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Prioritisation of engineering characteristics in QFD in the case of customer requirements orderings

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Quality Function Deployment is an effective tool to orient the design of a product and related production processes towards the real exigencies of the end-user. Its first phase – the house of quality – is aimed at translating customer requirements (*CR*s) into engineering characteristics (*EC*s) of the product of interest, also determining an *EC*s' prioritisation. All of the techniques proposed for tackling this problem are based on the assumption that the importance of each *CR* is expressed on interval or ratio scales (i.e. cardinal scales). To this end, customer evaluations – naturally expressed on ordinal scales – are artfully turned into numbers. This study introduces a novel technique – denominated as ordinal prioritisation method – that can be applied to prioritise *EC*s. The method addresses the problem of the prioritisation of *EC*s when the importance of *CR*s is given on an ordinal scale. The description of the method is supported by some application examples.

Keywords: Quality Function Deployment; house of quality; data fusion; aggregation; prioritisation; engineering characteristics; customer requirements; independent scoring method, ordinal scale

1. Introduction

Quality Function Deployment (QFD) is a tool that is used to guide the design of a product towards the needs of the end-user (Kogure and Akao 1983). Akao, Nagai, and Maki (1996) defined QFD as a 'method to transform user demands into design quality, to deploy the functions forming quality, and to deploy methods for achieving the design quality into subsystems and component parts and ultimately to specific elements of the manufacturing process'.

Over the years, an extensive literature on the subject has been produced and today QFD is widely recognised as an effective approach to pursue customer satisfaction (Matzler and Hinterhuber 1998; Cristiano, Liker, and White 2001; Franceschini 2001; Chen and Chuang 2008; Mehrjerdi 2010; Nahm, Ishikawa, and Inoue 2013). The implementation of QFD proved to bring significant improvements in the process of product development, including earlier and fewer design modifications, fewer start-up issues, improved cross-functional communications, improved product quality, reduced product development time and cost, etc. (Hauser and Clausings 1996; Cristiano, Liker, and White 2001; Mehrjerdi 2010).

Operatively, a complete QFD is composed of four phases which deploy customer requirements (*CR*s) throughout the planning process. In QFD, each phase's output becomes the input of the next phase. The construction of house of quality (HoQ) is the first phase of QFD. The goal of this phase was to transform *CR*s into engineering characteristics (*EC*s) of the product/service of interest, also determining an *EC*s' prioritisation. However, this conversion requires two controversial assumptions (Franceschini and Rupil 1999; Andronikidis et al. 2009):

- The importance of each *CR* is assumed to be expressed on a cardinal scale (interval or ratio scales), that is in the form of a number. This number is generally obtained by translating customer feelings – normally expressed on ordinal scales – into a numerical scale. This artificial encoding can lead to errors or inconsistencies in the evaluation.
- The prioritisation of *EC*s is traditionally carried out through methods – such as the independent scoring method – that generally require the numerical conversion of the relationship matrix symbols into numbers. This is again an artificial promotion of an information given on an ordinal scale into a cardinal one.

Alternatively, other less diffused approaches can be used for the prioritisation of *EC*s: multi-criteria decision aid (MCDA) techniques (Franceschini and Rossetto 1995; Han, Kim, and Choi 2004); Borda's method and equivalent techniques based on pairwise comparison (Dym, Wood, and Scott 2002); techniques based on fuzzy logic (Büyüközkan and Çifçi 2012; Yan, Ma, and Li 2013); hybrid methods using typical approaches deriving from decision-making contexts

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(Chan and Wu 1998; Li, Jin, and Wang 2014; Zaim et al. 2014); etc. With regard to the above-mentioned assumptions, although some of these methods partially avoid the latter, they all suffer the former. For this reason, this study proposes an alternative approach to prioritise *EC*s. The approach proposed is based on the *ordinal prioritisation method* (OPM), a method for the prioritisation of a set of alternatives basing on a set of ordered criteria. This method is a variant of Yager's algorithm (2001), specifically defined for being more 'suitable' for the application to HoQ.

The remainder of this study is organised into six sections. Section 2 briefly presents QFD particularly focusing on HoQ. Some criticalities about the deployment of HoQ are also presented. Section 3 discusses a possible analogy between decision-making processes and *EC*s prioritisation. Section 4 introduces the OPM and Section 5 formalises its application to HoQ. The concluding section highlights the main implications, limitations and original contributions of this work.

2. Quality Function Deployment

2.1 *The four phases of QFD*

Typically, a complete QFD system is composed of four phases which deploy the *CR*s throughout the planning process (see Figure 1). Operatively, the editing of each phase is demanded to a cross-functional team. In the first phase, (*HoQ* or *product planning matrix*), *CR*s are related to *EC*s of the product. Then, *EC*s are associated to critical part characteristics in the second phase (*part deployment matrix*). The *process planning matrix* relates the characteristics of the single subsystem with its respective production process. Finally the *process and quality control matrix* defines inspection and quality control parameters and methods to be used in the production process.

Being the first phase, the HoQ is widely recognised as fundamental and strategic (Franceschini 2001; Tontini 2007; Li et al. 2009; Li, Tang, and Luo 2010). Errors made at this stage can propagate throughout all the subsequent phases of QFD.

2.2 *Eight steps of HoQ*

With reference to its structure (Figure 2), the construction of HoQ can be broadly structured into ten steps:

Step 1: The first step is to define *CR*s for the product/service concerned. Possible approaches for collecting the so called 'voice of the customer' (VoC) include surveys, focus groups, individual interviews, etc. Then, the VoC is generally reorganised into basic *CR*s by means of several techniques (*CR*s tree, affinity diagrams, hierarchical cluster analysis, etc.).

