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A qualitative evaluation of mechatronic concepts

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processes, identified in Fig1, are [5]: mission analysis, stakeholders' needs and requirements analysis, definition of system requirements, design of logical and physical architecture. They are supported by three services, namely: system verification, system validation, and system analysis. System analysis is an activity that evaluates one or more system artifacts created during the activities involved in synthesizing possible solutions [5]. System analysis allows ensuring that decisions are based on necessary relevant knowledge and are duly justified and traceable to stakeholders needs. In particular, criteria on which rely both architecture evaluation and value assessments should be derived from functional and non-functional requirements [9].

B. Evaluation approaches for mechatronics

An evaluation is requested each time engineering choices must be made or justified, e.g. choice of major operations and solution concepts, research and resolution of inconsistencies between requirements, choice of logical vs. physical architecture.

Though SE does not promote any evaluation approach or method it is generally assumed that the evaluation process includes the generic activities consisting of: defining the evaluation objectives ("why and what"), preparing the job ("how"), producing results and conducting sensibility analyses ("do and check"), and finally delivering outcomes ("conclude").

How activities' of the evaluation process specify the relevant decision-making model. Such a model takes into account core elements such as evaluation criteria, stakeholders' preferences, the scoring function used to assign desirability levels to system attributes, and the aggregation methods chosen to estimate the DA overall desirability levels used to classify or rank design solutions.

The 'why and what' activity is critical since it orientates the engineering effort that has to be turned towards stakeholders' needs. At this aim, Quality Function Development (QFD) [3] fosters an enhanced consideration of the customer's voice. Four successive 'Houses of Quality' based on matrix formalism are built to cover the product development and production processes.

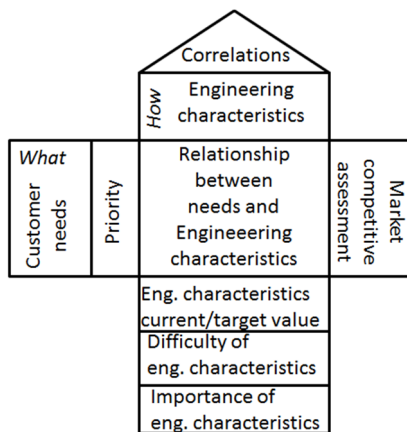


Fig.2. Technical and support processes in SE [3]

The first of them, shown in Fig.2, helps to: structure and prioritize the customers' needs, evaluate competitors strengths and weak, translate the needs into engineering characteristics (technical requirements in SE language), identify the correlations between engineering characteristics, consider how strongly needs are influenced by the design characteristics, estimate the importance and difficulty of the engineering characteristics, estimate the target values for the engineering characteristics. The next house of Quality is built on the same model and aims at finding which parts (element of architecture) characteristics can achieve the engineering characteristics.

QFD helps to define the importance of engineering characteristics but does not consider any customers' preferential interactions. It does not suggest how to take into account the difficulty to achieve engineering characteristics. So, QFD is an interesting support for decision making in the early stage of designing a product but does not provide evaluation or assessment rules or methods.

Among the evaluation methods of solution principles, the Pugh matrix [10] is a type of matrix diagram that allows for the comparison of several DAs at the conceptual stage of design: the columns of the Pugh matrix are labeled with design concepts, one of which acting as a baseline, the rows are labeled with criteria by which the DAs are compared to the baseline. The importance of criteria can be revealed by some ponderation. Each cell in the matrix is marked +, - or S whether a design concept is better than, worse than, or roughly the same as the baseline. After scoring (using for instance a weighted sum operator) the total of + and - gained by each candidate, different decisions can be made, for instance: eliminate certain weak concepts; further development of some concepts; merge some concepts. The Pugh matrix should be run iteratively as part of a convergence process. The method is questionable as the sum of positive or negative qualitative impacts generally does not represent the impact of a DA on the global satisfaction of the stakeholders. Moreover eventual preferential interactions cannot be taken into account and there is no consideration about the difficulty to realize the DAs.

