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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.

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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

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).

$$K = K(C) \quad (1)$$

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_vT 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).

$$Cx_{size_prod} = (idv + ddv + dr) \times \ln(\rho + v) \quad (2)$$

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

described and demonstrated by Summers and Ameri [12]. Thus, resulting are six complexity measures: size-function, size-connectivity, size-PAG, coupling-function, coupling-connectivity and coupling-PAG. The connectivity and PAG representations describe the physical arrangements of the parts and their connections, while the function structure is a flowchart of the material, energy and signals of the system. We will investigate the complexity measures in the two separate domains: the functional domain and the physical domain.

In the function structure, each block (operand) represents the function executed by a component or a set of components. As described in [1], when evaluating the size-complexity of the function structure, $\rho = 38$ and $v = 3$, always. $idv+ddv = dv =$ number of operands, or in this case blocks and input/output arrows. Finally, $dr =$ number of operators, or arrows between blocks. Therefore in the functional domain the equation reduces to equation (3)

$$Cx_{size_func} = (dv + dr) \times \ln(38 + 3) \quad (3)$$

In the physical domain, systems can be represented in either a connectivity graph or a PAG as described above. The PAG representation contains much information about the parts and their “mates” and is very time-consuming to construct. It is not applicable for the complicatedness model. The Connectivity graph is also a physical representation of the parts and connections. But in this simpler representation, less information is used to describe connection between components. Using size-complexity measure based on the connectivity graph, $\rho =$ number of types of connections (such as threaded, press and snap) and $v = 2$ for all cases [1]. $idv+ddv = dv =$ number of operands (blocks) and $dr =$ number of operators (lines between block). Therefore, the size-complexity measures for connectivity graph reduces to equation (4):

$$Cx_{size} = (dv + dr) \times \ln(\rho + 2) \quad (4)$$

As stated earlier, in this paper we aim to develop a model which evaluates complicatedness as a function of the system’s complexity and additional parameters. We will therefore use the relevant measures above on simple designs to further understand how they describe the complexity of the system.

3. Complexity Evaluation Experiment

Before deriving a model which evaluates complicatedness as a function of complexity, it is important to understand the complexity measures. We will use the complexity measures described in equations (3) and (4) to evaluate designs of ME students. The Technion’s Design and Manufacturing Lab offers an excellent opportunity to compare between designs, as students divide into groups which all have to design simple machines. All groups are given the same FRs, hence based on the varying skills and experience levels their designs vary. Students in the lab are at varying levels of progression in their education and some have internship experience in the industry. The designs that emerged from the lab were analysed according to two of the complexity measures in [1]: the Size-Function Structure and the Size-Connectivity Graph. The reason for choosing these

two methods was that of the six methods presented in the paper, they were the two most straight-forward and easiest to work with. This is essential in trying to analyse large and complex systems. The three comparative examples used in [1] were simple machines which don’t contain an overwhelming number of parts and functions. But for the scope of the desired complicatedness model, larger and more complex designs are to be evaluated. For this purpose, the other methods described the paper are impractical.

In the design & manufacturing lab, the students were required to design machines which pull paper from a paper roll and stamps it at least 10 times per meter in consistent intervals. They were free to use up to two motors, and unlimited parts from the lab inventory such as screws, nuts, snap rings, washers, bearings etc. Additionally, they were able to design custom parts to be manufactured by the in-house manufacturing shop. They then proceeded through the usual design process steps such as SDR, PDR and CDR. Figures 1-4 present SolidWorks models of the final design of the four groups in order.

