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EVALUATING COMPLICATEDNESS IN MECHANICAL DESIGN

Key words: complicatedness, complexity, mechanical design, engineering design.

Abstract: Few researchers recognize the differences between complexity and complicatedness. Recent research indicates that complexity is an inherent property of the system, and is not a negative attribute. Complicatedness is a design property that can be reduced starting at the design stage. Design solutions for complex systems can be complicated or simple. This study explores the current definitions of complexity and complicatedness. It is concluded that the complicatedness of mechanical design depends on the complexity of design properties such as number of parts and interfaces, manufacturing processes, and assembly. A model for evaluating complicatedness is derived based on these parameters. The derived complicatedness model is the only model to consider both functional and physical attributes as parameters. This model is the main goal of this research. We analyse three sets of functionally equivalent systems to verify the model. We then validate the model with an experiment in which experienced engineers review the designs of these systems and grade the complicatedness of each. Analysis of the results yields a perfect fit for two of the sets. For the third set, in which industrial design is embedded in the mechanical components, the results are inconclusive.

Ocena skomplikowania w projektowaniu konstrukcji mechanicznych

Słowa kluczowe: skomplikowanie, złożoność, projektowanie konstrukcji mechanicznych, inżynieria projektowania.

Streszczenie: Niewielu naukowców uznaje różnicę pomiędzy złożonością a skomplikowaniem. Jednak ostatnie badania wskazują, że złożoność jest nieodłączną cechą systemu i nie jest to cecha negatywna. Skomplikowanie jest natomiast cechą konstrukcji, która może być zredukowana już na etapie projektowania. Rozwiązania projektowe dla złożonych systemów mogą być skomplikowane lub proste. W prezentowanym artykule analizie zostały poddane definicje złożoności i skomplikowania. Stwierdzono, że skomplikowanie konstrukcji mechanicznych zależy od parametrów projektowych takich jak liczba części i interfejsów, procesów produkcyjnych i montażu. Model oceny skomplikowania oparty jest na tych parametrach. Jest to model, który uwzględnia zarówno funkcjonalne, jak i fizyczne cechy konstrukcji. Opracowanie tego modelu było głównym celem przeprowadzonych badań. Do weryfikacji modelu przeanalizowane zostały trzy zestawy funkcjonalnie równoważnych rozwiązań konstrukcyjnych opracowanych przez niedoświadczonych konstruktorów. Weryfikacja polegała na analizie skomplikowania projektów przez doświadczonych inżynierów, którzy przeglądali projekty tych konstrukcji i oceniali poziom skomplikowania każdego z nich. Analiza wyników pokazała idealne dopasowanie dla dwóch zestawów. Dla trzeciego zestawu, w którym jako elementy mechaniczne wykorzystano rozwiązania przemysłowe, wyniki są niejednoznaczne.

Introduction

In the last years, engineering design tools have gone through a dramatic change in all aspect of the design process. The introduction of novel computer aided design and manufacturing (CAD/CAM) tools, new computer aided engineering (CAE) tools, and the fast growing field of additive manufacturing (AM) provide new means to conduct the design process. During mechanical design process, the majority of mechanical designers attempt to achieve two objectives: (a) to design a functional design that meets a specified set of requirements, and (b) to design it in a "simple" way. But what a simple design means? The basic questions of defining a simple design and the way to achieve it have not been changed with time.

The literature that studied engineering design uses the term "design complexity" in order to evaluate the relations between functional requirements and design parameters.

In axiomatic design, product and problem are coupled through functional requirements and design parameters [1]. Suh proposed two design axioms: the independence axiom and the information axiom. The independence axiom states that the functional requirements should be maintained independent of each other. The coupling between functional requirements and design parameters should be kept to a minimum, ideally by using one-to-one mapping. Suh [2] describes the design process in terms of mapping Functional Requirement (FR) of a system into a set of Design Parameters (DP) and suggest that an uncoupled or decoupled design is less structurally complex than a coupled one. Suh also defines complexity as a measure of uncertainty in achieving the specified FRs and that complexity is related to the information content of the design. The information axiom states that a good design is one that is de-coupled and has minimal information content. In this context, information content is inversely related to the probability of the regarded solutions meeting the functional requirements. Braha and Maimon [3] argued that information content of a design is a relevant measure of complexity. They suggest that complexity is a function of the number of operands and operators of the design and therefore is size dependent. Defining design process complexity in the structural way means that, if two design processes successfully achieve the required specifications, the better design process (in terms of structural complexity) is the one with the minimum total information content.