The multiattribute utility theory (MAUT) remains the well-defined framework to assess alternatives described by several attributes. It provides axiomatics for rational decision making under multiple objectives [12]. In the framework of MAUT some works focus on defining most important criteria to improve without actual feasibility considerations [11], which may lead to define unachievable objectives. Reversely, some other works using goal model framework, focus on the capacity to achieve specific goals while not taking into account the commitment to do it [13, 14], which may lead to focus on meaningless goals. Some attempts seem nevertheless to be aware of the necessity to deal with both aspects when improving and designing systems [16, 17].

In [18] we propose to identify the coalition of criteria to be improved first while being the least difficult to satisfy. The priority between criteria coalitions is founded upon an estimation of the expected gain as defined in [11] by 'an index value'. The computation of the capacity to achieve a subset of criteria has been originally proposed in [16]. The method in

[16] consists in merging the qualitative confidence in the impacts (eventually contradictory) of design parameters on each expected performance and in deducing the overall confidence in the impact a DA may have on a set of criteria. However, in [16] only binary choice between improvement and deterioration is proposed, to each of them being associated a degree of belief. In this paper we investigate a qualitative evaluation approach taking into account the stakeholders' preference, several possible levels of satisfaction on criteria and the designers' confidence on the reachability of such satisfaction levels in relation with available means and resources.

III. A QUALITATIVE EVALUATION APPROACH

A. Problem characterization and definitions

In order to design a mechatronic product, the design parameters are the parameters whose values are chosen by the designers. For example, an autonomous robot can be characterized by several design parameters such as: type of rolling base, size of the body, engine type, embedded energy capacity... Each acceptable vector of values of these parameters is a configuration of the robot. Let us denote $N = \{1, 2, \dots, n\}$ the set of criteria that the system has to satisfy and $\gamma_1, \gamma_2, \dots, \gamma_m$ the design parameters of the system. For instance, $\gamma^0 = (\gamma_1^0, \gamma_2^0, \dots, \gamma_m^0)$ is an initial configuration of the system. Let us denote $ap = \{a_1, a_2, \dots, a_m\}$ the set of actions applied on the initial configuration $(\gamma_1^0, \gamma_2^0, \dots, \gamma_m^0)$: a_j corresponds to the action of modifying the value of the j^{th} parameter. Let us assume that to each criterion $i \in N$ and each configuration γ^l is associated its current performance measure p_i^l . The aim of the evaluation approach that we propose here is to synthesize qualitative and uncertain information about each configuration in order to find among a set of configurations the most satisfying ones taking into account the preference of the stakeholders and the feasibility of the configuration.

The synthesizing data processing is composed by two operations: (1) merging information concerning an alternative w.r.t to a criterion; (2) aggregation of the merged information on all the criteria.

The Qualitative Possibility Theory (QPT) offers an interesting representation framework for handling imprecise values pervaded with qualitative uncertainty [21]. Let T be an ordinal scale of levels of satisfaction, $T = \{1, 2, \dots, |T|\}$ where, for example, 1 corresponds to *very bad*..., and $|T|$ corresponds to *very good*. A possibility distribution is a mapping from T to an ordinal scale $T_\pi = \{0, a, b, \dots, 1\}$ where 0 corresponds to impossibility and 1 corresponds to total possibility. Imprecise scores (intervals, including single values) are modeled by a possibility distribution taking the value 1 in the interval and 0 outside. Blanks (absence of answers) are interpreted as a possibility distribution being 1 everywhere (modeling "unknown").

In a qualitative assessment approach, the Sugeno integral is an appropriate operator to aggregate performances related to criteria. Sugeno integrals are based on a capacity that allows taking into account the preferential interactions between

criteria in the aggregated result [19][20]. Let us recall some notations concerning this integral.

Let K be an ordered qualitative scale with 1_K its highest value and 0_K its lowest value. A function $\mu: 2^N \rightarrow K$ is called a fuzzy measure if it satisfies the following conditions:

1. $\mu(\emptyset) = 0_K$
2. $\mu(N) = 1_K$
3. μ is monotonic non decreasing for inclusion, i.e., for any $A, B \subseteq N$ $A \subseteq B \Rightarrow \mu(A) \leq \mu(B)$.

