A Formulation of the Preliminary Design Phase Using Complexity-Based Rules

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Abstract

This paper focuses on the application of complexity theory and entropy concepts in the design process. Broadly speaking, the design process involves three phases: problem definition, conceptual design and embodiment. In the conceptual design phase, concepts that satisfy the functional requirements of the desired product are identified and compared. It is said that approximately 75% of the total product life-cycle cost is committed in this phase. The conceptual design phase has two essential sub-phases, namely, obtaining a solution set and selecting the most suitable solutions. Our work focuses on the selection sub-phase. The aim within this sub-phase is to minimize the number of selected concept variants and to reduce their chances of rejection in later stages. However, the solution to this problem is quite elusive, mostly because information about concept variants is scarce and rather qualitative at this stage. A common method is to perform a cost-benefit analysis. However, the analysis relies heavily on expert intuition and is thus subjected to high uncertainties. Recently, axiomatic design is gaining popularity. This is a framework that incorporates two axioms, namely, the Independence Axiom and the Minimum Information Axiom, accompanied by several corollaries. However, criticism on the integrity of the Independence Axiom has appeared recently in the literature. Further, the formulation of axiomatic design appears to have logical flaws. Finally, the conceptual design phase, a distinct phase in the design process, cannot be distinguished clearly in axiomatic design.

In this paper we try to improve the selection phase of the conceptual design by improving the existing cost-benefit approach. In this vein, performance fea-

tures against which concepts would be evaluated are established. We propose the use of Kolmogorov complexity theory and entropy concepts from information theory and physics to evaluate the complexity of the performance features. The design concepts are then improved based on the rule to reduce complexity of each performance feature. Weights are finally assigned to each performance feature and an overall complexity index is obtained which is suitable to compare designs. The ideas are further elaborated on by examples.

1 Introduction

Product design being a vast field, the literature on the subject is immense. Many models of the design process have appeared in the past, e.g., (Rodenacker, 1976; Cross, 1989; Pahl and Beitz, 1996; French, 1999). Broadly speaking, these models are quite similar in that they involve problem definition, conceptual design and embodiment. These phases are the crux of the design process. We reproduce in Fig. 1 the design process model by French (1999) for illustration.

Over the last two decades, the development of computer hardware and software has benefited greatly to the embodiment phase. Only recently have the efforts diverted to the development of computer-aided tools for the conceptual design phase. Along these lines, it is imperative to formalize the conceptual design phase. The first attempt to systematize the design process can be traced back to Releaux (Moon, 2003), as he proposed a symbolic notation to represent mechanical objects occurring in machines. The design process received considerable attention in the

Figure 1: Design process model after French (1999)

20th century, which produced the *German School*, epitomized by Rodenacker (1976) and Pahl and Beitz (1996). According to Rodenacker, the main factor of systematic design is the determination of the underlying physical processes. A comprehensive account of work directed to establishing a theory and methodology of design, including Rodenacker’s work and the German School at large, is given by Pahl and Beitz (1996). Other attempts in this direction are due to Altshuller (1984), Hubka and Eder (1996) and Suh (2001).

Figure 1 reproduces the phases of conceptual design, as outlined by Pahl and Beitz (1996), where we observe that the two main phases of conceptual design are

1. Generating a solution set that satisfies the functional requirements and
2. selection of the most suitable solutions.

The generation of a solution set involves intuition and creativity. Methods with an intuitive bias such as brainstorming, set forth by Osborne in the 1940’s, and synectics (Gordon, 1960) are effective in solving simple problems, i.e., problems that have a limited number of solutions. For complex problems, two major approaches exist: The first defines creativity as an exact science (Altshuller, 1984); the second aims

Figure 2: Phases of the conceptual design after Pahl and Beitz (1996)

at aiding the human brain in the creative process by providing design guidelines and leaves the actual creative process to the human mind, e.g., (French, 1999), which leads to the question: Is creativity algorithmic? This is closely related to the mind-brain problem (Penrose, 1994), which is still an open question and we would rather not dwell on this. In this paper we would focus on evaluation of design variants.