Structural complexity of a system can be quantified by the information content of the design, i.e. the number and structure of parts, and the interfaces that represent the size and coupling respectively. The functional complexity of a system is a measure of the probability of a system to satisfy functional requirements [2]. Moreover, Braha and Maimon [3] suggested that functional complexity is a measure of the information content of a design in terms of the probability to satisfy system requirements.

When two systems comply with the same set of functional requirements under similar constraints with different mappings, they are defined as equivalent designs [4]. When one compares equivalent designs, reduced structural complexity is a measure for a good engineering outcome.

Ameri et al. [5] propose several different measures to evaluate system structural complexity, both size complexity and coupling complexity. They studied engineering design complexity and showed that different researchers provided different interpretations of the term "design complexity." Table 1 [5] presents a list of 10 published references and the various attributes that each of them used for measuring complexity. Therefore, we realized that the term "design complexity," which is widely used in the literature, was interpreted and might be understood in several different ways.

There are two references that proposed different terminology and suggested distinguishing between design complexity and complicatedness. Tang and Salminen [6] explained that "Complexity is an inherent property of systems; complicatedness is a derived function of complexity," They presented examples of "complex uncomplicated systems," as well as "complex complicated systems." It means that a system with complex requirements may be designed in a way that the outcome of the structural design process is either complicated or uncomplicated (simple).This representation agrees with our understanding that functional complexity refers to achieving given functional requirements, while structural complexity refers to complicatedness of the design outcome. Moreover, Ward [7] used the term complicatedness and showed that a designer that is adding unnecessary (structural) complexity during the design process creates a complicated design, while, by reducing (structural) complexity, one may achieve a simple design.

We propose to clarify the terminology that is used in the literature so that it will be understood not only by scholars but also by design engineers. We suggest that the term "complexity" will stand for "functional complexity." On the other hand, the two terms "complicatedness" and "simplicity" will be used to represent the two potential extremes of "structural complexity." Two equivalent designs [2], i.e. designs that meet similar functional requirements, performed by two different designers may have a different structural outcome. One is simple when an outstanding designer could reduce the number of parts and interfaces, or it is complicated when the designer added functionally unnecessary parts and interfaces.

Several methods exist for comparing design solutions on the basis of estimated cost, performance, and reliability [8]. But there is a strong correlation between these properties and between the complexity and complicatedness of the design; complexity stems from the nature of the functional requirement, whereas complicatedness is the outcome of the design process [5–7].

The main goal of this research is to quantify complicatedness as a metric. This will help mechanical engineers identify complicatedness and reduce it at the design stage. The question is then: How does one define and quantify complicatedness in mechanical design, and how does it relate to complexity?

Tang and Salminen [6] propose that complexity is an inherent property of the system (defined by requirements), so systems are complex by nature.

Thus, “more complex” is not necessarily “less good.” According to Lewis [9], design solutions to complex projects can be “elegant,” i.e. it increases the traceability and understanding of the design, which makes it less complicated. Thus, complicatedness is a derived property, which can be reduced starting at the design stage [6]. Designing with reduced complicatedness (i.e. simplicity) in mind, an engineer can design a functionally complex mechanical system in a non-complicated fashion, i.e. creating simple structural solution.

