Table 5, the shaded suppliers were below the limiting profile score and therefore did not progress in our analysis. In the traditional approach, the company uses a threshold of 60% but with a maximum provision of eight suppliers. This limit is set arbitrarily and is more difficult to justify than the limiting profile of the AHPSort.

4.5. *Evaluation stage*

This stage aims to identify the most suitable supplier, from the seven candidates who progressed from the previous stage.

4.5.1. Criteria weighting

Five evaluation criteria have been selected by the management of the studied company in the invitation to tender stage. These criteria are different from screening criteria. The screening criteria ensure a minimum adequacy of the supplier. They are generally chosen due to ease and speed of assessment. The evaluation criteria are used to rank the alternatives and require a deeper research on the candidates. Therefore, they are used only on the second stage.

Quality: The case study organisation has implemented requirements relevant to quality, which all suppliers must meet. The tendering companies will be evaluated with respect to their skills base. Skills include, but are not limited to, ongoing staff training, company focus, creative thinking, strategic thinking, complex stakeholder management, clear understanding of the challenge, success and risk factors, company culture, and team fit.

Value for Money: This criterion relates to the services offered relative to the price quoted, and is the organisations opportunity to analyse the price of the tender along with other financial implications.

Contract Management: The organisation requires the tendering company to show its ability to manage relationships with suppliers, its handling of sensitive information, print management, contract implementation, methodology for service and contract delivery, quality of methodology and project planning processes, quality of structure of programme to deliver on time and under budget. This criterion is of equal importance to the client service criterion.

Client Service: The tendering company is expected to demonstrate the willingness, ability and resource to work flexibly and to respond to tight deadlines. This criterion will also be judged on perceived team stability, development, presentation skills, responsiveness to challenges set, team participation, the ability to get the best from its people, own and additional supplier working hours and to be contactable.

Environment: This criterion relates to the suppliers demonstration and evidence of physical office security, physical plant security, document storage, process for dealing with online and 'soft' copy information and project resilience. The organisation also requires quality assurance documentation to be provided for inspection.
The weightings obtained from a questionnaire are presented in Table 6.

Table 6: *Criterion weighting*

Criterion	**AHP weighting**
Quality	0.598
Value for money	0.195
Contract management	0.084
Client service	0.084
Environment	0.039
Inconsistency Ratio = 0.04	

As with the pre-qualification round, the decision-maker gives an accentuated weighting importance on the criterion quality. The expertise in this area of evaluation can, and as proved to be the case, secure the supplier of selection. The inconsistency ratio is acceptable because it is below the upper limit prescribed by the methodology.

4.5.2. Ranking of suppliers

Suppliers are evaluated on the criteria listed in Table 6 with the AHP method. All inconsistency ratios are below 0.1 and the scores are given in Table 7.

Table 7: *Supplier ranking*

Supplier	**Position AHP**	**Score AHP**
Supplier C	1	.258
Supplier A	1	.258
Supplier B	3	.148
Supplier E	5	.110
Supplier D	4	.145
Supplier F	6	.065
Supplier G	7	.017

Supplier A and C are the joint preferred overall suppliers and progress to the e-Auction. In our analysis, supplier C is the preferred supplier for both the value for money and client service criterion. Supplier A is the preferred supplier on the quality criterion only, which has the overwhelming weighting. Both suppliers perform equally on the criteria contract management and the environment criteria (Figure 5). The sensitivity analysis provides us with the ability to assess what impact a difference in weighting would have to the overall outcome. As no clear dominance has been detected for non-price criteria, both suppliers have been invited to the e-auction stage. Due to a lower tender cost during the e-Auction session, Supplier A has been selected.