Step 2: *CR*s are prioritised basing on several alternative approaches. The simplest and most widely used methods require the involvement of customers who are asked to translate their preferences on cardinal scales (e.g. by providing judgments on a scoring scales from 1 to 5 or 1 to 10) (Griffin and Hauser 1993; Hauser and Clausings 1996). Notice that judgments are naturally expressed by customer on ordinal scales, their conversion into number represents an artificial promotion into a cardinal scale. Depending on the (arbitrary) choice of the scale, the results of the prioritisation may change significantly (Franceschini and Rupil 1999). An important and widely used alternative to this approach is analytic hierarchy process (Saaty 1988). This method – along with its many variants – has been widely used to measure the relative degree of importance of each customer need. A representative sample of customers is required to compare each pair of *CR*s. However, since customers are asked for a large number of comparisons – even for relatively simple cases – these approaches take the risk of becoming tedious, leading the customer to inconsistent judgments (Nahm, Ishikawa, and Inoue 2013).

Many other methods, which partially improve the aforementioned approaches, have been proposed (Saaty 2003; Partovi 2007; Tontini 2007; Lee, Wu, and Tzeng 2008; Nahm, Ishikawa, and Inoue 2013). The common feature of these

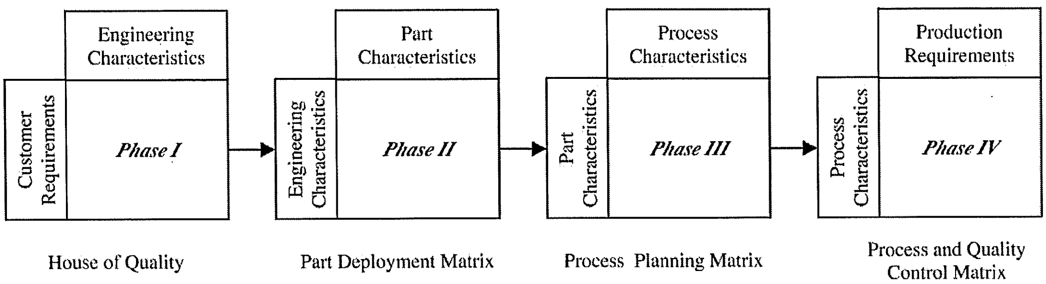

Figure 1. Scheme of the four phases of QFD.
Adapted from (Hauser and Clausings 1996).

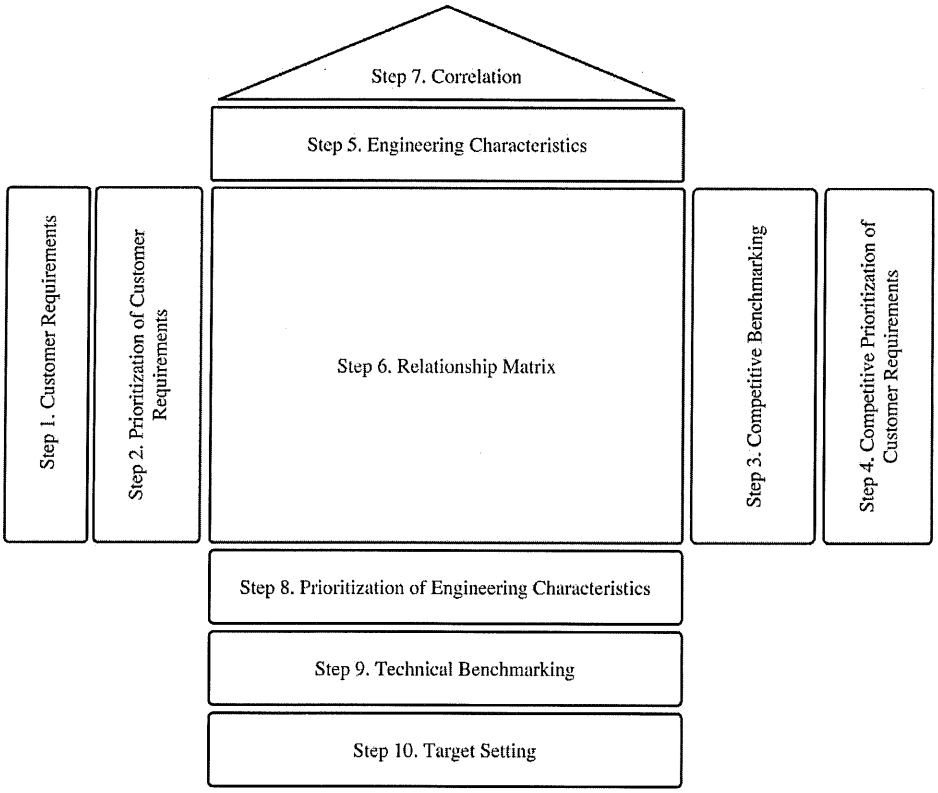

Figure 2. Main steps of house of quality (Nahm, Ishikawa, and Inoue 2013).

approaches is the translation of customer evaluations into cardinal information, that is, the promotion – without any metrological foundation – of subjective orderings into an artificial rating of *CR*s – generally named as *relative importance.*

Steps 3 and 4: Subsequently (and optionally) the obtained rating is corrected considering the perception of competitors positioning and according to some strategic considerations so as to obtain the so called *relative weight* (Franceschini 2001). Again, the ultimate result is an artificial rating of *CR*s.

Step 5: *EC*s related to *CR*s are identified by the cross-functional team. Proper *EC*s can be generated from current (or competitors') product/service standards or selected by cause–effect analyses (Franceschini 2001).

Step 6: The construction of HoQ requires the definition of a relationship matrix. In this step, the cross-functional team has to indicate how the technical decisions affect the satisfaction of each *CR*. In other words, the team is asked to qualitatively express the relationships between *CR*s and *EC*s. The relationships are expressed on an ordinal scale, typically codified into specific conventional symbols.

Step 7: The analysis of correlation among *EC*s allows to determine which *EC*s are redundant or supporting each other and which ones are in conflict.

