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# Tracking the consequences of design decisions in mechatronic Systems Engineering

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ABSTRACT

The design of mechatronic systems involves several technical and scientific disciplines. It is often difficult to anticipate, at the outset, the consequences of design decisions on the ultimate effectiveness of such complex systems, in which case the evaluation process is required to support the designers each time engineering choices must be made or justified. Since designers may belong to different technical and scientific cultures however, their understanding of both the design stakes and the evaluation process is too often biased. Moreover, design choices take place in an uncertain context and according to multiple criteria, some of which may be contradictory. In order to track the consequences of design decisions, we are proposing a conceptual data model to perform evaluations within the MBSE framework of Systems Engineering. We then proceed by relying on the relationships demonstrated by such a model to identify the potential impacts of design choices on future product performance. Since data available during the conceptual phase of the design are typically uncertain or imprecise, an original research protocol is extended to a qualitative impact analysis for the purpose of highlighting the most promising alternative system design solutions (ASDS). An example in the mechatronics field serves to illustrate our proposals.



## 1. Introduction

Mechatronic design is an interdisciplinary activity that continually strives to integrate widespread functionality into geometrically constrained products. In the competitive marketplace, both time and finances are often lacking when it comes to studying and finalizing several mechatronic concepts and then retaining only the most satisfactory one. Engineers therefore require support in reviewing alternative system design solutions (ASDS) and in making and defending the best design choices as of the earliest product design stages [1]. In a Systems Engineering (SE) context [2], such is the role of evaluation activities in assessing ASDS and in ensuring that design-related decisions take into account relevant multidisciplinary knowledge and can hence be duly justified. With this aim, various analytical approaches and methods can be applied to conduct effectiveness, cost and risk studies as well as to compare different ASDS.

The design evaluation process however faces a number of challenges, including:

(1) Though the initial choices are definitely critical to ensuring a successful design project, rating the merit factors of each candidate solution during the conceptual design stage is generally subject to uncertainty and inaccuracy.
(2) Designing complex mechatronic products requires multidisciplinary knowledge. Since designers tend to have narrow technical and scientific backgrounds, their understanding of system design objectives and their vision of the evaluation process are often only partial and incomplete.
(3) Assessing the consequences when choosing from among several ASDS is a critical step to the process and to this day has still not been resolved effectively [3].
(4) System requirements may at times be interpreted as contradictory when considering a given ASDS. The challenge then is to identify satisfactory ASDS that achieve an acceptable balance between these requirements, as opposed to finding the optimal ASDS.

Although the core of design problematic is how to produce solutions, design solutions synthesis is not the scope of the presented research work. This paper aims to provide some basic elements to address the issues raised in 1 through 4 above by considering just the effectiveness evaluation; due to constraints placed on the paper's length, risk and cost aspects will not be included.

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After defining the role of evaluation within the design process, Section 3 will tackle the 2nd issue raised above in proposing a conceptual data model considered herein as the abstract syntax of a possible language dedicated to evaluation within the Systems Engineering (SE) framework. The intention is for members of a multidisciplinary design team to be capable of sharing a common vision of data as a prerequisite to evaluating ASDS, regardless of their profession, objectives or specialization. Based on this proposed common view, Section 4 will contribute to resolving issue 3 by means of facilitating the identification of potential impact relations between design choices and effectiveness criteria. Once potential impacts have been identified, the consequences of such impacts on the degree of ASDS satisfaction in a multi-criteria context must be analyzed. To this end, Section 5 will formalize the interactions proposed in this research work between a behavior model of the system being designed and a model of stakeholders' expectations. Our proposal seeks to address issue 4 above by adapting a formal approach to determine the level of criterion satisfaction, which entails applying qualitative or quantitative reasoning depending on the uncertainty inherent in the design specification. Section 6 will illustrate our proposals through an example of developing the electrical assistance function for a wheelchair. Section 7 will draw a conclusion regarding future perspectives.

## 2. Evaluation in design

Let's consider, without the ambition of achieving completeness, a number of current design theories and methodologies that deal with evaluation issues [4–7]. According to [8], designers are making progress towards defining the systems under design in more concrete terms by iteratively performing the steps indicated in Fig. 1:

- **Synthesis**: The creative activity by which known elements are placed together in new and more useful combinations in order to produce ASDS.
- **Analysis**: Deriving an estimation and prediction of design parameter values.
- **Evaluation**: Comparison of each ASDS with other ASDS and verification of compliance with customer requirements.