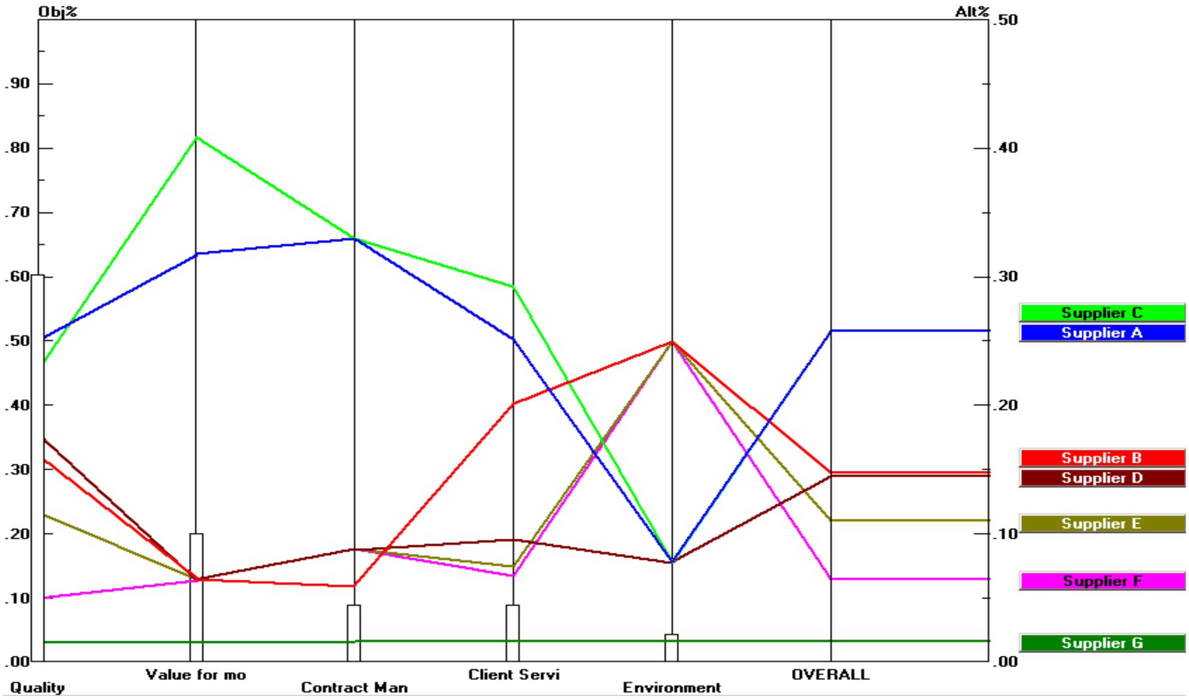

Figure 6: Sensitivity analysis

5. Discussion

This section provides the detailed findings of the analysis undertaken and its recommendations, facilitated by further information obtained through critical professional discussion with the management of the organisation. In particular, we compare our approach with the one used in the past, which is based on a simple weighted sum of direct scores.

AHPSort

Process

The AHPSort can be used to filter out unsuitable suppliers by evaluating them against a limiting profile. This reduces the amount of pair-wise comparisons (judgements) required and thus making the model valuable in a practical context.
When each supplier is judged against each other supplier, many comparisons are required, as is the case with the final selection stage. The basis for an initial qualification stage is to limit the number of comparisons required by rejecting those suppliers that do not reach an expressed benchmark. This has been practically achieved

with the AHPSort. This method requires, for each criterion, only one judgement for each supplier against each limiting profile. The standard method of the AHP would require, using our case study, 66 judgements for each criterion, and thus 66 x 5 = 330 comparisons in total. However using the AHPSort, this has been reduced to just 12 x 5 = 60 comparisons! This difference will only increase as the size of the model and the amount of suppliers increases.

Limiting profile

The use of a defined limiting profile can be of assistance in a 'screening' stage. This method provides a transparent and consistent benchmark which can also be used for providing supplier feedback. In fact, the case study organisation did not communicate, or indeed have, a formal limiting profile in their past supplier selection processes. In order to document the screening stage, a predefined limiting profile was required. In this study a questionnaire was used to ascertain the importance of relevant criteria. This was then documented and presented to the case study organisation, who expressed their desire to implement a defined profile.

The current process allowed for subjectivity and inconsistency, which are expressed requirements in their process.

In the traditional approach, the organisation used a 60% scoring benchmark for progression to the next stage. This was discussed as a minimum level of compliance but is ultimately arbitrary and is therefore not justifiable.

AHP

The AHP is suitable for use in a supplier selection context to facilitate the decision making process. In our case study, one criterion received a weight of over 50%, which normally does not happen in the traditional approach. In a direct weighting, it is against the traditions of the company to give a weight higher than 50% because it is then evident that it becomes a knock-out criterion. In a pair-wise evaluation, weights are indirectly calculated; therefore decision-makers are freer to express their preferences as the corporate psychological effect does not exist.

Sensitivity analysis

Sensitivity analysis can be used to review the decision made and the impact of a change in criteria weighting. The value of sensitivity analysis, whereby users can adjust the weighting of criteria to ascertain its impact on the overall scores, was already recognised by its use in the case study organisation. Indeed they have already implemented sensitivity reporting measures into their software packages, allowing procurement employees to analyse, evaluate and provide feedback to suppliers on their performance.