2 Evaluation of Design Variants

A common method to evaluate alternatives involves defining a cost function and weights, as propounded by Pahl and Beitz (1996). However, guidelines provided for the evaluation of solution variants against technical and economic criteria are quite abstract and rely heavily on designer’s intuition. A logical or mathematical design evaluation methodology, or simply design methodology, for this class of design problem is still missing.

Suh (2001) proposed two design axioms and several corollaries within his axiomatic design framework. In formulating the Independence Axiom, Suh first defines the *functional requirements* $\mathbf{f}$ and the *design pa-*

parameters $\mathbf{x}$, to be determined by the designer, both items being multidimensional vector arrays. In the next phase, Suh presupposes *linear* relations between the two foregoing items, related by a *design matrix* $\mathbf{A}$, i.e.,

$$\mathbf{f} = \mathbf{A}\mathbf{x} \quad (1)$$

Further, Suh calls ‘ideal’ a design job in which the design matrix is diagonal, and hence, square, such designs being termed *uncoupled*. When the design matrix is triangular, and hence, square, the design is called *decoupled*. For all other cases the design is said to be *coupled*.

The Minimum Information Axiom, in turn, presupposes a measure of the information contained in a design, which is based on the classical definition of information content (Wiener, 1948), i.e., the logarithm of the reciprocal of the probability of an event. In axiomatic design the event is meeting a functional requirement. In this vein, the i th functional requirement is assigned, *somehow*, a probability p_i of being met, the information content I_i for this requirement being defined as

$$I_i = \log_2 \left(\frac{1}{p_i} \right) \quad (2)$$

which is a positive quantity; the unit of information content is, thus, the *bit*. Hence, the information content I of a given design, in bits, is, for n functional requirements,

$$I = \log_2 \left(\frac{1}{p_1 \cdots p_n} \right) \quad (3)$$

In the axiomatic design paradigm, the ‘ideal’ design is one with a diagonal design matrix. However, we know from perturbation analysis that a diagonal matrix with its entries of quite disparate orders of magnitude has a large condition number (Golub and Van Loan, 1989), and hence, implies highly disparate sensitivities of the design functions to changes in the design-parameter values, thus leading to a fragile design, as opposed to a robust design. Next, Suh’s matrix representation (1) implies a *linearization* of nonlinear relations, which requires smooth functional relations at the outset; however, such relations may not even be available for practical applications, e.g., when selecting a component from a catalogue. Further, no hint is given on the units of the entries of the design matrices, which are handled rather casually. This is particularly evident in Suh’s quantitative measures, namely, *reangularity* and *semangularity*. These measures estimate the degree of coupling

between the functional requirements and the design parameters. Finally, for the best design, the use of logarithms makes the information content I equal to zero. This is against common sense—a design without any information content cannot be modelled. Is the best design a no-design?

Axiomatic design has logical and mathematical flaws. At the conceptual level, functional requirements are usually utterances and cannot be reproduced as vectors, or even in a mathematical form. Equation(1) has no algebraic value and is rather borrowed from mathematics to represent a set of utterances. The design matrix represents preferred relations set by rules in axiomatic design, derived from observations in design field. However, these rules can change from application to application and defining a global rule, such as the independence axiom, is misleading (Angeles, 2002; Frey and Engelhardt, 2000).

3 Suggested Design Model

Conceptual design and embodiment of schemes are two distinct phases of the design process. Although identified as different phases in the design literature, these phases are often mixed together while outlining the framework of the design phases. In axiomatic design (Suh, 2001), the entries of the design matrix are circles and crosses intended for expressing design relations, rather than influence coefficients. In fact, a binary matrix exhibiting relations between functional requirement and design parameters may be readily obtained by replacing crosses and circles of the design matrix with ones and zeros, respectively. The design matrix is thus not intended for numerical computation. Hence, the designer, in most cases, cannot draw a line between the embodiment phase and the conceptual design phase. French (1999) even advocates overlapping the conceptual design phase and the embodiment phase.