The monotonicity of μ means that the weight of a subset of criteria cannot decrease when new criteria are added to it [21].

Let $k = (k_1, k_2, \dots, k_n) \in K^N$ a vector of values in K . The Sugeno integral of k with respect to μ , denoted $S_\mu(k)$ is given by:

$$S_\mu(k) = \max_{i=1, n} (\min(k_{\sigma(i)}, \mu(A_{\sigma(i)})),$$

where σ is a permutation on N such that $k_{\sigma(1)} \leq k_{\sigma(2)} \leq \dots \leq k_{\sigma(n)}$, with $A_{\sigma(i)} = \{\sigma(i), \sigma(i+1), \dots, \sigma(n)\}$.

B. Steps of the proposed qualitative evaluation

Let us select a configuration γ^0 as a baseline to which all other configurations should be compared (as in the Pugh matrix) by one or a panel of experts. Some expertise is expected to provide, for each action a_j and each criterion i :

- A score, i.e. an estimation of the degree to which an action a_j improves or distracts the i^{th} criterion compared to the baseline. Any score value α_{ij} is chosen in an ordinal scale L comprising discrete values between 0_L and 1_L . The score 0_L is applied in case of satisfaction equivalent to the one of the baseline (0_L : satisfaction is equal to the baseline one). A case of 'no opinion' is mentioned '?'. A score may be imprecise and represented as an interval of values in L .
- The confidence level δ_{ij} which corresponds to the confidence one may have on the impact of action a_j on criterion i . δ_{ij} takes its values in an ordinal scale S (0_S corresponding to not confident at all, level 1_S to very confident). This parameter models the capability of an action to act as expected given the available means and resources in the studied project.

Then, to compute the global score of a configuration tacking into account the confidence of actions, the proposed method relies on the QPT as presented in [22]. The main steps of the method are resumed hereafter.

1) Incertitude modeling

After collecting for each configuration ap , the score α_{ij} and the feasibility δ_{ij} data, the uncertainty attached to each score value on scale L is formalized by a qualitative possibility $\pi: L \rightarrow L_\pi(\{0, a, b, \dots, 1\})$. Firstly, the score α_{ij} is given as an interval. The highest possibility value 1, is attributed to the values of L in the interval given by the experts, the lowest 0 is attributed to the other score in L . Secondly, due to the lack of available quantitative knowledge at the preliminary stage of

the design, a fuzzification transformation is applied to π : it is assumed that adjacent score values to the one chosen by the experts receive non null possibility values. In the case of no opinion (“?”) all the scores values (positive and negative) take the possibility 1. We denote π_{ij} the qualitative possibility distribution for the criterion i when choosing action a_j : it is the fuzzy representation of the score α_{ij} (single or interval) of action a_j relatively to the criterion i . More precisely, since actions may improve or distract performances, two fuzzy representations are distinguished: π_{ij}^+ (resp. π_{ij}^-) when the improving (resp. distracting) action a_j is applied. $\pi_{ij}^*(k)$, where * stands for + or – and k takes its value in L , is then the degree of possibility of the score value k relatively to the criterion i when applying a_j .

2) Merging actions scores on a criterion

To get the global score (deterioration or improvement) of the envisaged configuration (a configuration corresponds to a set of actions a_j that are parameters’ changes relatively to the baseline) with respect to each criterion, we process the fusion of the elementary scores π_{ij}^* , taking into account the level of confidence δ_{ij} in their achievability. π_{ij}^+ and π_{ij}^- are processed in parallel (improving and degrading actions a_j are separately processed). This merging operation may be performed by a disjunctive or conjunctive operator, depending on whether or not, the scores are conflicting. The conflict is yet computed as proposed in [22]:

$$\text{conflict}(i) = \max_{k \in L} (\min_j (\pi_{ij}^*(k)))$$

When $\text{conflict}(i) = 0$ then a disjunctive operator is used else a conjunctive one is preferred. Conjunctive fusion is applied only if there is no conflict in the above sense.