Ward [7] discusses the relationship between complexity, simplicity, and complicatedness. Though only creating conceptual relationships, he notes how complexity evolves in a mechanical system. According to Ward, in the beginning of the design process, the engineer adds complexity by adding functional utility, until he reaches a critical point, which Ward calls the “peak of complexity.” From there, the engineer can either simplify, by streamlining the processes, integrate and remove elements, making the design “simple,” or add unnecessary complexity, making the design “complicated.” Tang and Salminen [6] and Ward [7] are the only researchers to explicitly differentiate between complexity and complicatedness. But Ward does not attempt to evaluate the properties, but rather to build a basis for the relationship, while Tang and Salminen present a numerical model, which is less applicable for mechanical design. Since all the other researchers only consider the term “complexity,” and since complicatedness depends on complexity, it is important to explore and understand the existing methods for evaluating complexity.

It should be noted that complexity in mechanical design is associated with any of three tightly related steps described by Ko et al. [10]. The steps are as follows: design requirements, design process, and design artefact. The present study focuses only on the complexity and complicatedness of the design artefact, which is the physical product. Some methods to handle complexity in mechanical design involve the optimization of design parameters, assessment of all possible design solutions, and the optimization of assembly processes [11–13]. Suh’s approach to complexity is based on his two design axioms, as detailed in his book *The Principles of Design* [1]. According to Suh’s theory, one-to-one pairing should be reached between Design Parameters (DPs) and FRs.

To best compare design alternatives, a metric is needed, since “without metrics, comparisons, and predictions are difficult to achieve” [14]. It is therefore necessary to find a mathematical model to evaluate complexity and complicatedness numerically.

Some methods for evaluating complexity consider the physical properties of the design, while others consider the functional hierarchy of the system. In the physical domain, several methods evaluate the complexity on the basis of on the part geometry. Little et al. [15] utilize the symbolic form C.Dv.T to evaluate part complexity, and Wu and Levine [16] assess the parametric representation of geometrical shapes based on the Geon theory [17], while Caprace and Rigo [18] use the concept of “sphericity” to evaluate the geometry-based complexity of parts in the design. Other researchers base the complexity of systems on the assembly process; examples include Boothroyd Dewhurst [19], who evaluate assembly time, and Samy and ElMaraghy [20], who utilize tables for assessing the handling and insertion attributes of parts in the assembly. Some researchers utilize complexity indexes of both the parts and the assembly in order to evaluate the complexity of the entire system [18, 21].

In the functional domain, Suh [2] assesses the complexity of mechanical design by analysing the connections between FRs and DPs, while Bashir and Thomson [14] evaluate the complexity according to the hierarchical function structure of the system. These approaches do not consider the physical parts, their geometries, or the interface arrangements.

Some researchers divide complexity into components. Ko et al. [22] introduce the idea of static and dynamic complexities to evaluate the total complexity of the design process. Suh [4] divides complexity into time-dependent and time-independent complexities, and he further divides the time-independent complexity into “real” and “imaginary” components. These approaches are useful when studying the dynamics of complexity throughout the design process. But the goal of the present study is to evaluate the complicatedness of the design artefact, not the process. While imaginary complexity can exist in the process as Suh suggests, it can be reduced and practically eliminated by education, training, collaboration, and use of external resources. Therefore, since the goal is to assess the mechanical design artefact, these factors can be left out.

Ameri et al. [5] surveyed methods previously described in the literature. Their study was relied in some parts on design complexity theory, which was developed by Braha and Maimon [23, 24]. Ameri et al. [5] concluded that there are a few independent ways to measure complexity, and these complexity measures are based on graphical representations of the systems. Ameri et al. suggest two types of complexity: size complexity and coupling complexity. In the present research, only the size-complexity methods are discussed in detail.

Of the three representations described by Ameri et al. [5], the connectivity graph and the parametric associativity graph (PAG) describe the physical arrangements of the parts and their connections, while the function structure is a flowchart of the material, energy, and signals through the mechanical system. Therefore, these measures exist in two non-overlapping domains: the functional and the physical.

In summary, there are several approaches to quantifying complexity in mechanical design. Recent approaches include more than one parameter, such as the complexity of the components, assembly, and interfaces. Most of the models presented here consider complexity of either the functional structure or the physical structure of the system. Ameri et al. [5] are an exception, because they consider both domains, although separately. Since the methods presented by Ameri et al. are comprehensive and applicable at the design stage, it is beneficial to use them to analyse comparable systems.

