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Evaluating Complicatedness in Mechanical Design

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Abstract

In this paper, a model is proposed for evaluating the complicatedness of mechanical systems. The differences between a system's complexity and complicatedness are brought to light, and current methods for evaluating complexity are discussed and then illustrated. The concept of complicatedness is then derived from a combination of complexity-evaluating approaches. Subsequently, a model is presented, which calculates the system's complicatedness using existing complexity measures as its variables. Finally, a concluding discussion is conducted about the complexity measures which were included in the complicatedness model, and about further research and decisions that need to be made in order to finalize the model.

Keywords: Design; Complicatedness; Complexity; Mechanical Design;

1. Introduction

As the functional requirements (FRs) of modern technology increase both qualitatively and quantitatively with today's market needs, mechanical design of systems becomes more complex by nature [9], and with complexity comes complicatedness. In recent years, it has become widely accepted that the idea of complicatedness as a resulting byproduct of complexity is worthy of investigating [13], and if a methodology can be crafted to quantify and subsequently reduce it then the majority of the cost-lowering and reliability-improvement goals of complex projects will be met. Then the question becomes: how does one define and quantify complicatedness in mechanical design, and what's its relationship to complexity?

Tang and Salminen explain that complexity is an inherent property of the system [13]. So the idea of a system being "more complex" doesn't have to be negative and undesirable. Some systems are just more complex by nature, due to the desired functional requirements and the scale at which it operates. But complicatedness is a derived property which should be avoided starting at the design stage. The Merriam-Webster definition of Complicatedness is "the state or quality of having many interrelated parts or aspects" [15]. Designing with reduction of complicatedness (i.e. simplicity) in mind, an engineer can design a mechanical system as complex as necessary to satisfy the FRs but with low complicatedness. This helps to maintain the desired level of manufacturability, reliability and cost [1]. This paper is structured in the following order: Section 2 provides a thorough review of existing approaches to evaluate complexity. Section 3 illustrates the complexity evaluation of four mechanical designs in accordance using the most relevant complexity measures. Section 4 conceptually derives complicatedness as function of complexities and proposes a model. Finally, section 5 summarizes and concludes the paper by discussing the future validation and verification methods of the proposed mathematical model.

2. Literature survey

Complicatedness and complexity can be rather difficult to differentiate, though complicatedness carries a negative connotation. Only in recent years engineers began investigating the differences between the two terms and their relationship. Consequently, most relevant literature is concerned with only complexity. There are several definitions and takes on complexity used in different fields and applications. Suh summarizes several definitions of complexity from different fields of sciences [10]. Definitions range from a complex system being "one whose properties are not fully explained by an understanding of its component parts" [10] to Suh's own definition, "a measure of uncertainty in achieving the specified FRs" [10]. Complicatedness, on the other hand, does not have such a wide array of definitions. Tang and Salminen define it as "a measure of uncertainty in

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achieving the specified FRs" [13].

Complexity in design engineering can be evaluated for any of three tightly-related steps described by Ko et al [5]. The steps are: Design Requirements, Design Process and Design Artefact, or Product. Our focus is only on the complexity and complicatedness of the design artefact, i.e. the mechanical system that is the result of the process and design requirements.

Tang and Salminen present a model wherein complicatedness is calculated as a function of complexity [13] as conceptually illustrated in equation (1).

$$K = K(C) \tag{1}$$

They argue that when C=0, then $K(C)$=0 and that K_{max}=1. They illustrate "complicated" and "uncomplicated" complex systems and suggest that one can reduce the complicatedness by architecting the design of the system using modularity. They briefly discuss calibrating complicatedness and then illustrate the reintegration of modulated systems using their formulas.

To date, Tang's complicatedness model is the only one which distinguishes complicatedness from complexity and calculates it as a separate entity. However, this model considers the "bandwidth" of the interactions between components and is mostly relevant to systems which include software and computer programming. They also describe some implications on organizational structuring. But it is less relevant to mechanical design, since evaluating the complicatedness of a mechanical system cannot be done without considering the complexity of the individual components and the functional structure. But some of the core principles are similar.