AHPSort and other sorting methods

There are four main methods for sorting problems (Table 1). FlowSort (Nemery and Lamboray 2008) and ELECTRE-Tri (Yu 1992b, Yu 1992a, Mousseau and Slowinski 2000) belong to the outranking family. They require quantitative evaluation of the alternative performance as regards of each criterion. The decision-maker should also be able to express an indifference and preference threshold (ELECTRE-Tri additionally needs a veto threshold). If the user is able to provide this information, the outranking based sorting methods can be used. They do not require a normalisation, which is a

serious advantage because several normalisation techniques exist and may lead to different results (Ishizaka and Nemery 2011).
UTADIS and AHPSort belong to the full aggregation family. UTADIS (Jacquet-Lagrèze 1995) requires eliciting a utility function for each criterion, which may be difficult. The threshold of the classes is defined a posteriori on the global ranking result. This may be problematic because we do not know how the candidate scores on each criterion. A very weak performance on a criterion can be compensated and totally masked.
AHPSort is based on pairwise comparisons, which are easier to elicit. The threshold of the classes is defined a priori on each criterion, which leads to more precise results and information than UTADIS.

6. Conclusion

Decisions in business are of significant importance and the first essential step is to define the problem. Six problem formulations exist in multi-criteria decision aid. The AHP method has been widely used for ranking and choice problems where the number of actions and criteria is generally small (due to the number of pair-wise comparisons that have to be performed). However, as successful it has been, AHP is unable to provide a realistic and flexible approach to support real-world decision-making problems in situations where sorting is required.

This paper has introduced AHPSort. This new sorting method is based on AHP and therefore keeps its advantages, whilst removing the problem of the high number of comparisons. In order to validate the method, we applied it in a supplier selection exercise as an example of a contemporary decision, which warrants an extensive, transparent and critical process.

In order to tackle this problem, we have developed a two stage model with the AHPSort for sorting adequate suppliers and then the AHP for selecting a supplier. After discussion with the case study organisation in the post-analysis, it was clear that management were impressed with the AHPSort-AHP method. They noticed a significant reduction of time and effort in the decision process due to a structured methodology. The decision makers achieved a consensus quicker, because the hierarchy model provides a common reference, which can facilitate discussion and debate. The decision quality is also enhanced, due to the consistency check and sensitivity analysis embedded in the AHPSort/AHP method. The methodology ensures an equal treatment for all bidders, often an enforced requirement. Finally the decision made is documented, unambiguous and justifiable.
However, even if it has not been apparent in our case, the definition of the limiting profile may be a sensitive step. Its definition must be done carefully because all the sorting process depends on it. If the decision-maker is unsure about its correct level, we would recommend running a sensitivity analysis with several limiting profiles to test the robustness of the process.

In the future, we wish to solve description problems by developing a new variant of AHP in order to unify the problem formulation with a unique AHP method.

References

Aissaoui, N., Haouari, M. & Hassini, E., 2007. Supplier selection and order lot sizing modeling: A review. *Computers & Operations Research,* 34 (12), 3516-3540.

Akarte, M., Surendra, N., Ravi, B. & Rangaraj, N., 2001. Web based casting supplier evaluation using analytical hierarchy process. *Journal of the Operational Research Society,* 52 (5), 511-522.

Bana E Costa, C., 1996. Les problématiques de l'aide à la décision: Vers l'enrichissement de la trilogie choix–tri–rangement. *RAIRO - Operations Research,* 30 (2), 191-216.

Barbarosoglu, G. & Yazgac, T., 2000. A decision support model for customer value assessment and supply quota allocation. *Production Planning & Control: The Management of Operations,* 11 (6), 608 - 616 [Accessed May 06, 2010].

Barbarosoglu, G. & Yazgac, T., 1997. An application of the analytic hierarchy process to the supplier selection problem. *Production and Inventory Management Journal,* 38 (1), 14-21.

Bayazit, O., Karpak, B. & Yagci, A., 2006. A purchasing decision: Selecting a supplier for a construction company. *Journal of Systems Science and Systems Engineering,* 15 (2), 217-231.

Bhutta, K.S. & Huq, F., 2002. Supplier selection problem: A comparison of the total cost of ownership and analytic hierarchy process approaches. *Supply Chain Management: An International Journal,* 7 (3), 126-135.