Step 8: This step is to prioritise *EC*s. To this purpose, several approaches are possible. The traditional and most used method is the *independent scoring method* (Akao 1988). Basing on the ratings of *CR*s and the relationship matrix, it provides a rating of *ECs*. It requires two operative steps. The first and more controversial step consists in converting the relationship matrix into a cardinal matrix according to an arbitrary convention: the most typical approach is that of expressing the relationships between *CR*s and *EC*s on four levels – that is strong, medium, weak and absent relationships – and then encode them into four numeric values, respectively, 9, 3, 1 and 0. Then, the so called *relative importance* (or the *relative weight*) of each *EC*, that is its rating, is evaluated as a function of the relative importance of *CR*s and the transformed relationship matrix (Akao 1988). The typical model used is:

$$w_j = \sum_{i=1}^{n} d_i r_{ij} \tag{1}$$

where w_j is the relative importance of the j-th *EC*, d_i is the relative importance of the i-th *CR* and r_{ij} is the numerical value corresponding to the relationship between the j-th *EC* and the i-th *CR*.

Alternatively, other less diffused approaches can be used for the prioritisation of *EC*s: (i) MCDA techniques (Franceschini and Rossetto 1995; Han, Kim, and Choi 2004); (ii) Borda's method and equivalent techniques based on pairwise comparison (Dym, Wood, and Scott 2002); (iii) techniques based on fuzzy logic (Büyüközkan and Çifçi 2012; Yan, Ma, and Li 2013); (iv) hybrid methods using typical approaches deriving from decision-making contexts (Chan and Wu 1998; Li, Jin, and Wang 2014; Zaim et al. 2014); etc.

Steps 9 and 10: The technical benchmarking compares the company and its competitors in terms of quality performance regarding each *EC*. Then, for each *EC*, a target value is established according to the results of the benchmarking and the importance of *EC*s. These target values are used as input data for the design of the final product/service.

2.3 *Aim of the paper*

Andronikidis et al. (2009) propose an analysis of QFD highlighting the main criticalities of the traditional approach. In particular, the prioritisation of *CR*s and *EC*s (i.e. Steps 2 and 8) are among the most controversial and discussed steps of HoQ:

(i) With regard to Step 2, a critical point is the assignment of an importance rating to each *CR* so as to define an ordering among *CR*s. To this end, subjective information such as customer feelings is – more or less artfully – converted into numerical weights (relative importance).
(ii) The prioritisation of *EC*s, instead, is traditionally carried out through the independent scoring method. Such approach requires the numerical conversion of the relationship matrix symbols into numbers. This is again a promotion of an ordinal scale into a cardinal one. Depending on the arbitrary choice of the adopted numerical scale, the result may change significantly (Franceschini and Rupil 1999).

This study aims at defining an alternative approach to overcome the above-mentioned issues.

With reference to the prioritisation of *CR*s, the approaches briefly listed in the previous section substantially differ in the way they collect customers' opinion about the importance of CRs. This information can be collected through different type of judgments:

(i) pairwise comparisons between different *CR*s. In this case, a sample of customers is asked to compare each pair of *CR*s, stating which one is more important;
(ii) assessments of *CR*s on cardinal scales. In this framework, the sample of customer has to rate all the *CR*s on an arbitrary numerical scale;
(iii) preference ordering. Each customer has to sort *CR*s in order of importance (eventually including ties or incomparabilities); etc.

Pairwise comparison is an effective approach when dealing with a small number of *CR*s, since the number of *CR*s increases the complexity of data collection.

On the other hand, the assessments of *CR*s on cardinal scales is by its nature more complex: in this case, the customer is asked to translate his feelings in a numerical scale (Franceschini and Rupil 1999). The effort required by this encoding can lead to errors or inconsistencies in the evaluation. Moreover, the choice of the resolution of the rating scale is arbitrary and can lead to different results.

For these reasons, authors believe that the option to ask for an importance order of *CR*s is easier and more 'natural' for customers. Therefore, a legitimate issue is that concerning the problem of *EC*s prioritisation when, instead of a set of ratings, an importance ordering between the *CR*s is available.

In other terms, the purpose of this paper was to answer the question: 'how to define a hierarchy of *EC*s when the importance of *CR*s is given on an ordinal scale?'

In order to answer this question, an analogy between the HoQ problem and a decision-making process is proposed in the following section.

3. Prioritisation of *EC*s as a decision-making process

In general, decision-making can be regarded as the cognitive process driving to the selection of a course of action among several alternatives. In this sense, the prioritisation of *EC*s can be interpreted as a decision-making process in which multiple decision-makers need to define an importance order among a set of possible actions. *CR*s can be considered as the decision-makers and *EC*s as the possible alternatives. For each *CR*, the relationship matrix specifies an importance ordering among *ECs*. In detail, the following general assumptions are considered:

- *CR*s and *EC*s uniquely defined.
- The relationship matrix is also defined by the cross-functional team on an ordinal scale with Q levels $(L_1, L_2, \ldots, L_Q)$.
- A weak ordering between the *CR*s exists, that is an importance order with possible ties is admitted.

In general, the *ECs* prioritisation problem can be stated as the problem of identifying the best fused ordering of *ECs*, considering (i) the importance order among *CR*s and (ii) the set of orderings among *EC*s related to each *CR*.

As an example, consider the schematic HoQ proposed in Table 1. This HoQ has four *CR*s and five *ECs*. In this specific framework, *CR*s are assumed to be ranked as: $CR_1 > CR_2 > CR_3 \sim CR_4$.

*CR*s are related to the *ECs* through the relationship matrix which is encoded on an ordinal scale with $Q = 4$ levels. In detail, strong, medium and weak relationships are the first three levels of the ordinal scale, while the fourth one corresponds to the absence of a relationship.

With reference to CR_1, Table 1 shows that $EC_2 > EC_1 > EC_3 > EC_4 \sim EC_5$. Also, it is known that the relationship between CR_1 and EC_2 is 'strong'; between CR_1 and EC_1 is 'medium' and between CR_1 and EC_3 is 'weak'. Furthermore EC_4 and EC_5 are not related to CR_1. Referring to CR_2, Table 1 indicates that $EC_2 \sim EC_4 > EC_1 \sim EC_3 \sim EC_5$. It is also known that the relationship between CR_2 and both EC_2 and EC_4 is 'strong', while CR_2 is not related to EC_1, EC_3 and EC_5. Similar considerations hold for CR_3 and CR_4. All this is summarised in Table 2.