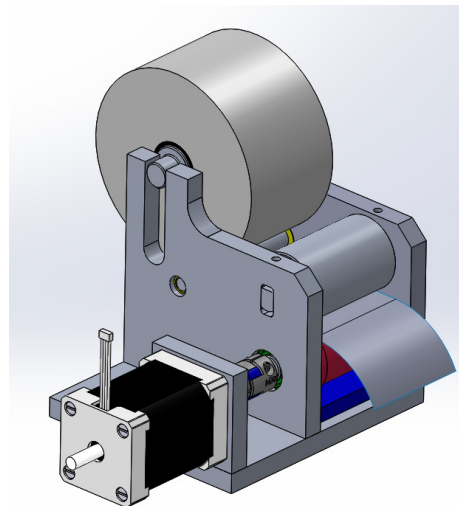


Fig. 1. Group 1 stamper design

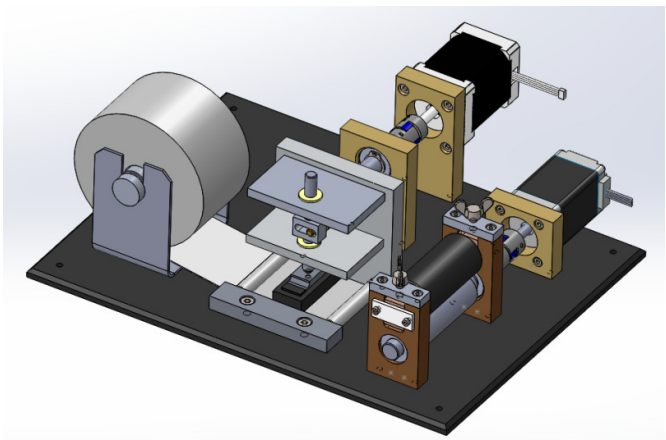


Fig 2. Group 2 stamper design

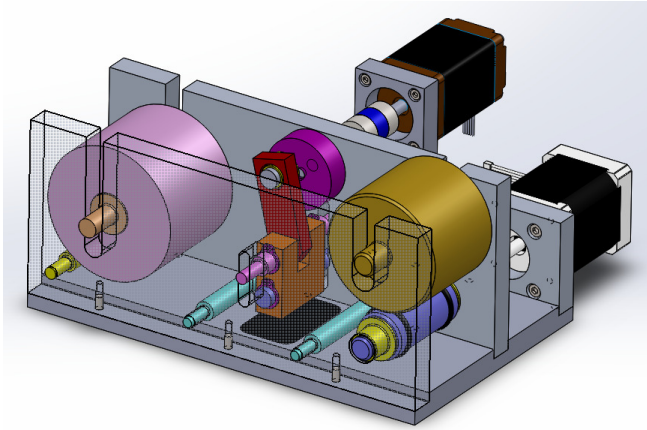


Fig. 3. Group 3 stamper design

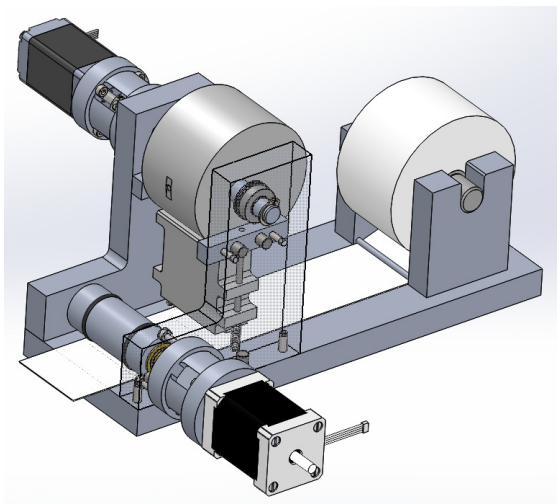


Fig. 4. Group 4 stamper design

All four designs were manufactured, assembled, and their performances was demonstrated in the lab. In order to receive credit for their work, each group's design had successfully pull and stamp 2 meters of paper, stamping consecutively at least 10 stamps per meter.

As mentioned above, the functional requirements were: 1. Pull the paper, and 2. Stamp the paper, which, without breaking down into a function structure isn't very complex. But which design is the most complicated? Which is the least complicated, and which would deliver the lowest manufacturing cost and highest reliability?

In order to evaluate the size complexity based on the function structure and the connectivity graph, each design was analysed and the relevant representations were created using Summers et al.'s instructions [1]. First, we will evaluate the complexity based on the size-function structure.

Figures 5-6 display the function structure illustrations for the four designs.

We added names of some of the components next to the functions they perform to make the above figures easier to check and understand. According to the definitions of parameters explained in [1], the following size complexity measures are calculated: For Group 1: $\rho=35+3=38$; $\nu=3$; $dv=idv+ddv=4+8=12$ and $dr=8$. Plugging this into equation (3) we get a complexity of 74.3 as shown in eqn. (5):