The reason for the above mix-up is the existence of a strong feedback loop between the embodiment of schemes and the conceptual design phase, as illustrated in Fig. 1.

On the other hand, when the conceptual design and embodiment phases are analyzed separately, we observe that a clearcut definition of a *design concept* is still missing. Further, the selection approaches, as proposed, for example, by Pugh (1991), Pahl and Beitz (1996) and Aurand *et al.* (1998), are not satisfactory and have been criticized in the literature (Otto and Wood, 1995; Wang, 2002). The main flaw in these approaches is the use of crisp values in the

conceptual design phase, which, in fact, has a fuzzy nature.

We thus propose: *A design concept is a set of sketches, that clearly demonstrate how design specifications stemming from the analysis-of-functions phase, would be met. The main difference between a conceptual design and a detailed design is the absence of a mathematical model in the conceptual design.*

A mathematical model describes the behaviour of a system with respect to the design-environment parameters and the design variables, e.g., the set of equations of motion of a given mechanical system.

Figure 3: Suggested design process layout

In extending the phases of product design, as proposed by French (1999) and Pahl and Beitz (1996), we propose the design procedure shown in Fig. 3 and outlined stepwise below:

- 1: An analysis is first performed on the client's requirements to obtain a *clearcut*, or *sharp*, set of design specifications.
- 2: The candidate morphologies satisfying the design specifications are generated.

3: This step, namely, the rule-based filter, is the main thrust of our research. We realize that a design concept rejected in design step 4, i.e., the locally robust design phase, increases the cost of the design activity. In fact, nearly 75% of the product life-cycle is committed by the end of conceptual design (Nevins and Whitney, 1989). Hence, within this step, we aim at improving the candidate morphologies, to minimize the number of morphologies selected and to minimize rejection chances within the robust design phase. Fulfilling these aims would decrease the cost of the design activity and improve product quality. In this vein, we first define performance features against which candidate morphologies must be evaluated. These candidate morphologies are then filtered by a *rule-based filter*. The objective of the rules is to reduce the Kolmogorov complexity and/or the Shannon entropy of the performance features specified.

4: Mathematical models or performance functions of selected morphologies are obtained, and optimum design variables for a robust design are determined (Al-Widyan, 2004). Finally, if the design is acceptable, it is sent for detailing; otherwise, we must go back to either step 1, the analysis-of-functions, or step 2, the morphology-selection.

4 Complexity of Concepts

Complexity means different things to different people. While everybody uses the term in day-to-day situations, and certainly in engineering, philosophical problems come into play when one attempts to define it. To be true, a mathematical theory of complexity is available, in the context of information theory, that was put forth by Solomonof, Kolmogorov, Chaitin, Martin-Löf and Levin around 1970 (Delahaye, 1999, 2003). The theory is now known as *Kolmogorov complexity* or *algorithmic complexity*.

4.1 Kolmogorov Complexity

Kolmogorov complexity deals with the amount of information of individual objects. Strictly speaking, Kolmogorov complexity is defined over binary strings. Hence the scope of Kolmogorov complexity is limited to objects that can be mathematically modelled or algorithmicized.

The Kolmogorov complexity of a binary string is the size of its smallest effective (computable) description relative to a specification method previously chosen. However, this definition makes the complexity dependent on the specification method. We give below some important definitions and conclusions. For details, the reader is referred to (Li and Vitányi, 1997).

Let $|\cdot|$ be the size of a binary string. Let $f : \{0,1\}^* \rightarrow \{0,1\}^*$ be any given partial function, $\{0,1\}^*$ the set of all binary strings of size greater than or equal to zero.