Since complicatedness of a mechanical system depends on its complexity, and since existing literature only addresses complexity and doesn't separate the two terms, we will present the current takes on complexity in the following paragraphs.

Rigo and Caprace mention that "several factors that will influence product complexity have been identified such as the number of components, the number of interactions/ connections, the number of assembly operations, the number of subassemblies, the number of branches in the hierarchy, the number of precedence levels in the hierarchy, the type of interactions/connections, the properties of interactions/ connections, the type of components, geometry, shape, material, production process, size, density, accessibility, weight, etc." [3]. Indeed, different approaches include different parameters in order to optimize a model which evaluates complexity. Braha and Maimon define two types of complexity measures: structural complexity and functional complexity [2]. The complexity measures are based on the information content, in accordance with Suh's theory [10, 11].

Suh evaluates the design complexity with regards to the information content in the system. His Axiomatic Design theory suggests that complexity is inversely related to the probability of satisfying the functional requirements with the proposed design parameters [11]. This approach is based on Suh's two design axioms: the Independence Axiom and the Information Axiom, as detailed in The Principles of Design.

Other approaches consider the physical properties rather than the information content. Such complexity measures involve the complexity of the assembly and individual components. Measures for component complexity range from Rigo and Caprace's "shape complexity", C_{sh} [3] to the symbolic form C.D$_V$T presented by Little et al. [7]. The latter considers three fundamentals of complexity, but yields a string rather than a number. Alternatively, C_{sh} is based only on sphericity to evaluate complexity, but yields a single metric [3].

For assembly-related complexity, recent theories suggest that a balance should be reached between part complexity (DFM) and assembly complexity (DFA) [8]. Recent approaches lean towards an assembly-oriented design. But it has also been shown that still, much work is required in order to optimize assembly sequencing, since finding an algorithm to optimize assembly sequence is NP-hard [4]. Thus work is required to optimize an accurate assembly-related complexity measure.

Sinha and de Weck propose a complexity model which indeed considers the complexity of the components, their interactions and the architecture [9]. Their model is comprehensive in the physical domain, but the paper concludes with further work that needs to be performed to finalize all the variables. Similarly, Caprace and Rigo propose a model to calculate the complexity of ship design, C_T [3] utilizing factors at the component and assembly levels. Their model for measuring system complexity in this work is mostly applicable to ships. But the individual complexity components may be of interest when evaluating the complicatedness of any system.

Some complexity measures divide the concept of complexity into independent components. Ko et al. introduce the idea of static and dynamic complexities to evaluate the total complexity of the design process [6]. Suh similarly divides complexity into time-dependent and time-independent complexities [10]. He further divides the time-independent complexity into "real" and "imaginary" components. These approaches do not contribute to the complicatedness model. This is because we are concerned with the complicatedness of the final (non-time-dependent) design artifact and not the process. Additionally, while imaginary complexity can exist, it can be reduced and practically eliminated by education, training and collaboration. It therefore doesn't affect the complicatedness of the final design.

Ameri et al. also conducted a thorough survey of the existing complexity measures and models. Based on the methods and formulas currently described in literature, they conclude that there are two independent types of complexity measures: size complexity and coupling complexity [1]. They argue that the complexity measures depend on a graphical illustration of the system. They demonstrate three types of illustrations: a function structure, a connectivity graph and a parametric-associativity graph (PAG). The "size" complexity is based directly on the representation and is calculated using equation (2).

$$Cx_{size\_prod} = (idv + ddv + dr) \times \ln(\rho + v) \tag{2}$$

In this equation, ρ is the number of operands, and v is the number of operators. idv and ddv are the numbers of independent and dependent variables respectively, and dr is the number of design relations as described in [1]. The "coupling" complexity is based on a bi-partite graphs