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REPRESENTATION OF DESIGN CONCEPTS AND CONCEPT EVALUATION CRITERIA THROUGH DESIGN PARAMETERS AND PERFORMANCE VARIABLES

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1. Introduction

It is widely accepted that *conceptual design* is the most important phase of design process because the decisions made during this phase affect decisively all subsequent phases and determine the quality of the final outcome (product, artifact, system, machine, etc) [Ullman 1992]. Usually, during conceptual design, different *functions* of the designed artifact are located and, for the implementation of each such function, different *concepts* are proposed. In *detailed design*, a phase that follows conceptual design, only one concept – of the multitude of concepts - is further elaborated so that, by the end of this phase, a final detailed and documented artifact description is produced. The choice of the concept that will be further elaborated from the set of all available concepts is a task known as *concept evaluation*.

The majority of the methods and techniques use one or more concept attributes (characteristics) and apply different quantitative and/or qualitative approaches in order to conclude about their values with respect to design specifications. The latter are actually customer requirements that have been transformed to an engineering “syntax” and have been quantified in order to be used – among others - for concept evaluation. For this task, the term “criterion” is often used alternatively. Then it may be concluded that concept evaluation is a process where multiple concepts are subjected to a systematic evaluation process with respect to one or more criteria and, as a result, a single concept is finally chosen in order to be further elaborated in the following design phases. This concept may be either one of the initial concepts or a new synthesis that combines attributes presenting “good” values from a set of initial concepts. For most of the cases, on or more attributes of the chosen concept present optimal values regarding the evaluation criteria.

In the current bibliography there is a multitude of different methods and techniques for concept evaluation in engineering design. Apart from the classical textbooks about design that make references to the subject, there are many published journal articles as well as conference papers that discuss various aspects of the concept evaluation process. Ullman cites several evaluation methods by distinguishing two main categories according to the type of comparison made [Ullman 1992]. The methods in the first category are *absolute* in the sense that every concept is compared with some set of designer-defined requirements while the second category contains *relative* methods which make relative comparisons among the concepts. The first category contains three (3) methods, namely *feasibility judgment*, *technology readiness assessment* and *go/no-go screening* that act as a filter for the fourth relative comparison technique called *decision-matrix method*.

The method of *go/no-go screening* practically performs absolute comparisons between each concept and the set of customer requirements. According to Ullman, the method helps in generating new ideas from the concepts being evaluated by modifying those concepts that present high percentages of “go” scores [Ullman 1992].

The most popular method for concept evaluation and comparison in engineering design is *Pugh’s method*, also known as *decision-matrix method* [Pugh 1991]. It provides scores to the concepts being examined according to the obtained fulfillment of customer requirements and then locates the best alternative according to the highest score obtained. The method is flexible, it can function efficiently in cases when extended collaboration among the members of the design team is needed and its implementation is done by structuring a decision – matrix that is iteratively refined and transformed in order to provide the final scores for the different alternatives.

Morphological analysis may also be considered as an alternative for the decision-matrix method. Generally, the method, first introduced by [Zwicky 1969], structures and investigates the total set of relationships contained in multi-dimensional, non-quantifiable, problem complexes [Ritchey 2008]. Norris studies the application of the method to engineering design [Norris 1963]. One of the recently published works in the field is the paper by Ölvander et al [Ölvander et al. 2008] that present a computerized optimization framework for morphological matrix applied to aircraft conceptual design.

The Analytic Hierarchy Process (AHP) and its generalization, the Analytic Network Process (ANP) were introduced by Saaty [Saaty 1990], [Saaty 2004] and consist of multicriteria decision-making approaches that may be used to reduce the number of conceptual design alternatives. Zavbi and Duhovnik [Zavbi and Duhovnik 2000] perform conceptual design of technical systems using functions and physical laws. Ayag uses (AHP) and integrates it with a simulation generator in order to perform economic analyses for the AHP’s high-score alternatives [Ayag 2005]. Yan et al. develop a bidding-oriented collaborative product conceptualization system that aims to enable cooperation among SMEs [Yan et al. 2006]. The system resolves subjective bid evaluation issues and select preferred product concepts containing ambiguous and qualitative information via (AHP) technique. The same technique may be used when design knowledge is characterized by uncertainty, imprecision and fuzziness. Scott [Scott 2007] offers a means to quantify how differently two alternatives must be ranked by AHP to instill confidence that one is truly better than the other.