For instance, given a configuration ap and a criterion i , in the case of a disjunctive operator the qualitative possibility distribution π_i^* is computed as follows:

$$\forall k \in L, \pi_i^*(k) = \max_j (\min(\pi_{ij}^*(k), \delta_{ij}))$$

We assume here that $S = L_\pi$.

So any value k of L having high possibility degree and resulting from an action with a high degree of confidence is favored. Moreover, in case of low confidence δ_{ij} or low possibility degree $\pi_{ij}(k)$ then the minimum of the two values has little chance to be the result.

In case of no conflict at all, the qualitative possibility distribution π_i^* should be computed by a conjunctive operator as follows:

$$\forall k \in L, \pi_i^*(k) = \min_j (\max(\pi_{ij}^*(k), \text{inv}(\delta_{ij})))$$

where $\text{inv}(\delta_{ij})$ denotes the value corresponding to the reversal scale of S (e.g., the equivalent of $1 - \delta_{ij}$ in the scale $[0,1]$). π_i^* has finally to be normalized before applying the extension principle in the next aggregation step.

3) Aggregation of scores on several criteria

At the issue of step 2), to each configuration ap and for each criterion i is associated two normalized qualitative

possibility distributions π_i^+ (merging improvement values) and π_i^- (merging deterioration values).

Let $\mu : N \rightarrow L$ be a fuzzy measure defined on the set of criteria N . For $I \subseteq N$, $\mu(I)$ represents the importance of the expected improvement of criteria in I according to the preference of the stakeholders. This fuzzy measure is then used to build the aggregation operator, i.e. the Sugeno integral in our qualitative assessment framework.

The global score of the configuration ap with respect to all the criteria can be computed: the criteria distributions π_i^+ (resp. π_i^-) are merged into two possibility distributions π_{ap}^+ and π_{ap}^- over L using the extension principle of Zadeh:

$$\begin{aligned} \forall k \in L, \pi_{ap}^*(k) \\ = \max_{k = S_\mu^*(k_1, \dots, k_n)} (\min_{k_i \in L} (\pi_1^*(k_1), \pi_2^*(k_2), \dots, \pi_n^*(k_n))) \end{aligned}$$

where the computations of S_μ^+ and S_μ^- are inspired from [23]:

- for the improvement scores (better than those of the baseline), for any k_i in $\{0_L, \dots, 1_L\}$:

$$S_\mu^+(k_1, k_2, \dots, k_N) = \max_{i=1, n} (\min(k_{\sigma(i)}, \mu(A_{\sigma(i)})),$$

where σ is a permutation on N such that $k_{\sigma(1)} \leq k_{\sigma(2)} \leq \dots \leq k_{\sigma(n)}$, with $A_{\sigma(i)} = \{\sigma(i), \sigma(i+1), \dots, \sigma(n)\}$.

- for the deterioration scores (worse than those of the baseline), for any k_i in $\{0_L, \dots, 1_L\}$:

$$S_\mu^-(k_1, k_2, \dots, k_N) = \max_{i=1, n} (\min(k_{\sigma(i)}, \mu(A_{\sigma(i)})),$$

where σ is a permutation on N such that $-k_{\sigma(1)} \leq -k_{\sigma(2)} \leq \dots \leq -k_{\sigma(n)}$, with $A_{\sigma(i)} = \{\sigma(1), \sigma(2), \dots, \sigma(i)\}$.

4) Exploitation of the results

In conclusion, to each configuration are associated two qualitative possibility distributions π_{ap}^+ and π_{ap}^- . π_{ap}^+ expresses the possibility to obtain improvement levels in L w.r.t the baseline and π_{ap}^- expresses the possibility to obtain deterioration levels. The most promising configurations are those with the highest possibility values (the highest feasibility confidence levels) on the highest improvement score values.

The configurations with a possibility of deterioration w.r.t the baseline higher than the possibilities of improvement should be rejected. To this end, the following decision rule is introduced:

If $\max_k \pi_{ap}^-(k) > \max_k \pi_{ap}^+(k)$ then the configuration ap is rejected ($\pi_{ap} = 0$) otherwise the expected possibility of improvement is modeled by $\pi_{ap} = \max_k \pi_{ap}^+(k)$.