Definition 1 *The complexity of object $x \in \{0,1\}^*$ with respect to a specification method f is defined as $C_f(x) = \min_{f(p)=x} |p|$. If there is no description p it is said, by definition, that $C_f(x) = \infty$.*

Definition 2 *We say that method f minorizes (or additively minorizes) a method g if there exists a constant $c > 0$ such that, for all x , $C_f(x) \leq C_g(x) + c$.*

Theorem 1 *There exists a recursive partial function u , called universal, such that for any recursive partial function f and binary string x , and for some $c_f > 0$, $C_u(x) \leq C_f(x) + c_f$ and c_f depends only on f .*

By fixing a universal recursive partial function u , called universal of reference, we can define $C_u(x) = C(x)$, where $C(x)$ is the Kolmogorov complexity of object x .

In proving Theorem 1, the concept of machine simulation and the existence of a universal Turing machine (that simulates all other machines) play an important role.

Informally, a description of an object in one programming language can always be simulated in another programming language, provided that an interpreter code is available. The size of this interpreter is constant and hence, the choice of programming language is not important.

The Kolmogorov complexity of an object thus represents the information that must be supplied so that the object can be computationally (algorithmically) constructed (or computed). Thus, the Kolmogorov complexity of an object represents quantitatively the information immanent in this object.

4.2 Application of Kolmogorov Complexity to Product Design

The information content of a design variant gives us a measure of its complexity, which we want to keep to

a minimum. The Kolmogorov complexity is adequate to this task as it measures the information content of the objects it is applied on. However, the *Kolmogorov complexity is not computable* (Ditto and Munakata, 1995). Hence, if we use the Kolmogorov complexity (the absolute information content) as a means of characterizing designs, the non-computability of the Kolmogorov complexity suggests that there can be a better design but not the best one, i.e., the design process is *partially subjective*. This leads to the conclusion that *expert knowledge and heuristics* is required to deal with this problem.

Although the Kolmogorov complexity is not computable, it is *semi-computable* (Campani and Menezes, 2004), i.e., it may be approximated. This is good news, specially when we are interested in comparing design variants. Evaluation or comparison of design variants may be done by comparing their (approximate) complexities and thus finding which of them are more complex than others, e.g., by comparing the compressed file sizes of the final CAD drawings of a product.

When applied at the conceptual design stage, the absence of a mathematical model, even preliminary design parameters, makes it impossible to evaluate the Kolmogorov complexity of a concept. Hence the Kolmogorov complexity cannot be applied, as is, in most cases. However we are suggesting the use of the Kolmogorov complexity to measure the complexity of certain abstract function requirements within the conceptual phase, e.g., measuring the information content of the ‘ease of operation of a certain product.’ Such function requirements can be evaluated if the relevant algorithm of the function requirement is obtained and the Kolmogorov complexity measure is then applied to measure the information content. This is the main thrust of this paper.

4.3 Shannon’s and Boltzmann’s Entropy

The classical paper of Shannon (1948) introduces the theory of information. In this theory we are only interested in the problem of communicating a message between a sender and a receiver. We are not concerned with the meaning of the message and hence, Shannon’s information theory does not capture the information content of the individual object itself. *The entropy measure formulated by Shannon in terms of probability theory is thus relative.* In this context we first define an ordered pair $\mathcal{V} = (\mathcal{X}, \mathcal{P})$ where $\mathcal{X} = \{x_i\}_1^n$ is a finite set, known as a source alphabet,

and $\mathcal{P}$ is a probability distribution on $\mathcal{X}$. We denote the probability of x_i by p_i . Shannon's entropy can be expressed as

$$H_b(\mathcal{X}) = - \sum_{k=1}^m p_k \log_b p_k \quad (4)$$

where $b \in \mathcal{Z}$ and $b > 1$. If $b = 2$, H has units of bits.