At this stage, the issues of HoQ are how to obtain the best fused ordering out of the ones presented in Table 2. To this purpose, next section introduces the OPM.

4. Ordinal prioritisation method

The OPM is a variant of Yager's algorithm (2001) specifically defined for being more 'suitable' for the application to HoQ. Since the OPM is derived from a decision-making context, the concept of 'importance ordering' is herein deliberately confused with that of 'preference ordering'.

Assume that there are M decision-makers $(D_1, D_2, \ldots, D_M)$, each of which defines an evaluation of n alternatives $(a, b, c, \ldots)$ on an ordinal scale with Q levels $(L_1, L_2, \ldots, L_Q)$. This evaluation scale is assumed to be shared among decision-makers. Notice that the present discussion is made in general terms, leaving Q as a parameter. However, in HoQ, Q is generally set to a relatively low value, typically $Q = 4$ as for the examples in this study. This choice comes from the necessity to take into account two aspects: (i) Q must be large enough to ensure a sufficient discrimination between different judgments and (ii) small enough as to guarantee the simplicity of evaluation. In fact, the greater the number of levels Q, the greater is the probability that the evaluator may confuse neighbouring levels.

Since each alternative is evaluated by any decision-maker, a preference vector corresponding to each decision-maker can be defined. The preference vector directly stems from the opinion expressed by decision-makers. To this end, the following convention is adopted. For each (j-th) decision-maker, alternatives are ordered in a preference vector of size Q. For simplicity, this vector will be denominated as the decision-maker itself, that is D_j. Alternatives are positioned in the component of the preference vector according to the relevant level of the ordinal scale.

As an example, consider the situation in Table 3 in which six alternatives (a, b, c, d, e and f) are evaluated on a 4 level ordinal scale $(L_1, L_2, \ldots, L_4)$.

The resulting preference vector will conventionally be $[\{a, f\}, \{b, d\}, \text{null}, \{c, e\}]^T$. By adopting this convention, the number of elements of a vector will coincide with the number of levels of the ordinal scale in use.

Table 1. Schematic example of HoQ, relationship matrix.

	EC_1	EC_2	EC_3	EC_4	EC_5
CR_1	○	●	△		
CR_2		●		●	
CR_3		△	●	△	
CR_4			○	○	○

Note: Relationship: ●, strong; ○, medium; △, weak.

Table 2. Importance ordering related to *CR*s.

Relationship	CR_1	CR_2	CR_3	CR_4
Strong	$\{EC_2\}$	$\{EC_2, EC_4\}$	$\{EC_3\}$	Null
Medium	$\{EC_1\}$	Null	Null	$\{EC_4, EC_3, EC_5\}$
Weak	$\{EC_3\}$	Null	$\{EC_2, EC_4\}$	Null
Absent	$\{EC_4, EC_5\}$	$\{EC_1, EC_3, EC_5\}$	$\{EC_1, EC_5\}$	$\{EC_1, EC_2\}$

Table 3. Example of alternatives evaluation.

Alternatives	a	b	c	d	e	f
Evaluation	L_1	L_2	L_4	L_2	L_4	L_1

Notes: Six alternatives are considered: a, b, c, d, e, f.
Each alternative is evaluated on a 4 level ordinal scale ($L_1, L_2, \ldots, L_4$).

Also, it is assumed an ordering over the decision-makers, based on their individual importance. In these ordering, for any two decision-makers D_i and D_j, exactly one of the statements $D_i > D_j$, $D_i \sim D_j$, $D_j > D_i$ is true, where symbols '$>$' and '$\sim$' respectively mean 'preferred to' and 'indifferent to'.

The problem of interest is to combine decision-makers' individual preference orderings into a 'fused' preference ordering according to a specific synthesis logic.

4.1 *Algorithm description*

The description of the OPM can be organised into three phases, as illustrated in Table 4. Each phase is presented in the following sub-sections.

4.1.1 *Phase 1: construction and reorganisation of decision-makers' preference vectors*

For each decision-maker, a preference vector of the alternatives is constructed according to the convention introduced in the previous section.

Preference orderings are then reorganised considering the ordering among the decision-makers: decision-maker(s) with the same importance are aggregated into a single reorganised vector (D_j^*) in which each component contains the alternatives with corresponding level of importance.

As an example, consider the case exemplified in Table 5 where four fictitious decision-makers (D_1–D_4) provide four corresponding orderings of six alternatives (a, b, c, d, e, f) given on an ordinal scale with 7 levels ($L_1 > L_2 > L_3 > L_4 > L_5 > L_6 > L_7$).

Assuming that there is an importance ordering between decision-makers $D_4 > (D_2 \sim D_3) > D_1$, the resulting reorganised vectors can be constructed as exemplified in Table 6.

Vector D_2^* – given by the union of two decision-makers with equal importance (i.e. $D_2 \sim D_3$) – contains two occurrences of each alternative. Since aggregation is performed through a level-by-level union of the alternatives and both D_2 and D_3 have no alternatives with maximum importance, the first level of vector D_2^* does not contain any alternative.

The total number (m) of 'reorganised' vectors will be smaller than or equal to that (M) of the initial vectors (3 against 4 in the example presented).

Table 4. Fundamental phases of the OPM.

Phase 1	Construction and reorganisation of decision-makers' preference vectors
Phase 2	Definition of the reading sequence
Phase 3	Generation of the fused ordering

Table 5. Preference vectors related to the orderings by four fictitious decision-makers (D_1–D_4).