Recently, techniques and methods resulted from the latest advances in the area of computational intelligence have been applied in order to solve “hard” problems in the field of engineering design [Saridakis and Dentsoras 2008], [Huang et al. 2006]. In a relevant paper, Wang et al. [Wang 2002] are interested in collaborative conceptual design and they review the literature for relative approaches and applications. From this survey, it becomes evident that there is a necessity for handling different types of uncertainty and vagueness - inherently characterizing the design process - through systematic methods and techniques. Jiao et al. [Jiao et al. 1998] introduce a fuzzy ranking methodology for concept evaluation within the framework of configuration design for mass customization and Wang [Wang 2001] utilizes a fuzzy outranking model to determine the non-dominating design concepts. In the domain of mechatronics, Moulianitis et al. [Moulianitis et al. 2004] have developed an evaluation model on the basis of fuzzy t-norms and averaging operators. This model focuses on evaluating candidate solutions during the conceptual phase of the design of robot grippers. Other soft computing techniques and methods such as Artificial Neural Networks and Genetic Algorithms have been also used either as stand-alone or as hybrid tools in the field of concept evaluation [Saridakis and Dentsoras 2008].

The concept attributes that take part in evaluation process are dictated by the evaluation criteria. Since these criteria are the same for all concepts being evaluated, the attributes should be determinable for every participating concept; otherwise no evaluation could be done. For example, if, for a certain design case, mass should be kept to a minimum (evaluation criterion), then, for all concepts participating in the evaluation process, mass should be determinable in order to be further evaluated regarding its value. Otherwise, if mass is not determinable for a concept, then this concept should be excluded from the process.

A concept attribute is connected to and arises from one or more entities pertaining to the concept. The nature of these entities may be topological (dimensions, assemblies), mechanical (stresses, displacements), informational (information flow), etc. Since the values of these entities may vary within specific domains, they are usually under the general abstract term “design parameter”. One of these parameters or a combination of parameters may reliably represent the aforementioned concept attribute. The term “performance variable” is used frequently in order to represent this attribute and it is the value of this variable that is usually subjected to the evaluation process.

In the present paper, an attempt is made to establish a formal concept representation scheme and to introduce a method for concept comparison and evaluation based on design parameters and performance variables. For each concept and for the chosen abstraction level, typical associative digraphs of design parameters are formed. Then, by adding objective and/or subjective weights for the relationships among these parameters, complete weighted digraphs are produced. From the aforementioned digraphs, simple approximative calculation formulas may be formed than can provide dimensionless values for the design parameters.

Performance variables are common for all concepts and represent simple or composite criteria necessary for concept evaluation. Each performance variable is connected to different design parameters for each concept and/or other performance variables. For each criterion and according to the concept under consideration, formulas of performance variables may be formed for the determination of its dimensionless value.

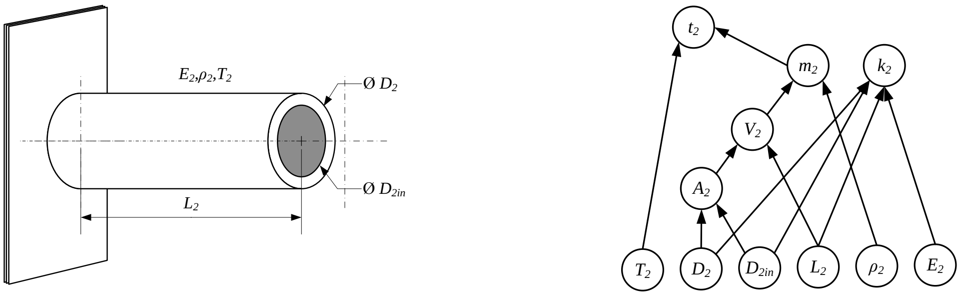
The proposed method allows representation of the inherent knowledge at an abstraction level that may be different for each concept. The weighted digraphs represent the relevant knowledge at that particular level and serve as a basis for calculating dimensionless values for all design parameters. Performance variables are common for all concepts and their dimensionless values are not affected by the difference of abstraction levels for the different concepts. As a result, the values of evaluation criteria that are calculated through formulas of performance variables may be safely used for concept evaluation.

