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On the computation of the information content of a coupled design with two functional requirements

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Abstract

Computing the information content of coupled designs is seldom discussed in the literature, probably because the Axiomatic Design (AD) practitioners know that coupled design solutions should be avoided. On the other hand, Suh's theorem 7 states, "the information contents of coupled and decoupled designs depend on the sequence by which the DPs are changed to satisfy the given set of FRs". From this theorem, one could be tempted to conclude that the information contents of coupled designs cannot be computed, because they have not a "right" sequence for changing the values of the DPs in order to satisfy the given FRs. This misunderstanding could then be used to stress that AD is not useful as a decision-making approach for coupled designs. Yet, coupled designs do exist, they are many times unavoidable and their information contents can be computed, although this is often hard to perform. This paper presents the computation of the information content for the simple case of a 2-FR, 2-DP coupled design and illustrates how this topic is related to Suh's theorem 8 on independence and tolerance.

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1. Introduction

The large majority of the design methodologies of the 20th century follow the costly and time-consuming cycle "design-model-test-redesign-model-test" or, even worst, "design-build-test-redesign-build-test", when physical prototype testing is required due to uncertainty. This is, for example, the case of the methodologies proposed by Pahl and Beitz [1] or by Hubka [2]. This drawback, which is common to the traditional heuristic methodologies, turned out to be crucial some years after the World War II, when an overwhelming demand of new high-quality products with a short time-to-market came into play. Definitely, something new and methodologically different should happen to allow engineers to break the above said development cycle, so that they could consistently "do it right at the first time", timely and at an affordable cost.

In the end of the 1970s, Nam Pyo Suh introduced a new engineering design theory that was made known to the public in 1990, under the name of Axiomatic Design (AD), through a seminal book on the subject [3]. Suh's motivation was to provide scholars and designers with a theoretical foundation for design that follows the pattern and the criteria of modern science, as to stimulate substantial improvements in teaching and in practicing design.

The wide scope of AD makes it valuable in any function-ally-driven design context, especially in conceptual design; and its breath is so large that it proved its usefulness outside the traditional engineering fields, such as in the planning of intricate surgery sessions [4], in the management of healthcare systems [5], or in approaches to raise venture capital [6].

In AD, design is regarded as an intellectual endeavor that could be described as decision-making process, which success depends on the accurate knowledge about the functional goals and constraints, as well as on the mastering of the engineering sciences and the technologies related to the likely alternative design solutions. The AD fundamental decision criteria are stated in the form of two axioms: the independence axiom and the information axiom [3].

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The independence axiom states that the functional requirements (FRs) of any good design solution should be fulfilled in an independent manner, while the information axiom states that best of the alternative solutions is the one with the minimum information content.

Two kinds of design solutions fulfill the independence axiom: uncoupled designs, in which the values of the design parameters (DPs) can be adjusted in an arbitrary order, and decoupled designs in which the values of the DPs can be set in a certain order, so that setting the value of each DP only impacts one FR. A third kind of designs exists: the coupled designs that breach the independence axiom and therefore should be avoided.

Tackling new designs should begin by trying to fulfill the independence axiom. This allows identifying the good and the poor alternative solutions, and the next step is to select the best solution, for which the information content is minimum, as per the information axiom.

But what if all the alternatives are poor? The AD's traditional approach is to look for more alternative solutions until at least an uncoupled or decoupled solution is found. In this paper, we argue that there are many cases where one cannot find any good solution, at least in a realistic term, case of which one could have to compare two or more coupled designs to make a decision.

Thus, this paper presents a method for the computation of the information contents for the simple case of a 2-FR, 2-DP coupled design and illustrates how this topic is related to Suh's theorem 8 on independence and tolerance.

2. Trying to decouple some typical coupled designs

Coupled designs occur very often. In "design for cost", for example, cost can be taken as a requirement. In this case, adjusting the value of any design parameter would impact the cost of the product, which will become a coupled design.