		D_1	D_2	D_3	D_4
Preference vector	L_1	{*c*}	Null	Null	{*a*}
	L_2	{*b*}	{*a*}	{*a*, *f*}	{*b*}
	L_3	{*a*}	{*d*, *e*}	{*b*}	{*c*}
	L_4	Null	{*b*}	{*c*, *d*, *e*}	{*d*, *e*}
	L_5	Null	{*f*}	Null	Null
	L_6	Null	{*c*}	Null	{*f*}
	L_7	{*f*, *d*, *e*}	Null	Null	Null

Notes: Six total alternatives are considered: *a*, *b*, *c*, *d*, *e*, *f*.
The decision-makers' importance ordering is $D_4 > (D_2 \sim D_3) > D_1$.
i is the position of an element, starting from the top.

Table 6. 'Reorganised' vectors related to the orderings by the four decision-makers in Table 5. Vectors (D_j^*) are strictly decreasing in terms of importance. The alternatives in the second vector (D_2^*) are duplicated, since this vector originates from the level-by-level union of the alternatives from two preference vectors (D_2 and D_3).

D_1^* (D_4)	D_2^* ($D_2 \sim D_3$)	D_3^* (D_1)
{*a*}	Null	{*c*}
{*b*}	{*a*, *a*, *f*}	{*b*}
{*c*}	{*b*, *d*, *e*}	{*a*}
{*d*, *e*}	{*b*, *c*, *d*, *e*}	Null
Null	{*f*}	Null
{*f*}	{*c*}	Null
Null	Null	{*f*, *d*, *e*}

4.1.2 *Phase 2: definition of the reading sequence*

The next step is to define the reading sequence of the elements in the reorganised vectors. The reading procedure can be summarised as follows:

(1) Initialise the sequence number to $S = 0$.
(2) Consider the most important vector D_j^*, by setting $j = 1$.
(3) Consider the element with highest scale level and set $i = 1$.
(4) Set $S = S + 1$.
(5) Associate the element of interest with the sequence number *S*.
(6) If $j = m$, go to step 9.
(7) Set $j = j + 1$.
(8) Consider the element with position *i*, related to the *j*-th vector D_j^* and Go To Step 4.
(9) If $i = n$, go to step 12.
(10) Set $i = i + 1$.
(11) Consider $j = 1$ and go to step 4.
(12) End.

In practical terms, the procedure establishes a reading sequence for the reorganised vectors, based on a level-by-level reading of vector elements, moving from vectors of greater importance to those of lesser importance. The logic of the sequence is to read the most preferred alternatives first.

Considering the reorganised vectors in Table 6, the resulting sequence is shown in Table 7. A sequence number (*S*) is associated to each vector element.

4.1.3 *Phase 3: generation of the fused ordering*

The procedure for determining the total fused ordering is as follows:

Table 7. Resulting sequence number (*S*), related to the reorganised vectors in Table 5.

D_1^* (D_4)	D_2^* ($D_2 \sim D_3$)	D_3^* (D_1)
1	2	3
4	5	6
7	8	9
10	11	12
13	14	15
16	17	18
19	20	21

(1) Initialise the gradual ordering.
(2) Initialise the counter of the occurrences, for each (k-th) alternative, to $O_k = 0\ \forall k$.
(3) Initialise $S = 1$.
(4) Initialise the set of residual elements (R) as the set of all the alternative(s).
(5) Consider the element (I) with the sequence number S.
(6) If I is 'null', go to step 14.
(7) Initialise the set of alternatives to be excluded $E = \varnothing$.
(8) For each (k-th) alternative in I, set $O_k = O_k + 1$.
(9) If the k-th alternative is in R and $O_k \geq T_k$, include the alternative of interest in the set of those to be excluded (E).
(10) If $E = \varnothing$, go to step 14.
(11) Include the alternative(s) in E, at the bottom of the gradual ordering. In case of multiple alternatives, consider them as indifferent.
(12) Remove the alternative(s) in E from R, that is $R = R \backslash (R \cap E)$.
(13) If $R = \varnothing$, go to step 15.
(14) Increment $S = S + 1$ and go to step 5.
(15) End.

It may be noticed that the selection of a k-th alternative and its addition to the fused ordering is more 'gradual' than in Yager's original approach, as it is performed when the number of occurrences (O_k) overcomes a predefined threshold (T_k). The choice of the threshold value (T_k) is deliberately left to the user so as to allow a tuning of the method as well as a testing of the robustness of the obtained results.

Table 8 shows the results of the step-by-step application of the algorithm when $T_k = 2$ for all the alternatives. The last column contains the total ordering. Applying the OPM, the total fused preference ordering related to the example in Table 5 is $a > b > c > d \sim e > f$.

Deriving from Yager's algorithm, the OPM has different strengths, discussed by Yager (2001) in detail. Apart from its simplicity and ability to be automated, the fusion technique of preference vectors satisfies some interesting properties, such as:

- *Idempotency.* If all of the preference vectors are the same, the resulting fused preference vector is this one.
- *Monotonicity.* If alternative a is preferred to alternative b in all preference vectors, then this relationship will be respected in the fused ordering.
- *Positive association.*. Assume $D_1^*, \ldots, D_m^*$ are a collection of preference vectors, resulting in a fused preference where alternative a is preferred to alternative b. Let $\hat{D}_1^*, \ldots, \hat{D}_m^*$ be another collection of preference vectors where, if $\hat{D}_i^*$ differs from D_i^*, it only differs in that either a has moved up or b has moved down or both; then in the fused ordering of these new vectors, alternative a will be preferred to alternative b.

5. Examples

5.1 *OPM application example*

With reference to the example introduced in Section 3, the goal of *EC*s prioritisation was to produce the best aggregate ordering out of the multiple orderings related to each *CR*. Thus, the OPM can be suitably applied in this context. The first phase requires the definition of the reorganised vectors (see Table 9).

Table 8. Step-by-step application of the OPM. The first three columns are related to the reading sequence: S is the sequence number, while j denotes the decision-maker selected. The subsequent columns refer to the construction of the total ordering. We remark that an alternative is added to the total ordering only when the number of occurrences is greater than or equal to T_k. Data are related to the example of Tables 5 and 6.