This article is structured as follows: Section 2 provides an analysis of functionally equivalent systems using the relevant methods, and subsequently develops the complicatedness model. Section 3 presents the use of the complicatedness model to evaluate the complicatedness of three sets of systems. Section 4 describes the validation experiment design, and presents the results and findings of the experiment. Section 5 provides a discussion of the results, and finally, Section 6 summarizes the research and suggests future research.

1. Complicatedness Model

Before developing a model to evaluate complicatedness as a function of complexity, it is important to understand the existing methods for evaluating complexity. In this section, the most relevant complexity measures are used to evaluate a set of four functionally equivalent systems. The results will help determine what aspects of the existing methods can be applied when evaluating complicatedness.

In the following analysis, we use the methods presented by Ameri et al. [5], whose size complexity measure is illustrated in Equation (1).

$$Cx_{size-prod} = (idv + ddv + dr) \times \ln(\rho + v) \qquad (1)$$

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. The meanings of these variables change according to the type of representation used [5].

We use two methods illustrated by Ameri et al. [5] to analyse the systems: the Size-Function Structure and the Size-Connectivity Graph. There are several reasons for choosing these two methods. Most importantly, both methods are applicable at the design stage by representing the systems with easy-to-follow schematics. In their article, Ameri et al. demonstrate these methods on three systems that are of similar scale but are not functionally equivalent.

The above methods will be used to analyse machines that were designed by four groups of inexperienced designers. These same machines will be used again later in an analysis of complicatedness, and the findings

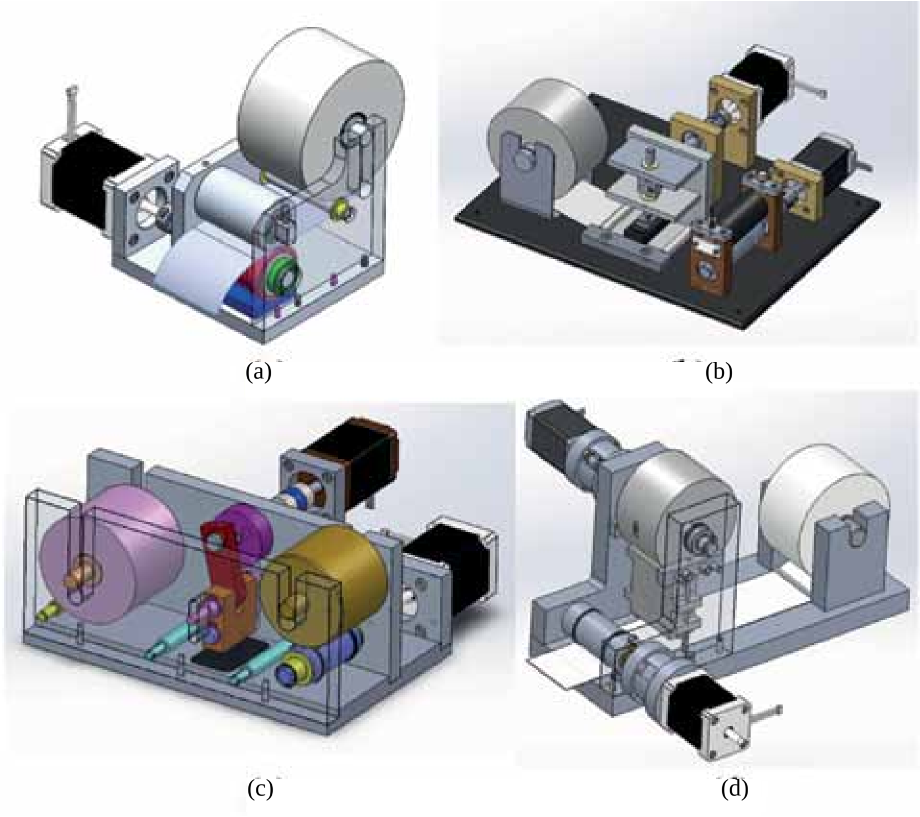
(a) (b)
(c) (d)

Fig. 1. CAD Models of Print Stamping Machine Designs by (a) Group 1, (b) Group 2, (c) Group 3, and (d) Group 4

will be discussed. They designed systems that satisfy presented FRs. They were free to use two step motors and unlimited fasteners from the inventory. Additionally, they were able to design custom parts for manufacturing at the in-house manufacturing shop. The FRs were pull paper from a paper roll and stamp it 10 times per meter in consistent intervals. Fig. 1 presents the CAD models of the designs of the four groups in order.