The association of set $\mathcal{X}$ with probabilities suggests the consideration of a discrete random variable as a source of information. This association conveys information about the variability of the behavior of $\mathcal{X}$ around some central tendency. Suppose that we select at random an arbitrary element of $\mathcal{X}$, say x_i , with probability p_i . Before the sampling occurs, an amount of uncertainty associated with the outcome is present. However, an equivalent amount of information is gained about the source after sampling, and therefore, uncertainty and information are related. If $\mathcal{X} = \{x_i\}_i^n$, then there is no uncertainty and no information gained. At the other extreme, maximum uncertainty occurs when the alphabets carry equal probabilities of being chosen. In this situation, maximum information is gained by sampling. This amount of information reveals the maximum uncertainty that preceded the sampling process.

Shannon's entropy is a measure of a discrete source of information and can be used as a complexity measure when the argument p_i is defined as the probability of success. In the case of a continuous information source $\mathcal{X}$, with $f(x)$ as a probability distribution function (pdf), Boltzmann's information measure $h(f)$ can be used; this measure is defined as

$$h_b(f) = - \int_S f(x) \log_b f(x) dx \quad (5)$$

where S is the support set of the random variable.

Another interesting aspect is the choice of a logarithmic function. Shannon, in his classical paper on information theory (Shannon, 1948), explains the choice of logarithmic measure. In his views the three reasons to select the logarithmic measure are

1. this measure is practically useful, since the parameters of engineering importance such as time, bandwidth, etc., tend to vary linearly with the logarithm of the number of possibilities;
2. the measure is nearer to our intuitive feeling as to the proper measure. One feels, for example, that three bits should carry thrice the information carried by one bit, while actually three bits carry eight times so; and
3. the measure is mathematically more suitable.

Shannon further suggested the units of 'binary digits' for base-2 measures for discrete systems and 'natural units' for base-e measures for continuous systems.

Although discrete and continuous systems can be handled with the above choices, a choice for a mixed system is not available. All practical design process are mixed systems. An example of a discrete system is the selection of a part from catalogues.

In Axiomatic Design, Suh justifies the use of a logarithmic scale so that the information content I will be additive when there are many functional requirements that must be satisfied simultaneously (Suh, 2001). This is potentially misleading. The only requirement that we need to include an additive property is that the measure of information content be dimensionless or, at least, dimensionally homogenous.

4.4 Use of Shannon's and Boltzmann's Entropy in Conceptual Design

In the design context, Suh proposed Shannon's entropy as a measure of complexity in the context of the information axiom and defined the information content of a design as the reciprocal of the probability of meeting the design specifications (Suh, 2001). Boltzmann's entropy may be considered as the continuous analogous to Shannon's entropy. Both these types are relative measures.

Shannon's entropy explains why a relatively more complex part that is mass-produced is cheaper than a simpler part which is not mass-produced. Shannon's entropy also explains why concepts which are more complex but extensively used are more popular than concepts which are relatively simpler but sparingly used. An example of this is the reciprocating engine compared with a rotary engine. The production volume of reciprocating engines is overwhelming compared to the rotary engine. The rotary engine, although conceptually simpler, was never able to make its way into the mainstream of internal combustion engines.

When should then a custom part be produced? When should a new product be launched? Which design is a better design? These questions are, in fact the same. It would be misleading to use only Shannon's entropy to answer them. We need both Kolmogorov's complexity (absolute information content) and Shannon's entropy to answer this question.

Both the quantity of information and information entropy have been incorporated in a formulation proposed by ElMaraghy and Urbanic (2003). In this formulation complexity is described as a function of three factors: the absolute quantity of information; the diversity of information; and the information content. However, this formulation is more suitable for the embodiment phase and, in its current form, is only applicable to the manufacturing complexity of the product. A more comprehensive formulation may be based on Shannon's entropy (Shannon, 1948) and Kolmogorov's complexity theory (Li and Vitányi, 1997), as proposed here.