				Occurrences (O_k)							
S	j	Element (I)	E	a	b	c	d	e	f	Residual elements (R)	Gradual ordering
0	–	–	–	–	–	–	–	–	–	$\{a, b, c, d, e, f\}$	–
1	1	$\{a\}$	–	1	0	0	0	0	0	$\{a, b, c, d, e, f\}$	–
2	2	Null	–	1	0	0	0	0	0	$\{a, b, c, d, e, f\}$	–
3	3	$\{c\}$	–	1	0	1	0	0	0	$\{a, b, c, d, e, f\}$	–
4	1	$\{b\}$	–	1	1	1	0	0	0	$\{a, b, c, d, e, f\}$	–
5	2	$\{a, a, f\}$	$\{a\}$	3	1	1	0	0	1	$\{b, c, d, e, f\}$	a
6	3	$\{b\}$	$\{b\}$	3	2	1	0	0	1	$\{c, d, e, f\}$	$a > b$
7	1	$\{c\}$	$\{c\}$	3	2	2	0	0	1	$\{d, e, f\}$	$a > b > c$
8	2	$\{b, d, e\}$	–	3	3	2	1	1	1	$\{d, e, f\}$	$a > b > c$
9	3	$\{a\}$	–	4	3	2	1	1	1	$\{d, e, f\}$	$a > b > c$
10	1	$\{d, e\}$	$\{d, e\}$	4	3	2	2	2	1	$\{f\}$	$a > b > c > d \sim e$
11	2	$\{b, c, d, e\}$	–	4	4	4	3	2	1	$\{f\}$	$a > b > c > d \sim e$
12	3	Null	–	4	4	4	3	2	1	$\{f\}$	$a > b > c > d \sim e$
13	1	Null	–	4	4	4	3	3	1	$\{f\}$	$a > b > c > d \sim e$
14	2	$\{f\}$	$\{f\}$	4	4	4	3	3	2	$\varnothing$	$a > b > c > d \sim e > f$
End	–	–	–	–	–	–	–	–	–	–	–

Then, the step-by-step application of the second and third phase of the OPM produces the results in Table 10. Depending on the choice of the threshold value, different aggregate orderings can be obtained. For instance, if the threshold is equal to 1 ($T_k = 1\ \forall\ k$), the fused preference ordering is $EC_2 > EC_4 > EC_3 > EC_1$. Otherwise, if the threshold is equal to 2 ($T_k = 2\ \forall\ k$), the fused preference ordering is $EC_2 > EC_3 \sim EC_4 > EC_1$.

Varying the threshold allows a sensitivity analysis of the resulting fused ordering. In the original version of the method, Yager proposes to use a drastic value of the threshold ($T_k = 1\ \forall\ k$), while the OPM generalises this constraint delegating the choice to the user. It is worth noting that greater values of T_k assign less significance to the ordering of decision-makers (*CR*s).

5.2 *HoQ application example – pencil*

This first example refers to the design of a pencil. HoQ – adapted from (Wasserman 1993) – relates $N = 4$ *CR*s to $M = 5$ *EC*s. The relationships are expressed on a 4 level ordinal scale, as shown in the legend of Table 11.

Consistently with the original problem, it is assumed that CRs are ordered according to the following preference ordering: $CR_3 > CR_2 > CR_1 \sim CR_4$. Thus, the reorganised vectors are shown in Table 12.

Table 13 shows the results of the step-by-step application of the method.

As a result, the total fused preference function – respectively corresponding to $T_k = 1$ and $T_k = 2$ for all the alternatives – are both coincident to EC3 $\sim EC_5 > EC_4 > EC_2 > EC_1$. Notice that the result obtained is consistent (in this case exactly coincident) with the one obtained in the original example by the use of the independent scoring method (Wasserman 1993).

Table 9. Reorganised vectors deriving from Table 2.

Relation	CR_1	CR_2	$CR_3 \sim CR_4$
Strong	$\{EC_2\}$	$\{EC_2, EC_4\}$	$\{EC_3\}$
Medium	$\{EC_1\}$	Null	$\{EC_4, EC_3, EC_5\}$
Weak	$\{EC_3\}$	Null	$\{EC_2, EC_4\}$
Absent	$\{EC_4, EC_5\}$	$\{EC_1, EC_3, EC_5\}$	$\{EC_1, EC_1, EC_2, EC_5\}$

Table 10. Results of the step-by-step application of the proposed method to the example of Table 2.

Pass	Element (I)	Cumulative occurrences (O_k) EC_1	EC_2	EC_3	EC_4	Gradual ordering ($T_k = 1$)	Gradual ordering ($T_k = 2$)
0	–	0	0	0	0	–	–
1	$\{EC_2\}$	0	1	0	0	EC_2	–
2	$\{EC_2, EC_4\}$	0	2	0	1	$EC_2 > EC_4$	EC_2
3	$\{EC_3\}$	0	2	1	1	$EC_2 > EC_4 > EC_3$	EC_2
4	$\{EC_1\}$	1	2	1	1	$EC_2 > EC_4 > EC_3 > EC_1$	EC_2
5	Null	1	2	1	1	$EC_2 > EC_4 > EC_3 > EC_1$	EC_2
6	$\{EC_4, EC_3\}$	1	2	2	2	$EC_2 > EC_4 > EC_3 > EC_1$	$EC_3 \sim EC_4 > EC_2$
7	$\{EC_3\}$	1	2	3	2	$EC_2 > EC_4 > EC_3 > EC_1$	$EC_3 \sim EC_4 > EC_2$
8	Null	1	2	3	2	$EC_2 > EC_4 > EC_3 > EC_1$	$EC_3 \sim EC_4 > EC_2$
9	$\{EC_2, EC_4\}$	1	3	3	3	$EC_2 > EC_4 > EC_3 > EC_1$	$EC_3 \sim EC_4 > EC_2$
10	$\{EC_4\}$	1	3	3	4	$EC_2 > EC_4 > EC_3 > EC_1$	$EC_3 \sim EC_4 > EC_2$
11	$\{EC_1, EC_3\}$	2	3	4	4	$EC_2 > EC_4 > EC_3 > EC_1$	$EC_1 > EC_3 \sim EC_4 > EC_2$
12	$\{EC_1, EC_1, EC_2\}$	4	4	4	4	$EC_2 > EC_4 > EC_3 > EC_1$	$EC_1 > EC_3 \sim EC_4 > EC_2$

Table 11. House of quality of a pencil.