In order to evaluate the complexity using the methods mentioned above, the function-structure and connectivity graphs have to be composed for each system. This is shown explicitly in the CIRP paper [25]. Of these two methods, only one representation of one system is presented here as an example. This is because, as we will discuss later, only the connectivity graph representation will be referenced in the complicatedness model. Fig. 2 illustrates the connectivity graph of print stamping machine designed by Group 1, as an example. After having constructed the function structure and connectivity graphs, the size complexity is calculated for each design based on the equations presented by Ameri et al. [5]. The equations for function structure and connectivity complexity measures are adaptations of Equation (1) and use similar notation. These modified versions are shown in Equations (2) and (3) for function structure and connectivity complexity measures, respectively:

$$Cx_{size-func} = (dv + dr) \times \ln(38 + 3) \tag{2}$$

$$Cx_{size-connec} = (dv + dr) \times \ln(\rho + 2) \tag{3}$$

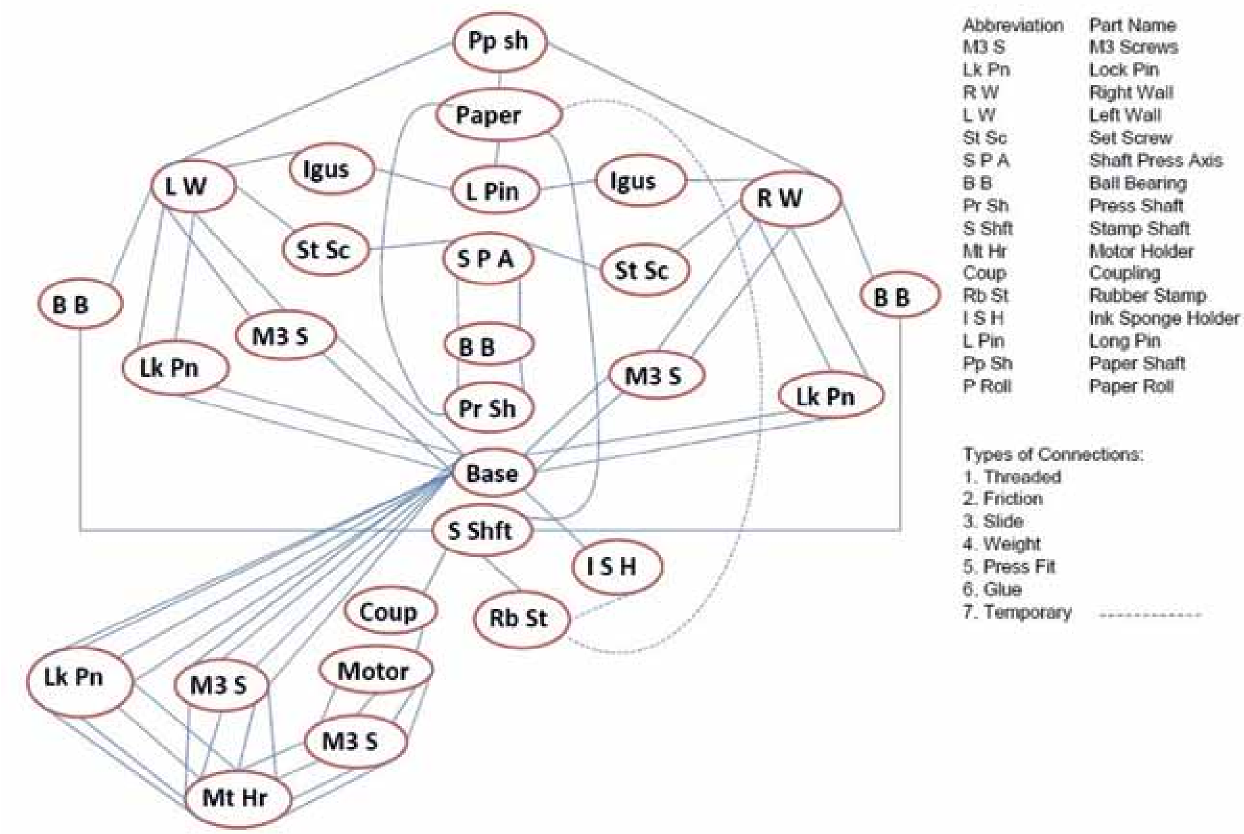

Fig. 2. Connectivity Graph for Print Stamping Machine Design by Group 1

The analysis of functionally equivalent systems presented by Ben-Yehuda et al. [25] illustrated the differences between functional complexity and connectivity-related complexity. The most important conclusion from this analysis was that, in order to evaluate complicatedness in mechanical design, both the physical and functional attributes have to be taken into account. In fact, the notion that the complicatedness of the mechanical system depends on the ratio of physical complexity to functional complexity serves as the basis of the model developed in this research, as elaborated below. We developed the complicatedness model based on the above analysis and through exploring the existing methods and noting their advantages and disadvantages. The complicatedness model will be presented first, and then the selected parameters will be explained in detail. Equation (4) presents the preliminary complicatedness model:

$$Ctd = \frac{Cx_{size-connec}}{NFR} \times \left(Cx_{cmpont}\right) \times (Cx_{assem}) \quad (4)$$

In Equation (4), *Ctd* represents the complicatedness measure, $Cxs_{ize-conne}$ is the size-connectivity complexity, *NFR* is the number of functions executed by the system, Cx_{cmpont} is the average component complexity, and Cx_{assem} is the assembly-related complexity.