5 Example: Design of a Domestic-Refrigerator Door

Figure 4: Possible design variants

We now attempt to apply the design procedure outlined above to the design of a refrigerator door, while focusing on the morphology selection instead of morphology generation. The two major functions of a door are (i) to provide restricted access to the user and (ii) isolation from temperature, dust, humidity, odor, vision, etc., between the outside and the in-

side. The performance features to be expected include space intrusion during operation, ease of operation, re-operability, aesthetics, manufacturing, and running and maintenance costs, among others.

For a refrigerator door, in particular, the major functions are to provide

- Access to the refrigerated space and
- isolation of the refrigerated space from the surrounding environment.

With these functional requirements there can be a number of design solutions based on materials, door orientation, door mechanism, etc. *Again, we will not dwell on the generation of the conceptual design variants but rather on their evaluation.* Let us assume that we have generated the five design concepts depicted in Fig. 4

C₁: A vertical-hinge door, Fig. 4(a);

C₂: two horizontal-hinge doors, Fig. 4(b);

C₃: a horizontally sliding door, Fig. 4(c);

C₄: a door with a parallelogram 4-bar linkage (Π joint), Fig. 4(d); and

C₅: an air curtain, Fig. 4(e).

Next, we specify the performance features against which these designs will be compared, namely,

P₁: Ease of access to refrigerated objects;

P₂: volume swept by the door;

P₃: volume of the space obstructed by the open door;

P₄: isolation quality with respect to temperature, humidity and odour; and

P₅: running cost.

We discuss each feature separately in the subsections below.

5.1 Ease of Access to Refrigerated Objects

Here we attempt to use Kolmogorov complexity to evaluate the five candidate solutions $\{C_i\}_1^5$ proposed

above. To this end, we define a set $\mathcal{M}$ containing three move-functions, i.e.,

$$\mathcal{M} = \begin{cases} m_1 : \{0, 1\} \rightarrow \{\text{open door, close door}\} \\ m_2 : \{0, 1\} \rightarrow \{\text{bend body posture, straighten} \\ \quad \text{body posture}\} \\ m_3 : \{x, y, z\} \rightarrow \{\text{joint trajectory of} \\ \quad \text{operator's hand}\} \end{cases} \quad (6)$$

where x, y, z are binary numbers representing Cartesian coordinates of the target position. We assume x, y and z to be eight-bit numbers for our calculation. Finally, we need two more bits to refer to the three move functions.

Within this framework, if we need, for example, p moves of type m_1 and q moves of type m_3 , then we need a total of $2(p + q) + p + 24q$ bits to define the ‘fetch command’. It is not too difficult to show that the complexity associated with the access to food, based on the the set of moves defined in set $\mathcal{M}$, are $K_1 = K_2 = K_3 = K_4 = 38$ and $K_5 = 32$, where K_i subscripted is the Kolmogorov complexity associated with the corresponding concepts, in bits, so that K_i corresponds to C_i . Hence, C_5 is a better design with respect to access to goods.

Note that a flaw in this formulation appears in cases in which each move has a different level of difficulty. A remedy would be to introduce weights. However, this remedy needs further investigation.

5.2 Volume Swept and Volume of Obstructed Space

The sharp evaluation of this function requirement is not possible in the absence of dimensions, which are not available at the conceptual level. However, a fuzzy evaluation may be possible.

5.3 Isolation Quality

In the interest of space we will discuss only thermal isolation. This performance feature can be evaluated using the entropy concept drawn from the Clausius inequality in thermodynamics (Moran and Shapiro, 1995), namely

$$\oint \left(\frac{\delta Q}{T} \right)_b \leq 0 \quad (7)$$

where δQ represents the heat transfer at a part of the system boundary b during a portion of the cycle, and T is the absolute temperature at that part of the boundary. For given refrigerator temperature T_1 and

ambient temperature T_2 , the time rate of change of entropy $\dot{S}$ is given by