Customer requirements	Engineering characteristics	Length of the pencil EC_1	Time between sharpening EC_2	Lead dust generated EC_3	Hexagonality EC_4	Minimal erasure residual EC_5
Easy to hold	CR_1	○			●	
Does not smear	CR_2		○	●		●
Point lasts	CR_3	△	○	●		●
Does not roll	CR_4	△			●	

Note: Relation: ●, strong; ○, medium; △, weak.

Table 12. Reorganised vectors for the pencil example (Wasserman 1993).

CR_3	CR_2	$CR_1 \sim CR_4$
$\{EC_3, EC_5\}$	$\{EC_3, EC_5\}$	$\{EC_4, EC_4\}$
$\{EC_2\}$	$\{EC_2\}$	$\{EC_1\}$
$\{EC_1\}$	Null	$\{EC_1\}$
$\{EC_4\}$	$\{EC_1, EC_4\}$	$\{EC_2, EC_2, EC_3, EC_3, EC_5, EC_5\}$

5.3 *HoQ application example – climbing harness*

This application example refers to the design of a climbing harness. HoQ – adapted from (Hunt 2013) – relates $N = 8$ *CRs* to $M = 8$ *ECs*. The relations are expressed on a 4 level ordinal scale (see Table 14).

Consistently with the original problem, it is assumed that *CRs* are ordered according to the following preference ordering: $CR_2 \sim CR_5 \sim CR_7 > CR_4 \sim CR_6 > CR_1 \sim CR_8 > CR_3$. Given this ordering, it is possible to define the reorganised vectors as described in Section 2. The aggregation result is shown in Table 15.

So far, the proposed method can be applied. Table 16 shows the results of the step-by-step application of the method.

Table 13. Steps of the OPM.

Pass	Element (I)	Cumulative occurrences (O_k) EC_1	EC_2	EC_3	EC_4	EC_5	Residual elements (R) ($T_k = 1$)	Gradual ordering ($T_k = 1$)
0	–	0	0	0	0	0	$\{EC_1, EC_2, EC_3, EC_4, EC_5\}$	–
1	$\{EC_3, EC_5\}$	0	0	1	0	1	$\{EC_1, EC_2, EC_4\}$	$EC_3 \sim EC_5$
2	$\{EC_3, EC_5\}$	0	0	2	0	2	$\{EC_1, EC_2, EC_4\}$	$EC_3 \sim EC_5$
3	$\{EC_4, EC_4\}$	0	0	2	2	2	$\{EC_1, EC_2\}$	$EC_3 \sim EC_5 > EC_4$
4	$\{EC_2\}$	0	1	2	2	2	$\{EC_1\}$	$EC_3 \sim EC_5 > EC_4 > EC_2$
5	$\{EC_2\}$	0	2	2	2	2	$\{EC_1\}$	$EC_3 \sim EC_5 > EC_4 > EC_2$
6	$\{EC_1\}$	1	2	2	2	2	–	$EC_3 \sim EC_5 > EC_4 > EC_2 > EC_1$
7	$\{EC_1\}$	2	2	2	2	2	–	$EC_3 \sim EC_5 > EC_4 > EC_2 > EC_1$
8	Null	2	2	2	2	2	–	$EC_3 \sim EC_5 > EC_4 > EC_2 > EC_1$
9	$\{EC_1\}$	3	2	2	2	2	–	$EC_3 \sim EC_5 > EC_4 > EC_2 > EC_1$
10	$\{EC_4\}$	3	2	2	3	2	–	$EC_3 \sim EC_5 > EC_4 > EC_2 > EC_1$
11	$\{EC_1, EC_4\}$	4	2	2	4	2	–	$EC_3 \sim EC_5 > EC_4 > EC_2 > EC_1$
12	$\{EC_2, EC_2, EC_3, EC_3, EC_5, EC_5\}$	4	4	4	4	4	–	$EC_3 \sim EC_5 > EC_4 > EC_2 > EC_1$

Table 14. House of quality for a climbing harness.

Customer requirements		Engineering characteristics	Meets safety standards EC_1	Harness weight EC_2	Webbing strength EC_3	No. of colours EC_4	No. of sizes EC_5	Padding thickness EC_6	No. of buckles EC_7	No. of gear loops EC_8
Usability	Easy to put on	CR_1					○		●	
	Comfortable when hanging	CR_2					○	●	○	
	Fits over different clothes	CR_3					○	○	●	
	Accessible gear loops	CR_4								●
Performance	Does not restrict movement	CR_5		○			○	●	○	
	Lightweight	CR_6		●	○			○	△	△
	Safe	CR_7	●	○	●					
	Attractive	CR_8		△		●		△	△	

Note: Relation: ●, strong; ○, medium; △, weak.

Table 15. Reorganised vectors.

$CR_2 \sim CR_5 \sim CR_7$	$CR_4 \sim CR_6$	$CR_1 \sim CR_8$	CR_3
$\{EC_6, EC_6, EC_1, EC_3\}$	$\{EC_8, EC_2\}$	$\{EC_7, EC_4\}$	$\{EC_7\}$
$\{EC_5, EC_7, EC_2, EC_5, EC_7, EC_2\}$	$\{EC_3, EC_6\}$	$\{EC_5\}$	$\{EC_5, EC_6\}$
Null	$\{EC_7, EC_8\}$	$\{EC_2, EC_6, EC_7\}$	Null
$\{EC_1, EC_2, EC_3, EC_4, EC_8, EC_1, EC_3, EC_4, EC_8, EC_4, EC_5, EC_6, EC_7, EC_8\}$	$\{EC_1, EC_2, EC_3, EC_4, EC_5, EC_6, EC_7, EC_1, EC_4, EC_5\}$	$\{EC_1, EC_2, EC_3, EC_4, EC_6, EC_8, EC_1, EC_3, EC_5, EC_8\}$	$\{EC_1, EC_2, EC_3, EC_4, EC_8\}$

Table 16. Steps of the method.