The first part of the equation is the ratio between $Cxs_{ize-connec}$ and the number of functions executed by the system. This part of the equation relates directly to the insights gained from the analysis of the two methods described above. It was realized that the functional domain and the physical domain cannot be separated when evaluating the complicatedness of the mechanical design. As the physical, connectivity-based complexity increases disproportionately to the functionality of the system, it becomes more complicated. But dividing $Cx_{size-connec}$ by $Cx_{size-func}$ would suggest that a system with a smaller functional structure is more complicated. This is not necessarily the case, and often is the opposite of reality, because minimizing part-and-interface count by consolidating internal functions does not make the system more complicated. Therefore, *NFR* was used instead.

To evaluate the complicatedness of a system, it is not enough to evaluate the ratio present in the first part of the equation. Simply reducing the number of parts (i.e. part count) does not necessarily yield a less complicated system. Therefore, an "average" part-complexity component must be included in the model. Additionally, the complexity of the assembly process must be included as well, as it may have an effect on the complicatedness of the system, independently of the number of interfaces and parts. The notion that both part complexity and assembly complexity should be taken into account is widely accepted in design engineering [26, 21].

The selection of parameters for evaluating the average part complexity and the assembly complexity components must be discussed further. There are several existing methods for measuring both. For the average part complexity, existing methods include the geometry-based C.D$_v$T [15], the Geon parametric theory [16], and measures of components' technology readiness level [21]. But manufacturing technologies are rapidly changing, and consequently, so is the definition of part complexity. Emerging technologies, such as 3D printing, substantially lower costs and speed up the manufacturing process of many geometrically complex parts. It is often said that with 3D printing, "complexity is free" at the component level [27]. Therefore, using the average manufacturing cost of parts is the proposed parameter. Using this approach is equally applicable for traditional and rapid manufacturing processes. Equation (5) presents the evaluation of part complexity:

$$Cx_{cmpont} = \frac{\ln\left(Avg\_mfg\_cost\right)}{\ln\left(MSR\right)} = \frac{\ln\left(\frac{\sum cost_{dp}}{NDP} + \frac{\sum cost_{pp}}{NPP}\right)}{\ln(MSR)} \quad (5)$$