Mechatronic engineering combines mechanical engineering, electrical engineering and computer science within an interactive way. The VDI2206 guideline recommends conducting the design of mechatronics systems according to the so-called "V-model" pattern [9]. The design process distinguishes between the problem solving process of the individual designer (micro-level) and the generic process related to design phases (macro-level). At the macro-level the system is specified functionally, working principle

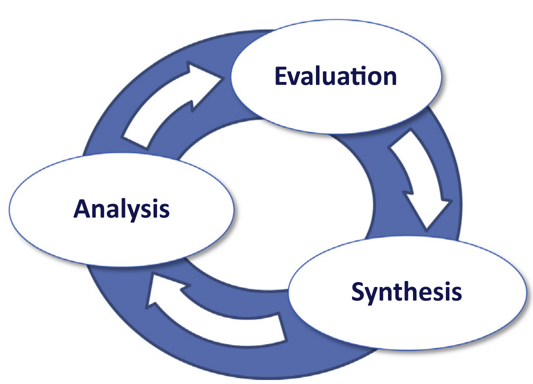


**Fig. 1.** Evaluation vs. analysis and synthesis [9].

variants are evaluated and selected. Then sub-parts allocated to each involved discipline such as mechanics, electronics, and computer science are specified, realized and integrated to form a system.

Several passes through the v-shaped model are necessary to obtain a mature product. Micro-level problem-solving activities are being performed during the design process to generate and then to assess candidate solutions. The present work will distinguish between the evaluation of ASDS (at the macrolevel) and the evaluation of the design ideas generated at the microlevel (during the synthesis step of Fig. 1) in order to produce acceptable solutions (ASDS).

The Function–Behavior–Structure approach supports systematic modeling and reasoning in the systems designing [10] and attempts to explain the act of generating design solutions (thus at the synthesis step of Fig. 1). The Function–Behavior–Structure activities include: a formulation which transforms functions into a set of expected behaviors; a synthesis of a structure which exhibits the expected behavior; an analysis of the behavior produced by the structure; an evaluation between the expected and the produced behavior.

The Function–Behavior–State modeler provides an approach for systematic modeling and reasoning in conceptual design [11]. In [12] it has been extended to incorporate a visualization of geometric information and has introduced interval-temporal logics. It then becomes possible for the system architect to evaluate the consistency between spatial relations in a Function–Behavior–State model and the corresponding geometric model.

Another design approach is represented by the Axiomatic Design, which is a general method for facilitating the synthesis of suitable design requirements, design solutions and design processes. Two principles must be verified according to Suh [13]: the independence axiom indicates to 'Maintain the independence of functional requirements', while the information axiom recommends to 'Minimize the information content of the design'. The independence axiom provides the designer with a measure for rating the correctness of the design, in insisting that an independent relationship, as represented by an uncoupled or decoupled design matrix, is essential for a successful design [14]. Evaluating design solutions according to these two axioms aims at verifying that the system is well designed but does not guarantee that the solutions are the most satisfying to fulfill the stakeholder's needs.

In order to qualify a mechatronic system, a mechatronic index is presented in [15] in terms of flexibility, intelligence and complexity, as these three characteristics account for much of mechatronic products. The intelligence level of a mechatronic system is determined by both its control functionality (which includes programmability, self-diagnosis, self-repair, negotiation, learning and self-organization) and its information computing ability (e.g. knowledge discovery and analysis, inference mechanism and communication) from the low-level control to the general management level. The flexibility property of a mechatronic system translates its capacity to easily change in order to fit new requirements or situations. Complexity is a consequence of the tradeoff involved when increasing the intelligence and flexibility and moreover may be observed through seven indices (including quantity of components, number of interconnections, number of design solution alternatives and number of feedback loops). The benefit of monitoring such indexes is to help mechatronic engineers in better designing their systems (i.e. a verification point of view) by taking into account the typical characteristics of mechatronic products: flexibility, intelligence, complexity, and strongly-coupled physical phenomena.

The approach of evaluation exposed in this paper is complementary to the above research works as it focuses on how to rank ASDS outputted from the synthesis activities and how to select the

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