Brans, J.-P. & Mareschal, B., 1994. The promcalc & gaia decision support system for multicriteria decision aid. *Decision Support Systems,* 12 (4-5), 297-310.

Brans, J.-P. & Vincke, P., 1985. A preference ranking organisation method. *Management science,* 31 (6), 647-656.

Cebi, F. & Bayraktar, D., 2003. An integrated approach for supplier selection. *Logistics Information Management,* 16 (6), 395 - 400.

Chakraborty, P.S., Majumder, G. & Sarkar, B., 2005. Performance evaluation of existing vendors using analytic hierarchy process. *Journal of Scientific & Industrial Research,* 64 (9), 648-652.

Chamodrakas, I., Batis, D. & Martakos, D., 2010. Supplier selection in electronic marketplaces using satisficing and fuzzy ahp. *Expert Systems with Applications,* 37 (1), 490-498.

Chan, F., 2003. Interactive selection model for supplier selection process: An analytical hierarchy process approach. *International Journal of Production Research,* 41 (15), 3549-3579 Available from: http://www.informaworld.com/10.1080/0020754031000138358.

Chan, F. & Kumar, N., 2007. Global supplier development considering risk factors using fuzzy extended ahp-based approach. *Omega,* 35 (4), 417-431.

Chan, F., Kumar, N., Tiwari, M.K., Lau, H.C.W. & Choy, K.L., 2008. Global supplier selection: A fuzzy-ahp approach. *International Journal of Production Research,* 46 (14), 3825-3857.

Chan, S.T.F. & Chan, K.H., 2004. Development of the supplier selection model- a case study in the advanced technology industry. *Proceedings of the Institution of Mechanical Engineers. Part B. Journal of engineering manufacture,* 218 (12), 1807-1824.

Chen, L.-H. & Hung, C.-C., 2010. An integrated fuzzy approach for the selection of outsourcing manufacturing partners in pharmaceutical r&d. *International Journal of Production Research,* 48 (24), 7483-7506.

Chen, Y.M. & Huang, P.-N., 2007. Bi-negotiation integrated ahp in suppliers selection. *International Journal of Operations & Production Management,* 27 (11), 1254 - 1274.

De Boer, L., Labro, E. & Morlacchi, P., 2001. A review of methods supporting supplier selection. *European Journal of Purchasing & Supply Management,* 7 (2), 75-89 Available from: http://www.sciencedirect.com/science/article/B6VGR-42810YV-1/2/ae724c14a63a019179bb5bc1cd42e2a9.

El-Sawalhi, N., Eaton, D. & Rustom, R., 2007. Contractor pre-qualification model: State-of-the-art. *International Journal of Project Management,* 25 (5), 465-474.

Enyinda, C., Emeka, D. & Fesseha, G., Year. An analysis of strategic supplier selection and evaluation in a generic pharmaceutical firm supply chained.^eds. *ASBBS Annual Conference*, Las Vegas: ASBBS, 77-91.

Forman, E. & Gass, S., 2001. The analytic hierarchy process – an exposition. *Operations Research,* 49 (4), 469-486.

Ghodsypour, S. & O'brien, C., 1998. A decision support system for supplier selection using an integrated analytic hierarchy process and linear programming. *International Journal of Production Economics,* 56-57, 199-212.

Golden, B., Wasil, E. & Harker, P., 1989. *The analytic hierarchy process: Applications and studies* Heidelberg: Springer-Verlag.

Guitouni, A., Martel, J. & Vincke, P., 1999. A framework to choose a discrete multicriterion aggregation procedure. *Technical report.*

Handfield, R., Walton, S., Sroufe, R. & Melnyk, S., 2002. Applying environmental criteria to supplier assessment: A study in the application of the analytical hierarchy process. *European Journal of Operational Research,* 141 (1), 70-87 Available from: http://www.sciencedirect.com/science/article/B6VCT-45WYVSK-5/2/cc96e63c46b4546149e320de07e3281b.

Harker, P., 1987. Incomplete pairwise comparisons in the analytic hierarchy process. *Mathematical Modelling,* 9 (11), 837-848.

Hemaida, R. & Schmits, J., 2006. An analytical approach to vendor selection. *Industrial Management,* 48 (3), 18-24.

Ho, W., 2008. Integrated analytic hierarchy process and its applications - a literature review. *European Journal of Operational Research,* 186 (1), 211-228.