Other more sophisticated strategies may be envisaged for the comparison of any two possibility distributions. The interested readers may refer to [24].

Let us now illustrate below the proposed approach on an example.

IV. APPLICATION

A. Presentation of the example

The robotic challenge RobAFIS is organized annually by the French association of Systems Engineering AFIS to

promote Systems Engineering practice in engineers' schools¹. The scope of the challenge is for instance (Robafis_2013) to build an autonomous mobile robot able to compete with other robots and using some provided and imposed materials. Each robot is limited to a 0.3m square cube and has to achieve the following mission as quickly as possible: to grasp and transport some various colored spheres between several stock devices spread over a plan playground. Some dark lines are drawn on the ground to guide the robot between stock devices. The autonomous robot was broken down into four sub-systems: a gripper device, sensors equipment, a rolling base, a control device. The programmable control device type is also imposed to the competitors. The physical alternatives (the possible robot configurations) depend on the design options and on the skills of each competitor. The preference model depends on the strategy followed by each competitor. The solution principles are resumed in Table 1. There are three principles for designing the gripper device, three for the rolling base and two for the sensors equipment.

TABLE 1. SOLUTION PRINCIPLES

Gripper device	Rolling base	Sensors equipment
G1: Fork (taking the sphere from below)	R1: Four wheels rolling base	S1: two color sensors for following the dark lines, one light sensor for recognizing the sphere color
G2: Lateral gripper (pinching laterally the sphere)	R2: Two wheel drive and one third free wheel	S2: one color sensor for following the dark line, one color sensor for recognizing the sphere color
G3: Grapnel (taking over the sphere)	R3: rolling base with tracks	

Four criteria are considered to decide between configurations: the sparsity of used components (Cr1), the robot speed capacity (Cr2), the reliability of the robot (Cr3), and the maintainability of the robot (Cr4).

B. Data of the example

Let us choose configuration (G3, R3, S2) as the baseline configuration. The experts provide the scores of the design parameters on scale $L : 0_L < a < 1_L$ (+ for improvement, -for degradation) and the confidence level of their reachability values on scale $S = 0_S < u < v < w < 1_S$ as given in Tables 2 and 3.

TABLE 2. SCORE VALUES α_{ij}

	Cr1	Cr2	Cr3	Cr4
G1: Fork	+1 _L	-a	-a	+[a,1 _L]
G2: Gripper	+1	0 _L	+a	+a
R1: 4 wheels	+1 _L	-[a 0 _L]	-a	+[a 1 _L]
R2: 3 wheels	+a	+[a 1 _L]	0 _L	+a
S1:2+1	-[a 0 _L]	+[a 1 _L]	+[a 1 _L]	+[0 _L a]

For instance, the experts are very confident in the fact that designers will succeed to build a robot that will move faster than the baseline robot if they choose the 'two wheels and a third free wheel' rolling base. They are not so sure that, with

¹ robafis.fr

such a rolling base they will succeed in achieving a better maintainability than the baseline.

TABLE 3. REACHABILITY VALUES δ_{ij}

	Cr1	Cr2	Cr3	Cr4
G1: Fork	w	1 _S	w	u
G2: Gripper	w	v	v	w
R1: 4 wheels	w	1 _S	v	u
R2: 3 wheels	v	1 _S	v	u
S1:2+1	1 _S	v	v	v

Table 4 provides an example of competitors' preferences between the criteria as a qualitative capacity function defined on the set of all the possible criteria combinations, given the qualitative scale L .

TABLE 4. EXAMPLE OF COMPETITORS' PREFERENCE

{}	0 _L	{C1,C4}	a	{C1,C2,C3,C4}	1 _L	{C2,C3,C4}	1 _L
{C1}	0	{C1,C2,C3}	1 _L	{C2}	0 _L	{C3}	a
{C1,C2}	a	{C1,C2,C4}	1 _L	{C2,C3}	1 _L	{C3,C4}	a
{C1,C3}	a	{C1,C3,C4}	1 _L	{C2,C4}	a	{C4}	0 _L

For instance, according to Table4, it is more important to have a fast and reliable robot than to have a fast and maintainable robot (it is a tactic choice). It is not so important to achieve simultaneously reliability and maintainability to win the competition.