2. Concept Representation, Design Parameters and Performance Variables

In current design practice, it is widely accepted that concepts are more or less abstract “renderings” of structures capable of performing one or more simple or composite functions of the designed artifact. Despite the high abstractness level and the consequent lack of detailed knowledge and information, there should always be the ability to represent and handle – in the most efficient way – those concepts for the benefit of the design process. Within this context and for the needs of the present work it is assumed that, at a certain level of abstractness, the main features of a concept (C) may be represented by a set of few fundamental design parameters (DP) that form associative relationships among them that can be described by directed graphs (digraphs) (see figure 1). Then, if P_C is the set of design parameters for concept C, $Q_C = P_C, H_C$ is a parameter digraph, that is a pair of set P_C and a set of associative relationships $H_C, H_C \subseteq [P_C]^2$.

In a DP digraph, two types of DPs may be formally distinguished; primary parameters that possess the unique property to be input (primary) entities and non-primary (dependent) parameters instantiated through the associative relationships by the primary parameters [Dentsoras 2005]. The instantiation data for the primary parameters may be provided – manually or automatically - by the designer(s) and/or by external sources (databases, previous design cases etc.).

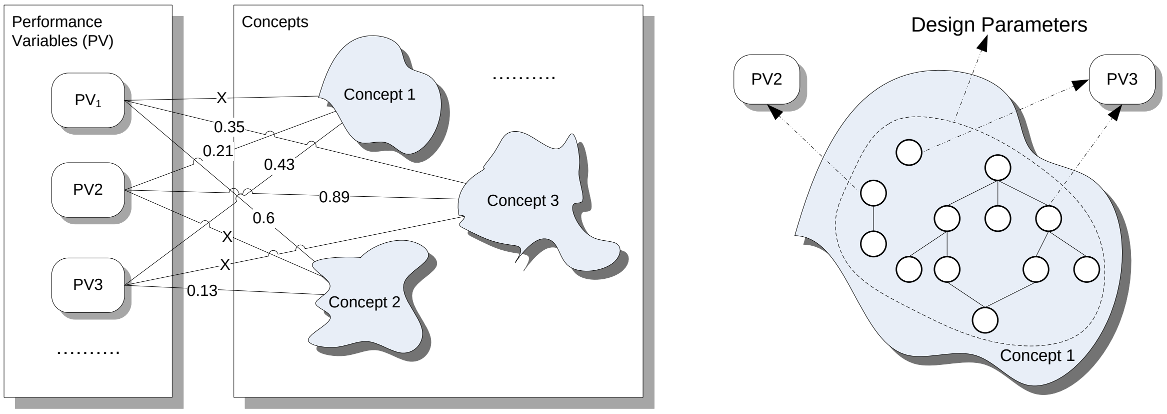
In figure 1.a, a simple concept for a stiffness element is shown that consists of a cantilever beam of circular hollow section. In figure 1.b a digraph of primary and dependent parameters for that beam is shown. In this digraph m_2 is a dependent parameter (cantilever mass) and its instantiation depends upon the instantiation of the primary parameters D_2, D_{2in}, L_2 and ρ_2 (constant π is omitted).



a. b.

Figure 1. Concept, design parameters and parameter digraphs.