Ishizaka, A., 2012. Clusters and pivots for evaluating a large number of alternatives in AHP, Pesquisa Operacional, 32(1), 1-15.

Ishizaka, A. & Labib, A., 2009. Analytic hierarchy process and expert choice: Benefits and limitations. *OR Insight,* 22 (4), 201–220.

Ishizaka, A. & Labib, A., 2011. Review of the main developments in the analytic hierarchy process. *Expert Systems with Applications,* 38 (11), 14336-14345.

Ishizaka, A. & Nemery, P., 2011. Selecting the best statistical distribution with promethee and gaia. *Computers & Industrial Engineering,* 61 (4), 958-969 Available from: http://www.sciencedirect.com/science/article/pii/S0360835211001562.

Ishizaka, A. & Pearman, C., 2010. Ahpsort for selection and evalaution of a large number of suppliers. *In* Mummolo, G. ed. *XV summer School Francesco Turco.* Monopoli, 15-19 September 2009.

Ishizaka, A. & Pearman, C., 2011. Ahpsort for supplier base reduction. *In* Benyoucef, L., Trentesaux, D., Artiba, A. & Rezg, N. eds. *Proceedings of the 4th International Conference on Industrial Engineering and Systems Management.* Metz: I4e2, 799-808.

Jacquet-Lagrèze, E., 1995. An application of the uta discriminant model for the evaluation of r&d projects. *In* Pardalos, P., Siskos, Y. & Zopounidis, C. eds. *Advances in multicriteria analysis.* Dordrecht: Kluwer Academic Publishers, 203-211.

Jacquet-Lagreze, E. & Siskos, J., 1982. Assessing a set of additive utility functions for multicriteria decision-making, the uta method. *European Journal of Operational Research,* 10 (2), 151-164 Available from: http://www.sciencedirect.com/science/article/B6VCT-48NBK56-2X7/2/f63440077037a82b46fb3663e4701e51.

Kahraman, C., Cebeci, U. & Ulukan, Z., 2003. Multi-criteria supplier selection using fuzzy ahp. *Logistics Information Management,* 16 (6), 382-394.

Keeney, R., 1992. *Value-focused thinking: A path to creative decision making* Cambridge: Harward University Press.

Kokangul, A. & Susuz, Z., 2009. Integrated analytical hierarch process and mathematical programming to supplier selection problem with quantity discount. *Applied Mathematical Modelling,* 33 (3), 1417-1429 Available from: http://www.sciencedirect.com/science/article/B6TYC-4RSJF11-2/2/77e1928cba8a63af2bfe28916b710257.

Kumar, S. & Vaidya, O., 2006. Analytic hierarchy process: An overview of applications. *European Journal of Operational Research* 169 (1), 1-29.

Labib, A., 2011. A supplier selection model: A comparison of fuzzy logic and the analytic hierarchy process. *International Journal of Production Research,* 49 (21), 6287-6299.

Lee, A., 2009. A fuzzy supplier selection model with the consideration of benefits, opportunities, costs and risks. *Expert Systems with Applications,* 36 (2, Part 2), 2879-2893 Available from: http://www.sciencedirect.com/science/article/B6V03-4RTM2WB-2/2/5e743791811266fc27b83cb89e201297.

Levary, R., 2007. Ranking foreign suppliers based on supply risk. *Supply Chain Management: An International Journal,* 12 (6), 392 - 394.

Levary, R., 2008. Using the analytic hierarchy process to rank foreign suppliers based on supply risks. *Computers & Industrial Engineering,* 55 (2), 535-542 Available from: http://www.sciencedirect.com/science/article/B6V27-4RP0MGX-4/2/e48651030d3ba87f2856fbf37836e30b.

Liberatore, M. & Nydick, R., 2008. The analytic hierarchy process in medical and health care decision making: A literature review. *European Journal of Operational Research,* 189 (1), 194-207.

Lieb, R. & Bentz, B., 2005. The north amarican third party logistics in 2004: The provider ceo perspective. *International Journal of Physical Distribution & Logistics Management,* 35 (8), 595-611.

Lieb, R. & Bentz, B., 2006. The 3pl industry in asia/pacific. *Supply Chain Management Review,* 10 (9), 10-15.

Lieb, R. & Butner, K., 2007. The north american third-party logistics industry in 2006: The provider ceo perspective. *Transportation Journal,* 46 (3), 40-52.