Decoupling the coupled designs might be tried through the two following approaches. The first approach is to take one or more design specifications as input constraints, and not as requirements. This might reduce the number of couplings, because the constraints do not integrate the design equation. Yet, doing it right at the first time means that the design specifications should be taken pro-actively as requirements, and not as constraints, since checking any solution against the constraints could only be made after a set of DPs is previously selected, that is, after a functionally viable design solution is found. The second approach is to use the "plant some trees" metaphor that could be briefly explained through a simple example.

Let us suppose that one wants to design a small electric power station that should burn some kind of fossil fuel. Therefore, let us consider that we have a functional requirement, the nominal power of the power station, P, and an eco-requirement, the rate of CO_2 emissions, E. A potential physical solution with two design parameters, the power rating of the generators that we are going to use, g, and the size of the power station in terms of number of generators, n, could be explored. In this case, we have a coupled design solution depicted by the design equation

$$\left\{ \begin{array}{c} P \\ E \end{array} \right\} = \left[\begin{array}{cc} \mathsf{x} & \mathsf{x} \\ \mathsf{x} & \mathsf{x} \end{array} \right] \left\{ \begin{array}{c} g \\ n \end{array} \right\}, \quad (1)$$

where x denotes the non-zero elements of the design matrix.

Equation (1) shows that we could achieve the nominal electric power of the power station by adjusting both the design parameters g and n. Doing so, we cannot use either g and n to achieve the targeted rate of the CO_2 emissions, because this would disturb the previously attained value for P. This is the point where the metaphor comes into play: we "plant some trees", in number of t, in order to counterbalance the harmful effects of the CO_2 emissions with the help of the trees' photosynthetic action. Adding the trees does not impact the produced electric power and the design equation becomes

$$\left\{ \begin{array}{c} P \\ E \end{array} \right\} = \left[\begin{array}{ccc} \mathsf{x} & \mathsf{x} & 0 \\ \mathsf{x} & \mathsf{x} & \mathsf{x} \end{array} \right] \left\{ \begin{array}{c} g \\ n \\ t \end{array} \right\}, \quad (2)$$

which right trapezoidal design matrix denotes a redundant decoupled design, as shown elsewhere [7]. Nevertheless, in other designs it is often hard, if not impossible, to find out the right "trees" that one has to "plant".

Incidentally, things are not always so simple and most of the eco-designs are coupled. This is easy to realize through the case study presented by Shin *et al.* [8] that found a design solution for a flashlight by making some design decisions through the appraisal of the flashlight's eco-friendliness. They started from a 12-FR, 12-DP deeply coupled design solution that proved impossible to decouple. Next, they used the Life Cycle Assessment (LCA) technique to find out three extra eco-functional requirements (eFRs) that were used to obtain the so-called augmented design matrix with 15-FR, 12-DP. This matrix also corresponds to a coupled solution according to Suh's theorem 1, which states, "When the number of DPs is less than the number of FRs, either a coupled design results or the FRs cannot be satisfied." [3, pp. 56-57].

Shin *et al.* [8] eventually succeeded to find a lesser-coupled design and could compare, under an ecological standpoint, the use of different materials to build the flashlight. Yet, LCA does not match the AD scientific goal, given that it uses benchmarks to assess the relative impact of eco-issues. On top of the subjectivity of benchmarking, LCA involves applying weighting factors in the appraisal of the joint impact of multiple eco-issues. This contravenes Suh's theorem 16 that states, "All information contents that are relevant to the design task are equally important regardless of their physical origin, and no weighting factor should be applied to them." [3, p. 321].

3. Why computing the information of coupled designs?

Coupled design solutions do exist and often we cannot avoid them. Nevertheless, other than the topologic structure of their design matrices, coupled designs are perhaps the less learned topic of AD.

The supremacy of AD becomes clear in conceptual design, when the first decisions are made with the help of the