A performance variable (PV) models an attribute of the designed artifact. Formally, a PV is a design entity defined with respect to sets of DPs and/or other PVs and its value is assigned via expressions of DPs and/or PVs. In the example of the stiffness element (see Figure 1), PV “stiffness” is defined with respect to DP k_2, while in the case of a design of a new type of chair, “comfort” is a PV related to more than one other DPs such as seat softness, chair foot height, arm support length etc.



a. b.

Figure 2. Relationships among concepts, design parameters and performance variables.

For the case of the stiffness element, a PV could be defined based upon previously defined PVs “stiffness” and “mass”. This PV will express uniquely the quantitative relationship between these two simple PVs and, by assuming that the stiffness element comprises a design concept that should be evaluated in conjunction to and with respect to other concepts, this PV may be part of an evaluation criterion such as “The stiffness should be maximum while the mass is kept to a minimum”.

Figure 2 shows schematically the relationships among concepts, design parameters and performance variables. In Figure 2.a, the PVs are defined in accordance with the design specifications (not shown) and then are mapped to the concepts. The PV values (figures on connecting lines) for each concept are calculated according to formulas, whose formulation is discussed below. An “X” on a connecting line between a PV and a concept means that the PV’s value cannot be estimated for that concept. In Figure 2.b, the internal structure of a concept is shown (digraphs of DPs), as well as the mappings between PVs and DPs.

The digraph in Figure 1.b. depicts directed associative relationships among the different DPs but, regarding the quantitative information being delivered, is quite simplistic. Indeed, It is evident that the value of the mass (DP m_2) of the stiffness element depends upon the values of D_2, D_{2in}, L_2 and ρ_2 but no information is provided in the digraph about the intensity of this dependency and the effect that each one of the primary DPs exerts on increasing or decreasing the value of m_2.

In some cases it is easy to deduce both the intensity and the effect through the available scientific/empirical knowledge in forms of analytical expressions, formulas, rules, databases, etc. For example, the dependence intensity for each primary DP determining the value of m_2 is easily deduced from formula $m_2 = \pi \; D_2^2 - D_{2in}^2 \; L_2\rho_2$ together with the corresponding increasing /decreasing effect. In other cases, especially for concepts characterized by lack of sufficient analytical and empirical knowledge, there is need to add subjective estimations about the dependency intensity and the increasing /decreasing effect in order to facilitate the establishment of quantitative interrelationships among the DPs.

A simple associative DP digraph may be converted to an associative weighted DP digraph (AWD) if signed weights are added to its edges. Figure 3 shows the AWD for the stiffness element of figure 1.a. These signed weights may help in determining the optimum values for the performance variables considered for a concept.

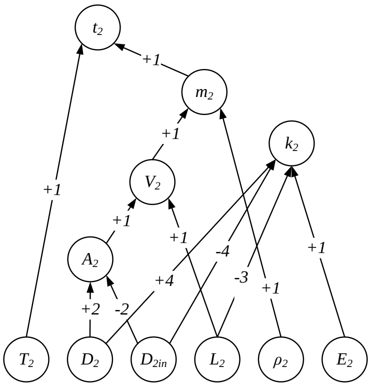


Figure 3. Associative Weighted Digraph for a stiffness element.

During conceptual design, the designers are practically interested in examining as much concepts as possible in order to end up either with the best (optimum) of them or with a synthesis of two or more concepts that may outperform all separate alternatives. In both cases, the designer should apply some metrics on all concepts and it is reasonable to assume that these metrics could be based on the values of performance variables. In other words, optimum values of PVs correspond to optimum concepts and vice versa. The determination of optimum values for the PVs is a matter of optimization of functions that provide these values by relating either DPs to PVs or PVs to other PVs. These functions may contain mathematical expressions that exhibit high complexity, contain mathematical expressions mixed with qualitative/empirical knowledge that is difficult to handle via analytical optimization methods, etc. Since the main interest is always the determination of optimum values for the PVs, a simpler approach could be followed as far as the aforementioned functions are concerned. The analysis below describes such an approach.