Liu, F.-H.F. & Hai, H.L., 2005. The voting analytic hierarchy process method for selecting supplier. *International Journal of Production Economics,* 97 (3), 308-317 Available from: http://www.sciencedirect.com/science/article/B6VF8-4F7Y98V-1/2/248d37ddaab8d4e429ae5c7e10317197.

Mikhailov, L., 2002. Fuzzy analytical approach to partnership selection in formation of virtual enterprises. *Omega,* 30 (5), 393-401 Available from: http://www.sciencedirect.com/science/article/B6VC4-475YDWN-K/2/dc9bcb7fa6f5263fb333b2cb14fd2401.

Millet, I., 1997. The effectiveness of alternative preference elicitation methods in the analytic hierarchy process. *Journal of Multi-Criteria Decision Analysis,* 6 (1), 41-51 Available from: http://dx.doi.org/10.1002/(SICI)1099-1360(199701)6:1<41::AID-MCDA122>3.0.CO;2-D.

Millet, I. & Harker, P., 1990. Globally effective questioning in the analytic hierarchy process. *European Journal of Operational Research,* 48 (1), 88-97 Available from: http://www.sciencedirect.com/science/article/B6VCT-48MYJ6R-K2/2/625bc18198ab422d436d594af293dea1.

Mousseau, V. & Slowinski, R., 2000. A user-oriented implementation of the electre-tri method integrating preference elicitation support. *Computers & Operations Research,* 27 (7/8), 757-777 Available from: http://search.ebscohost.com/login.aspx?direct=true&db=buh&AN=3033524&site=ehost-live.

Muralidharan, C., Anantharaman, N. & Deshmukh, S., 2002. A multi-criteria group decisionmaking model for supplier rating. *The Journal of Supply Chain Management,* 38 (4), 22–33.

Narasimhan, R., 1983. An analytic approach to supplier selection. *Journal of Purchasing and Supply Management,* 1, 27–32.

Nemery, P., 2008. *On the use of multicriteria ranking methods in sorting problems*. PhD dissertation. Université Libre de Bruxelles.

Nemery, P. & Lamboray, C., 2008. Flowsort: A flow-based sorting method with limiting or central profiles. *TOP,* 16 (1), 90-113 Available from: http://dx.doi.org/10.1007/s11750-007-0036-x.

Nydick, R.L. & Hill, R.P., 1992. Using the analytical hierarchy process to structure the supplier selection procedure. *International Journal of Purchasing and Materials Management,* 28 (2), 31-36.

Omkarprasad, V. & Sushil, K., 2006. Analytic hierarchy process: An overview of applications. *European Journal of Operational Research,* 169 (1), 1-29.

Ounnar, F., Pujo, P., Mekaouche, L. & Giambiasi, N., 2007. Customer–supplier relationship management in an intelligent supply chain network. *Production Planning & Control: The Management of Operations,* 18 (5), 377 - 387 Available from: http://www.informaworld.com/10.1080/09537280701403736 [Accessed February 07, 2011].

Partovi, F., Burton, J. & Banerjee, A., 1990. Application of analytical hierarchy process in operations management. *International Journal of Operations and Product Management,* 10 (3), 5-19.

Pearson, M., Lawrence, K. & Hickman, T., 2007. Selecting foreign distribution partners with ahp. *Marketing Education Review,* 17 (1), 7-13.

Percin, S., 2006. An application of the integrated ahp-pgp model in supplier selection. *Measuring Business Excellence,* 10 (4), 34 - 49.

Roy, B., 1968. Classement et choix en présence de points de vue multiples (la méthode electre). *Revue Francaise d'Informatique et de Recherche Opérationnelle*, 2(8), 57-75.

Roy, B., 1978. Electre iii: Algorithme de classement base sur une présentation floue des préférences en présence de critères multiples. *Cahiers du CERO,* 20 (1), 3-24.

Roy, B., 1981. The optimisation problem formulation: Criticism and overstepping. *Journal of the Operational Research Society,* 32 (6), 427-436.

Roy, B., Present, M. & Silhol, D., 1986. A programming method for determining which paris metro stations should be renovated. *European Journal of Operational Research,* 24 (2), 318-334 Available from: http://search.ebscohost.com/login.aspx?direct=true&db=buh&AN=7927221&site=ehost-live.

Saaty, T., 1977. A scaling method for priorities in hierarchical structures. *Journal of mathematical psychology,* 15 (3), 234-281.

Saaty, T., 1980. *The analytic hierarchy process* New York: McGraw-Hill.