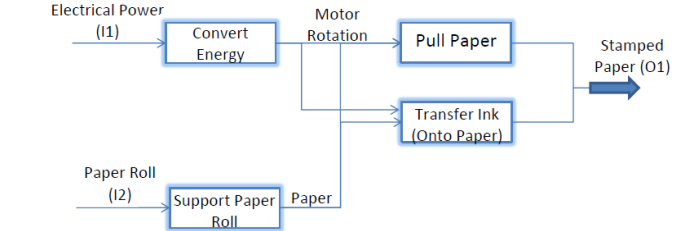


Fig. 5. Function structure for Group 1's stamper

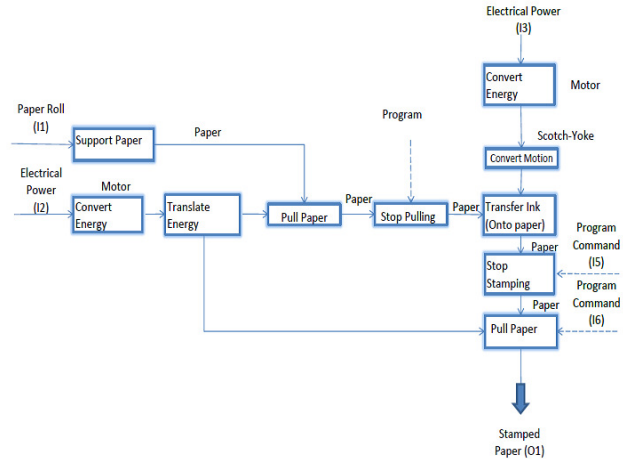


Fig. 6. Function structure for Group 2's stamper

$$Cx_{size_func}(Gr 1) = (12 + 8) \times \ln(38 + 3) = 74.3 \quad (5)$$

For Group 2: $\rho = 35+3=38$; $\nu=3$; $dv=idv+ddv=10+17=27$ and $dr=17$. Thus equation (6) is obtained:

$$Cx_{size_func}(Gr 2) = (27 + 17) \times \ln(38 + 3) = 163.4 \quad (6)$$

In a similar fashion, function structure diagrams are constructed for Groups 3 and 4. The size-complexity measures are calculated for them in equations (7) and (8), respectively.

$$Cx_{size_func}(Gr 3) = (29 + 18) \times \ln(38 + 3) = 174.5 \quad (7)$$

$$Cx_{size_func}(Gr 4) = (32 + 20) \times \ln(38 + 3) = 193.1 \quad (8)$$

Accordingly, based on the function structure representation the size-complexity of the four designs rank as follows, from least complex to most complex:

1. Group 1's design, $Cx_{size_func} = 74.3$
2. Group 2's design, $Cx_{size_func} = 163.4$
3. Group 3's design, $Cx_{size_func} = 174.5$
4. Group 4's design, $Cx_{size_func} = 193.1$

Next, the size complexity of the four designs is calculated based on the connectivity graph, as demonstrated in [1]. Figures 7-8 represent these graphically. Note that the part names used in the graphs are the part names that the student assigned to the parts, and therefore some part names may not seem appropriate, intuitive, or make sense.

From the definitions and examples in [1], the size complexity is calculated from the connectivity graphs. For Group 1: $\rho=1+7=8$; $\nu=2$; $dv=28$ and $dr=65$. The resulting complexity measure for group 1 based on the connectivity graph is shown in equation (9).

$$Cx_{size_conn}(Gr\ 1) = (28 + 65) \times \ln(2 + 8) = 214.1 \quad (9)$$

Similarly, for groups 2, 3 and 4 the size complexity measures are calculated in equations (10) through (12).

$$Cx_{size_conn}(Gr\ 2) = (70 + 135) \times \ln(2 + 9) = 491.6 \quad (10)$$

$$Cx_{size_conn}(Gr\ 3) = (39 + 80) \times \ln(2 + 8) = 274.0 \quad (11)$$

$$Cx_{size_conn}(Gr\ 4) = (48 + 101) \times \ln(2 + 8) = 343.1 \quad (12)$$

Hence, using the connectivity graph representation as a basis for measuring the size complexity yields the following ranking among the four designs, starting with the least complex and going up:

1. Group 1's design, $Cx_{size_conn} = \mathbf{214.1}$
2. Group 3's design, $Cx_{size_conn} = \mathbf{274.0}$
3. Group 4's design, $Cx_{size_conn} = \mathbf{343.1}$
4. Group 2's design, $Cx_{size_conn} = \mathbf{491.6}$

We then compare the results calculated using the two size-complexity measures, and present them in a summarizing illustration, shown in figure 9.

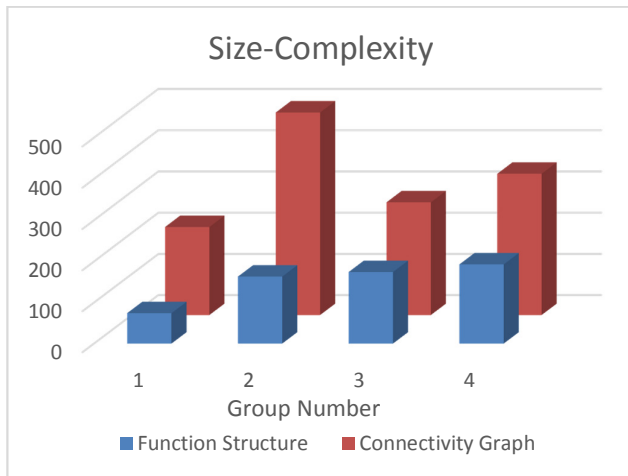


Fig. 9. Result comparison of size-complexity measures

As demonstrated in figure 9, the complexity measures between methods may vary. Designs 1, 3 and 4 retain their rankings with respect to each-other. But design 2 which is less complex than 3 and 4 in the function structure representation, surpasses both in the connectivity graph. The illustrated discrepancies between the two methods are acceptable and even somewhat expected. After all, if all 6 complexity measures presented in [1] always ranked systems in the same order, then using only one would suffice. But for a complicatedness model, a single metric is desired.