Consider a design problem where □ is the set of all concepts. Set $P_k^{(i)}, k = 1,2,...,m$ is the set of DPs for concept $c_i, c_i \in$ □ . Multiple PVs may be defined for the members of set □ . A

PV corresponds to and is defined as a function of one or more DPs. If $q_j^{(i)}$ is the $j-$PV that belongs to set □ formed by all PVs whose values should be considered for concept c_i, there may be one or more different functions of DPs that could be used in order to estimate the value of $q_j^{(i)}$. The most suitable one is a conventional analytical expression where one or more DPs are involved. For the example of the stiffness element, the analytical expression that provides the value of DP k_2 that corresponds to PV “stiffness’ is $k_2 = 3E_2\pi \;\; D_2^4 - D_{in2}^4 \;\Big/ 64L_2^3$.

The use of analytical functions for the estimation of PV values ensures the production of accurate results and is always welcome. However, such functions may not be always obtainable and usable and may also require complicated and time-consuming computations. The AWD of a concept may serve as an alternative that approximates the original – if any - analytical expressions (for certain concept cases that present high representation abstractness, such approximations seems to be the only solution). An AWD-based function may be the linear function of the sum of weighted values of DPs:

$$q_j^{(i)} \;\square\; \sum_{k=1}^{|P_{c_i}|} \pm \;{}^{(j)}w_k^{(i)} p_{k.d}^{(i)},\; j = 1,2,...,|\square| \tag{1}$$

where:

- $q_j^{(i)}$ is the value of the $j-$PV for the $(i)-$concept, $p_k^{(i)}$ is a DP that contributes to the determination of $q_j^{(i)}$ and $p_{k.d}^{(i)}$ is the dimensionless value of that DP with:

$$v \;\; p_k^{(i)} \;\;\square\;\; p_{k.d}^{(i)} = \frac{p_k^{(i)} - p_{k.\min}^{(i)}}{p_{k.\max}^{(i)} - p_{k.\min}^{(i)}}, p_{k.d}^{(i)} \in \;\; 0,1 \tag{2}$$

  In all subsequent expressions and for all terms the symbol v , when used, denotes dimensionless values

- ${}^{(j)}w_k^{(i)}$ is the signed weight for the dimensionless DP $p_{k.d}^{(i)}$ regarding $(i)-$concept and $j-$PV that is extracted from concept’s AWD, with the (+) sign denoting an increasing effect of the weighted value of $p_{k.d}^{(i)}$ on the value of $q_j^{(i)}$ and vice versa (practically, the weight sign for a DP may be different in different sub-domains of its value domain).

Given the AWD of a concept, the sum of weighted values that provides the value of a PV – according to expression (1) – may be easily and automatically calculated. An exhaustive search in the AWD will locate all paths and will calculate a value for the DP that corresponds to that PV by taking into account the current values of the DPs that – according to AWD – affect the PV under consideration. For example, in figure 1.b, if PV=”mass”, then the corresponding DP will be m_2, the application of depth-first-search will produce the list $m_2, V_2, A_2, D_2, D_{2in}, L_2, \rho_2$, the instantiation order will be $D_2, D_{2in}, A_2, L_2, V_2, \rho_2, m_2$ and, according to (1), the sum will be:

$$"mass" = 1v(V_2) + 1v(\rho_2) = 1v(A_2) + 1v(L_2) + 1v(\rho_2) = 2v(D_2) - 2v(D_{2in}) + 1v(L_2) + 1v(\rho_2) \tag{3}$$

Within the context of the current study, a PV is the design entity whose value will be optimized. Since at any design problem the optimization process is based upon an objective function, Euclidean norm has been chosen for the current approach. So, for a certain PV $q_j^{(i)}$:

$$\left\| q_j^{(i)} \right\| = \left[\sum_{k=1}^{|\square|-1} \left(\frac{q_k^{(i)} - q_{k\;\min}^{(i)\max}}{q_{k.\max}^{(i)} - q_{k.\min}^{(i)}} \right)^2 \right]^{1/2}, j = 1,2,...,|\square|, k \neq j \tag{4}$$

where:

- $q_{k\;\min}^{(i)\max}$ is a term that may exclusively get a value from the two-values set $q_{k.\min}^{(i)}, q_{k.\max}^{(i)}$ depending on whether if – within the context of the current optimization – minimization or maximization of PV $q_k^{(i)}$ is required

For PV $q_j^{(i)}$, its value belongs to $\left[0, \sqrt{n_c}\right]$, where n_c is the number of PVs required for the calculation of that value.

The dimensionless value of $q_j^{(i)}$ will be:

$$v\;\; q_j^{(i)} \;\; \square\; q_{j.d}^{(i)} = \frac{q_j^{(i)} - q_{j.\min}^{(i)}}{q_{j.\max}^{(i)} - q_{j.\min}^{(i)}} \tag{5}$$

For the concept depicted in Figure 1.a (concept 1), a PV $q_3^{(1)}$ could relate two simple PVs, “mass” ($q_1^{(1)}$) and “stiffness” ($q_2^{(1)}$). Then the Euclidean norm could be formed as follows:

$$\left\| q_3^{(1)} \right\| = \left[\left(\frac{q_1^{(1)} - q_{1.\max}^{(1)}}{q_{1.\max}^{(1)} - q_{1.\min}^{(1)}} \right)^2 + \left(\frac{q_2^{(1)} - q_{2.\min}^{(1)}}{q_{2.\max}^{(1)} - q_{2.\min}^{(1)}} \right)^2 \right]^{1/2} \tag{6}$$

and rewriting the above expression in accordance with (1) will result in:

$$\left\| q_3^{(1)} \right\| = \left[\begin{array}{l} \left(\dfrac{2v(D_2) - 2v(D_{in2}) + 1v(L_2) + 1v(\rho_2) - q_{1.\max}^{(1)}}{q_{1.\max}^{(1)} - q_{1.\min}^{(1)}} \right)^2 \\ + \left(\dfrac{4v(D_2) - 4v(D_{2in}) - 3v(L_2) + 1v(E_2) - q_{2.\min}^{(1)}}{q_{2.\max}^{(1)} - q_{2.\min}^{(1)}} \right)^2 \end{array} \right]^{1/2} \tag{7}$$

A careful examination of the above expression reveals that $q_3^{(1)}$ is a function of dimensionless DP values, weights and – occasionally - limit values of other PVs.

For every concept for which $q_j^{(i)}$ has a meaning, its value may be calculated through expression (1) for every “legal”– as far as value domains are concerned - combination of values of the engaged DPs. What is actually required is the combination(s) of DPs values that provide the optimum value of $q_j^{(i)}$ for the concept under consideration and, subsequently, the globally optimum value for the same composite PV for all concepts of the current design problem. The concept corresponding to that optimum value will be the optimum one.

If $q_{j.d}^{(i)}\;{}_{opt}$ is the optimum dimensionless value for PV $q_j^{(i)}$, then the optimum values of this PV - for all concepts on which it is defined - will form a list of values. This list may be rearranged in either ascending or descending manner depending on whether minimum or maximum values of $q_j^{(i)}$ are required. The concept corresponding to the first member of the rearranged list will be the optimum one regarding this PV.

3. Conclusions

In the present paper, an attempt is made to establish a formal concept representation scheme and to introduce a method for concept comparison and evaluation based on design parameters and performance variables. The proposed method allows representation of the inherent knowledge at an abstraction level that may be different for each concept. For each concept, the weighted digraphs represent the relevant knowledge at that particular level and serve as a basis for calculating dimensionless values for all design parameters. Performance variables are common for all concepts and their dimensionless values are not affected by the difference of abstraction levels for the different concepts. As a result, the dimensionless values of evaluation criteria that are calculated through formulas of performance variables may be safely used for concept evaluation.

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