Saaty, T., 2005. Making and validating complex decisions with the ahp/anp. *Journal of Systems Science and Systems Engineering,* 14 (1), 1-36.

Saaty, T., 2006a. Rank from comparisons and from ratings in the analytic hierarchy/network processes. *European Journal of Operational Research* 168 (2), 557-570.

Saaty, T., 2006b. There is no mathematical validity for using fuzzy number crunching in the analytic hierarchy process. *Journal of Systems Science and Systems Engineering,* 15 (4), 457-464

Saaty, T. & Forman, E., 1992. *The hierarchon: A dictionary of hierarchies* Pittsburgh: RWS Publications.

Saaty, T. & Ozdemir, M., 2003. Why the magic number seven plus or minus two. *Mathematical and Computer Modelling,* 38 (3-4), 233-244 Available from: http://www.sciencedirect.com/science/article/B6V0V-4B82PFC-1P/2/682cf3cdaea8f75fe79c914f2b28cbbb.

Schoenherr, T., Rao Tummala, V.M. & Harrison, T., 2008. Assessing supply chain risks with the analytic hierarchy process: Providing decision support for the offshoring decision by a us manufacturing company. *Journal of Purchasing and Supply Management,* 14 (2), 100-111 Available from: http://www.sciencedirect.com/science/article/B7579-4RY8VY1-1/2/5af507edc4ae78b5d120954ee3fd07c2.

Sevkli, M., Koh, L., Zaim, S., Demirbag, M. & Tatoglu, E., 2007. An application of data envelopment analytic hierarchy process for supplier selection: A case study of beko in turkey. *International Journal of Production Research,* 45 (9), 1973-2003.

Sevkli, M., Koh, L., Zaim, S., Demirbag, M. & Tatoglu, E., 2008. Hybrid analytical hierarchy process model for supplier selection *Industrial Management & Data Systems,* 108 (1), 122-142.

Shen, Y., Hoerl, A. & Mcconnell, W., 1992. An incomplete design in the analytic hierarchy process. *Mathematical and Computer Modelling,* 16 (5), 121-129 Available from: http://www.sciencedirect.com/science/article/B6V0V-45GVR82-3X/2/b5268d4b8277119dc4942c697f025252.

Shim, J., 1989. Bibliography research on the analytic hierarchy process (ahp). *Socio-Economic Planning Sciences* 23 (3), 161-167.

Sipahi, S. & Timor, M., 2010. The analytic hierarchy process and analytic network process: An overview of applications. *Management Decision,* 48 (5), 775-808.

Tam, M. & Tummala, V., 2001. An application of the ahp in vendor selection of a telecommunications system. *Omega,* 29 (2), 171-182.

Ting, S.-C. & Cho, D., 2008. An integrated approach for supplier selection and purchasing decisions. *Supply Chain Management: An International Journal,* 13 (2), 116 - 127.

Udo, G., 2000. Using analytic hierarchy process to analyze the information technology outsourcing decision. *Industrial Management & Data Systems,* 100 (9), 421 - 429.

Vargas, L., 1990. An overview of the analytic hierarchy process and its applications. *European Journal of Operational Research* 48 (1), 2-8.

Vetschera, R., Chen, Y., Hipel, K. & Marc Kilgour, D., 2010. Robustness and information levels in case-based multiple criteria sorting. *European Journal of Operational Research,* 202 (3), 841-852 Available from: http://www.sciencedirect.com/science/article/B6VCT-4WNGW7K-1/2/4530ee670fb368b09e5c9f92f0a9e3e5.

Wang, G., Huang, S. & Dismukes, J., 2004. Product-driven supply chain selection using integrated multi-criteria decision-making methodology. *International Journal of Production Economics,* 91 (1), 1-15 Available from: http://www.sciencedirect.com/science/article/B6VF8-49H1PK5-2/2/6e5d417af98064bb35c4149c5b852d23.

Wang, J.-J. & Yang, D.-L., 2007. Using a hybrid multi-criteria decision aid method for information systems outsourcing. *Computers & Operations Research,* 34 (12), 3691-3700 Available from: http://www.sciencedirect.com/science/article/B6VC5-4JDVP6W-1/2/4173cb46835b36568195cf835734d077.

Whitaker, R., 2007. Validation examples of the analytic hierarchy process and analytic network process. *Mathematical and Computer Modelling,* 46 (7-8), 840-859.

Xia, W. & Wu, Z., 2007. Supplier selection with multiple criteria in volume discount environments. *Omega,* 35 (5), 494-504.