4. Complicatedness model

We illustrated the complexity measure results of two models. The first one is based on the function structure of the system which only regards the functionality but not the number of parts or components involved in executing each function. The second is based on the physical structure of the system, i.e. connectivity graph which only considers the parts and their connection without regards to the function they perform. Therefore the two methods are independent, exist simultaneously in two, non-overlapping domains, and result in two different and sometimes contradictory measures. As seen in figure 2, design 2 uses a scotch-yoke mechanism for translating the rotational motion from the motor into a linear, motion required for stamping. Therefore in Group 2's function structure shown in figure 6, a single function presents the role of the mechanism (convert motion). But in the corresponding connectivity graph presented in figure 8, several interconnecting parts make up the scotch-yoke mechanism. In order to calculate the complicatedness of a mechanical system as a function of its complexity, both the physical and the functional complexity need to be considered. By definition, if two mechanical systems perform the same functions, but system B contains more parts than system A, then it is more complicated. Similarly, if two systems' function structures have a similar number of functions, and an operand is added to one system's function structure which translates to several additional operands and operators in the equivalent connectivity graph, then the complicatedness of that system has increased. That is because the physical, part and connection-related complexity has increased disproportionately to the functional complexity. Based on this notion, we claim that a complicatedness model shall include the ratio of physical complexity to the functional complexity. The physical complexity (i.e. number of parts, connections or interfaces, and types of connections) will indicate whether one design solution provides a simpler alternative to another, while the function structure complexity serves as the base of the comparison – the denominator. But to evaluate the complicatedness of a system, it is not enough to calculate the ratio between the size-connectivity and function structure complexities, as this model alone would suggest that a part-reducing approach results in a less complicated system, without regards to the manufacturing complexity of the individual parts or the effects on the assembly procedure. Therefore, we propose a model which takes into account the resulting ratio between the two complexities, and multiplies it by component-based and assembly-related complexity measures. This results in higher complicatedness for systems with few-but-overly-complex parts than for ones with a balance between the complexity of the components and the assembly. This is both intuitive and supported by widely-accepted approaches, such as described by Sinha et al. [9] and Rodriguez et al. [8]. Finally, the proposed model for measuring the mechanical's system complicatedness is presented in equation (13).

$$Ctd = \frac{Cx_{size_conn}}{Cx_{size_func}} \times (Cx_{compont}) \times (Cx_{assem}) \quad (13)$$

$Cx_{compont}$ and Cx_{assem} are the component and assembly complexity measures, respectively. We have not completed

experimental validations for this model, so there is still work to be done regarding these two variables. Note that this model uses *Ctd* as its symbol for complicatedness as opposed to “*K*” used by Tang and Salminen [13]. This distinguishes our mechanically-oriented complicatedness from Tang’s software-oriented complicatedness measure.

In the next phase of our research, the proposed model will be validated experimentally. Our plan for the experiment is as follows: thirty expert mechanical engineers with more than ten years of experience will compare designs of equivalent mechanical systems, designed for similar functionality. The experts will evaluate the complicatedness of the systems and rank them according to complicatedness level based on their knowledge and experience. Model calculated results will be compiled and analysed to determine whether the model agrees with the experts’ assessment.

5. Discussion and conclusion

The proposed model uses existing complexity measures to evaluate the system’s complicatedness. It uses size-connectivity and size-function complexities, as well as a component-related complexity and an assembly complexity. We showed that in order to calculate the mechanical complicatedness of a system it is necessary to have a ratio between the connectivity and the function-related complexity measures. Furthermore, we explained that it is necessary to multiply this ratio by a component complexity measure and by an assembly-related complexity measure. It is important to note that the assembly-related complexity measure is different from the connectivity-related complexity measure. While the former evaluates complexity based on the number of parts and connections, the latter evaluates complexity of the architecture and assembly procedure. Hence having a modular design vs. an integral design will affect the two measures differently. Similarly, other design properties may affect the assembly-related complexity measure differently than the connectivity graph. Example of such properties are: the presence of “hard-to-reach” components and the need for sophisticated tooling.

The derivation of component and assembly complexity measures is still an ongoing effort. We are in the process of evaluating the component complexity measure based on number of dimensions per each part, its symmetry and sphericity. At this stage, we are investigating several approaches for evaluating assembly complexity measure. We also started producing the experiment that will be used to validate the model.

Acknowledgements

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