C. Application of the method

Let us consider, for instance, the configuration $ap = (G1, R1, S1)$. Taking into account the expertise, the possibility π_{ij} values associated to the deterioration, equivalence and amelioration cases are ranked from left to right in vectors π_{ij} in Table 5. The possibility 1 is attributed to each score value α_{ij} provided by the experts (Table 2). For instance the possibility 1 at intersection of the S_1 line and Cr_1 column is affected to the score values $-a$ and 0_L .

TABLE 5. POSSIBILITY VALUES FOR $ap=(G1,R1,S1)$

π_{ij}	Cr1		Cr2		Cr3		Cr4	
	-1 _L -a 0 a +1 _L		-1 _L -a 0 a +1 _L		-1 _L -a 0 a +1 _L		-1 _L -a 0 a +1 _L	
	π^-	π^+	π^-	π^+	π^-	π^+	π^-	π^+
G1: Fork	0	0	0	0	0	0	0	1
R1: 4 wheels	0	0	0	0	0	1	0	0
S1:2+1	0	1	0	0	0	0	0	1

After a fuzzification we obtain the possibility values of Table 6. In Table 6 the possibility of scores adjacent to those proposed by the experts is here judged to be rather low (u value on the scale S).

Then, because of conflictual scores, the fusion of score on each i^{th} criterion is computed in Table 7 by:

$$\pi_i = \max_j (\min(\pi_{ij}(k), \delta_{ij}))$$

Before the aggregation, the data have to be normalized as shown in Table 8 (possibility values are translated until the maximum possibility value is 1).

TABLE 6. POSSIBILITY VALUES AFTER FUZZYFICATION

π_j	Cr1	Cr2	Cr3	Cr4
G1	000u1	u1u00	u1u00	00u11
R1	000u1	u11u0	u1u00	00u11
S1	u11u0	00u11	00u11	0u11u

TABLE 7. DATA FUSION FOR EACH CRITERION

π_i	Cr1	Cr2	Cr3	Cr4
(G1,R1,S1)	u11uw	u11vw	uwuvv	0uvvu

TABLE 8. NORMALISATION

π_i	Cr1	Cr2	Cr3	Cr4
(G1,R1,S1)	u11uw	u11vw	v1vww	vw11w

Finally the result of the aggregation is given in table 9 for 4 examples of the 18 configurations.

TABLE 9. FINAL SCORE & FEASIBILITY

π	Score values				
	-1_L	$-a$	0_L	a	1_L
(G1,R1,S1)	u	1	v	w	w
(G3,R3,S3)	0	u	1	u	0
(G2,R1,S2)	u	v	1	w	u
(G2,R2,S1)	u	v	w	1	1

Configuration (G₁, R₁, S₁) should be rejected since its possibility of degradation is higher than the possibility of amelioration. ‘u’ possibility values for the baseline configuration (G₃, R₃, S₃) are due to the ‘fuzzification’. Other two configurations should be retained. Configuration (G₂, R₂, S₁) should be preferred since $(\max_k \pi^+(G_2, R_2, S_1)(k) = 1) > (\max_k \pi^+(G_2, R_1, S_2)(k) = w)$. The validity of the proposed approach is analyzed by verifying that the final result values change accordingly to the changes of the scores values in Table 2 and of reachability values in Table 3. No guarantee can be given upon the real performance of the robot since it depends on the pertinence of the data provided by the experts in Table 2 and 3.

V. CONCLUSION

In this paper is proposed a qualitative method for the evaluation of concepts in the preliminary design stage of complex products such as mechatronics products. The method is based on qualitative possibility and explicitly takes into account the uncertainty of the designers’ knowledge at this design stage. Moreover the method may help the decision makers to select the most satisfying design alternatives considering not only the importance of sets of objectives (described through criteria) but also the confidence of the designers in their reachability. Although an illustration example has been provided, more concrete cases have to be treated for deeper validation of the method. Further research work is engaged firstly to consider aggregation of positive and negative scores and secondly to extend the method in a fuzzy logic framework.

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