Yahya, S. & Kingsman, B., 1999. Vendor rating for an entrepreneur development programme: A case study using the analytic hierarchy process method. *Journal of Operational Research Society,* 50 (9), 916-930 Available from: http://dx.doi.org/10.1057/palgrave.jors.2600797.

Yang, C.-C. & Chen, B.-S., 2006. Supplier selection using combined analytical hierarchy process and grey relational analysis. *Journal of Manufacturing Technology Management,* 17 (7), 926-941.

Yang, C. & Huang, J.-B., 2000. A decision model for is outsourcing. *International Journal of Information Management,* 20 (3), 225-239 Available from: http://www.sciencedirect.com/science/article/B6VB4-40CJYMT-6/2/526ce89495d52beca0dcf11c719f8a5a.

Yu, J.-R. & Tsai, C.-C., 2008. A decision framework for supplier rating and purchase allocation: A case in the semiconductor industry. *Computers & Industrial Engineering,* 55 (3), 634-646 Available from: http://www.sciencedirect.com/science/article/B6V27-4RTW3MY-1/2/7f8862ef04c44729d13b1365e2ba0903.

Yu, W., 1992a. *Aide multicritère à la décision dans le cadre de la problématique du tri: Concepts, méthodes et applications*. (PhD thesis) Université Paris-Dauphine.

Yu, W., 1992b. *Electre tri: Aspects methodologiques et manueld'utilisation*.

Zahedi, F., 1986. The analytic hierarchy process: A survey of the method and its applications. *Interface* 16 (4), 96-108.

Zopounidis, C. & Doumpos, M., 2002. Multicriteria classification and sorting methods: A literature review. *European Journal of Operational Research,* 138 (2), 229-246 Available from: http://www.sciencedirect.com/science/article/pii/S0377221701002430.

<u>Appendix 1:</u> Questionnaire for the PQQ stage

<u>Tender for the Provision of its Annual Report and Accounts</u>

Circle one number per row below using the scale:
1 = Equal 3 = Moderate 5 = Strong 7 = Very strong 9 = Extreme
2, 4, 6, 8 are intermediate values

Compare the relative performance of supplier against the **experience** criteria for the PQQ stage

Supplier A	**9**	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier B	**9**	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier C	9	**8**	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier D	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier E	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier F	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Limiting profile
Supplier G	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier H	9	8	7	6	5	4	3	2	1	2	3	4	5	6	**7**	8	9	Limiting profile
Supplier I	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	Limiting profile
Supplier J	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	**9**	Limiting profile
Supplier K	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	**8**	9	Limiting profile
Supplier L	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	**9**	Limiting profile

Compare the relative performance of supplier against the **flexibility** criteria for the PQQ stage

Supplier A	**9**	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier B	**9**	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier C	**9**	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier D	**9**	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier E	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier F	9	8	7	6	5	4	3	2	1	2	3	4	5	**6**	7	8	9	Limiting profile
Supplier G	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier H	**9**	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile

Supplier I	9	8	7	6	5	4	3	2	1	2	3	4	5	6	**7**	8	9	Limiting profile
Supplier J	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	**9**	Limiting profile
Supplier K	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	**9**	Limiting profile
Supplier L	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	**9**	Limiting profile

Compare the relative performance of supplier against the **security** criteria for the PQQ stage

Supplier A	**9**	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier B	**9**	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier C	**9**	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier D	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier E	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier F	**9**	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier G	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Limiting profile
Supplier H	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Limiting profile
Supplier I	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier J	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Limiting profile
Supplier K	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Limiting profile
Supplier L	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	**9**	Limiting profile

Compare the relative performance of supplier against the **resilience** criteria for the PQQ stage

Supplier A	**9**	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier B	**9**	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier C	**9**	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier D	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	Limiting profile
Supplier E	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	Limiting profile
Supplier F	**9**	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier G	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier H	**9**	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier I	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	Limiting profile
Supplier J	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Limiting profile
Supplier K	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	Limiting profile
Supplier L	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	**9**	Limiting profile

Compare the relative performance of supplier against the **environment** criteria for the PQQ stage

Supplier A	**9**	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile

Supplier B	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier C	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier D	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier E	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier F	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier G	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier H	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier I	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier J	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier K	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile
Supplier L	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Limiting profile