$$\dot{S} = \dot{Q} \left(\frac{1}{T_1} - \frac{1}{T_2} \right) \quad (8)$$

where $\dot{Q}$ is the rate of heat transfer from the environment to the refrigerator. The rate of change of entropy is thus proportional to the rate of heat transfer between the room and the refrigerator. However, evaluation of the heat transfer is not possible in the absence of a mathematical model. We would thus take advantage of handbooks and catalogues. The effectiveness η of an air curtain, is between 60% and 80% (ASHRAE, 2004), where

$$\eta = 1 - \frac{\dot{Q}_{ac}}{\dot{Q}_{wo}} \quad (9)$$

where $\dot{Q}_{ac}$ and $\dot{Q}_{wo}$ denote the heat transfer rate, for the *air curtain* and for *wide open*, between the inside space and outside space. Factors affecting η include (James and James, 2002):

- Temperature difference between the chilled air inside and the surrounding air;
- velocity of the curtain air
- thickness of the air curtain;
- pressure difference across the curtain thickness; and
- obstruction in the path of air curtain.

Hence, while designs C_1 , C_2 , C_3 and C_4 have negligible heat transfer, C_5 would transfer about 30% of what would be transferred via a wide open horizontal door.

5.4 Running Cost

The comparison with respect to this feature could again be based on entropy changes. As a rule, a part that causes low entropy changes is a better design compared to one that causes larger entropy changes. This implies that a design solution with a high energy consumption is an inferior design compared to one with a low energy consumption. Hence, C_4 , which requires a constant input of energy to perform its function, is a weak design, as compared to the other three types. We found from catalogues that an off-the-shelf air curtain for a 915-mm (3 ft.)-wide door consumes about 80 watt. Most mid-sized refrigerators have this width.

Performance feature	$\bar{K}_{i1}$	$\bar{K}_{i2}$	$\bar{K}_{i3}$	$\bar{K}_{i4}$	$\bar{K}_{i5}$
F ₁ : Access to goods	1.0	1.0	1.0	1.0	0.84
F ₂ : Entropy change rate with close door	0	0	0	0	1.0
F ₃ : Entropy change rate with open door	1.0	1.0	1.0	1.0	0.3
F ₄ : Running cost	0	0	0	0	1.0

Table 1: Performance evaluation of design variants

5.5 Evaluation of Complexity

We record our evaluations in Table 1. In this table $\bar{K}_{ij} \in [0, 1]$ is the normalized feature complexity of the design variant C_j of the performance feature F_i .

Next, we define complexity C_j of the design variant C_j , as a convex combination of normalized feature complexities $\bar{K}_{ij}$ as follows

$$C_j = \sum_{i=1}^4 w_i \bar{K}_{ij} \quad (10)$$

where w_i is the weight of the performance feature F_i . Further, $w_1 + \dots + w_4 = 1$ thus respecting the definition of a convex combination.

For example, if $w_1 = w_2 = w_3 = w_4 = 0.25$. The complexity $C_1, \dots, C_5$ of design variants $C_1, \dots, C_5$ is correspondingly 0.5, 0.5, 0.5, 0.79. Hence, C_5 is a weak design w.r.t. the performance features under consideration and under the assumption that each performance feature carry equal weight.

As an other example, let $w_1 = 0.4$, $w_2 = 0.1$, $w_3 = 0.4$ and $w_4 = 0.1$. This weight distribution would be suitable if we were to design a departmental store refrigerator instead. The corresponding complexities obtained for this distribution are 0.8, 0.8, 0.8, 0.66. For this case, C_5 becomes the preferred conceptual design.

6 Conclusions

We note here that we were able to quantify performance features using the notions of Kolmogorov complexity and entropy—by the use of handbooks and catalogues. Designs may then be improved at the conceptual design phase with respect to this measure. Further, note that the use of complexity in the design selection phase allows us to establish weights with minimal involvement of intuition, thereby helping us improve the selection procedure.

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