Pass	Element	Cumulative occurrences								Gradual ordering ($T_k = 1$)
		EC_1	EC_2	EC_3	EC_4	EC_5	EC_6	EC_7	EC_8	
0	–	0	0	0	0	0	0	0	0	–
1	$\{EC_6, EC_6, EC_1, EC_3\}$	1	0	1	0	0	2	0	0	EC_6
2	$\{EC_8, EC_2\}$	1	1	1	0	0	2	0	1	EC_6
3	$\{EC_7, EC_4\}$	1	1	1	1	0	2	1	1	EC_6
4	$\{EC_7\}$	1	1	1	1	0	2	2	1	$EC_6 > EC_7$
5	$\{EC_5, EC_7, EC_2, EC_5, EC_7, EC_2\}$	1	3	1	1	2	2	4	1	$EC_6 > EC_7 > EC_2 \sim EC_5$
6	$\{EC_3, EC_6\}$	1	3	2	1	2	3	4	1	$EC_6 > EC_7 > EC_2 \sim EC_5 > EC_3$
7	$\{EC_5\}$	1	3	2	1	3	3	4	1	$EC_6 > EC_7 > EC_2 \sim EC_5 > EC_3$
8	$\{EC_5, EC_6\}$	1	3	2	1	4	4	4	1	$EC_6 > EC_7 > EC_2 \sim EC_5 > EC_3$
9	Null	1	3	2	1	4	4	4	1	$EC_6 > EC_7 > EC_2 \sim EC_5 > EC_3$
10	$\{EC_7, EC_8\}$	1	3	2	1	4	4	5	2	$EC_6 > EC_7 > EC_2 \sim EC_5 > EC_3 > EC_8$
11	$\{EC_2, EC_6, EC_7\}$	1	4	2	1	4	5	6	2	$EC_6 > EC_7 > EC_2 \sim EC_5 > EC_3 > EC_8$
12	Null	1	4	2	1	4	5	6	2	$EC_6 > EC_7 > EC_2 \sim EC_5 > EC_3 > EC_8$
13	$\{EC_1, EC_2, EC_3, EC_4, EC_8, EC_1, EC_3, EC_4, EC_8, EC_4, EC_5, EC_6, EC_7, EC_8\}$	3	5	4	4	5	6	7	5	$EC_6 > EC_7 > EC_2 \sim EC_5 > EC_3 > EC_8 > EC_1 \sim EC_4$
14	$\{EC_1, EC_2, EC_3, EC_4, EC_5, EC_6, EC_7, EC_1, EC_4, EC_5\}$	5	6	5	6	7	7	8	5	$EC_6 > EC_7 > EC_2 \sim EC_5 > EC_3 > EC_8 > EC_1 \sim EC_4$
15	$\{EC_1, EC_2, EC_3, EC_4, EC_6, EC_8, EC_1, EC_3, EC_5, EC_8\}$	7	7	7	7	8	8	8	7	$EC_6 > EC_7 > EC_2 \sim EC_5 > EC_3 > EC_8 > EC_1 \sim EC_4$
16	$\{EC_1, EC_2, EC_3, EC_4, EC_8\}$	8	8	8	8	8	8	8	8	$EC_6 > EC_7 > EC_2 \sim EC_5 > EC_3 > EC_8 > EC_1 \sim EC_4$

The fused preference function – corresponding to $T_k = 2$ for all the alternatives – is $EC_6 > EC_7 > EC_2 \sim EC_5 > EC_3 > EC_8 > EC_1 \sim EC_4$. Notice that this result is consistent with that obtained in the original example by the use of the independent scoring method (Kogure and Akao 1983), that is $EC_6 > EC_7 > EC_2 > EC_5 > EC_3 > EC_1 > EC_8 > EC_4$. Of course, different threshold values could lead to different results.

6. Conclusions and future developments

The most common approach to prioritise *EC*s in QFD is the independent scoring method (Akao 1988). Although widely adopted, this method requires two questionable assumptions: (i) the definition of ratings in the prioritisation of *CR*s (ii) the conversion of the symbols in the relationship matrix into a corresponding cardinal matrix.

This study proposes the application of an alternative approach deriving from an algorithm initially proposed by Yager (2001). The method addresses the problem of aggregating preference/importance orderings of multiple, ordered decision-makers with respect to a set of possible alternatives. Interpreting the *EC*s prioritisation as a decision-making problem, this study suggests a novel approach to face up this problem in the case of *CR*s evaluated on ordinal scales.

The main aspects of the method are here summed up:

- It can be used to rank *ECs* when the importance of *CR*s is expressed on an ordinal scale.
- Also, it can be used as an alternative to traditional approaches (such as the independent scoring method) when the relative importance or weights are available by simply ordering *CR*s according to their weights.
- It does not require artificial numerical coding of the symbols contained into the relationship matrix.

- It can adapt to relationship matrices expressed on ordinal scales with a number of levels at will (not necessarily the 4 levels of the classic HoQs).
- The method is simple to implement, its simplicity in terms of processing is comparable with that of the independent scoring method.
- It allows to carry out a sensitivity analysis of the total fused ranking modifying the threshold value (T_k).

Summarising, there are three advantages in the application of this new method: (i) it can be applied when *CR*s are simply ranked according to a preference/importance ordering; (ii) it does not require special data manipulations of the information gathered in the QFD process and (iii) it does not require an artificial promotion of the scale properties of the symbols contained in the relationship matrix of HoQ and of the *CR*s importance.

Future development of this research will include the proposed method into a more general framework, with the aim of designing a QFD completely based on information given on ordinal scales.

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