In equation (5), $\Sigma cost_{\mathrm{dp}}$ is the sum of manufacturing costs for designed parts, *NDP* is the Number of Designed Parts, $\Sigma cost_{\mathrm{pp}}$ is the sum of manufacturing costs for purchased parts, and *NPP* is the total Number of Purchased Parts including fasteners. *MSR* is the Manufacturing Shop Rate. The currency can be changed per the location of the user, as long as it is consistent, and *MSR* is adjusted accordingly. The costs of manufactured and purchased parts are averaged separately, since off-the-shelf parts are typically less expensive, and using more of them does not lower the overall average part complexity. Moreover, since manufacturing costs range from a few dollars to hundreds of thousands, the natural log of the average part cost is used. Finally, to keep this variable unit-less like the rest of the variables in the model, the resulting cost value (in USD) is divided by the natural log of *MSR* (in USD). Since this research is conducted in Israel, an *MSR* of 65 USD is used in all the following calculations. Thus, Equation (5) defines the part complexity used in the complicatedness model.

Next, the assembly complexity variable must be defined. Again, there are several existing methods for this, and this research uses the index CI_{part}, as presented by Samy and ElMaraghy [20], and it can be evaluated solely on the basis of the tables provided in their article. According to their research, CI_{part} is a complexity index, which takes into account the handling and insertion assembly attributes of all the components in the system. Therefore, the complete model for evaluating complicatedness is presented in Equation (6).

$$Ctd = \frac{Cx_{size-connec}}{NFR} \times \frac{\ln\left(\frac{\sum cost_{dp}}{NDP} + \frac{\sum cost_{pp}}{NPP}\right)}{\ln(MSR)} \times CI_{part} \quad (6)$$

Now that the complicatedness model has been defined, it will be used to analyse the same four print stamping machines. Afterwards, two more sets of functionally equivalent systems are analysed using the model.

2. Using the Complicatedness Model

To assess the use of the complicatedness model, the print stamping machines shown in Section 2 are used. For the first part of the complicatedness model, $Cx_{size\text{-}connec}$, is recalled from Section 2:

Group **1**’s design, $\text{Cx}_{\text{size-connec}}$ = **214.1**
Group **2**’s design, $\text{Cx}_{\text{size-connec}}$ = **491.6**
Group **3**’s design, $\text{Cx}_{\text{size-connec}}$ = **274.0**
Group **4**’s design, $\text{Cx}_{\text{size-connec}}$ = **343.1**

Since the systems execute two functions (pulling and stamping), *NFR* = 2. Next, part complexity is evaluated. As shown above, in order to calculate part complexity, the average manufacturing cost must be estimated for the manufactured parts. SolidWorks Costing module is used in this research. For instance, Group 1 utilizes 9 manufactured parts, with a quantity of 1 each. The estimated manufacturing costs of these parts add up to 268.09 USD. Therefore, the average cost of manufactured parts for this system is simply 268.09/9 = 29.79 USD.

For purchased parts, the actual cost can be obtained. The cost of purchased components is averaged in a similar fashion. Cx_{cmpont} is then calculated for Group 1’s design, as shown in Equation (7):

$$Cx_{cmpont}(Gr1) = \frac{\ln\left(\frac{268.09}{9} + \frac{119.89}{30}\right)}{\ln(65)} = 0.84 \quad (7)$$

In a similar fashion, the average part complexity is calculated for the system designs of Groups 2, 3, and 4. The results are 0.77, 0.81, and 0.87, respectively.

Next, the assembly complexity indexes are evaluated based on the tables presented by Samy and ElMaraghy [20]. Cxassem for Groups 1 through 4 are 0.689, 0.668, 0.659, and 0.690, respectively [25]. Finally, once the variables have been evaluated individually, it is possible to evaluate the complicatedness indexes of the designs. This is illustrated using Equations (8) through (11).

$$Ctd(Gr1) = \frac{214.2}{2} \times 0.84 \times 0.689 = 62.2 \quad (8)$$

$$Ctd(Gr2) = \frac{491.6}{2} \times 0.77 \times 0.668 = 127.1 \quad (9)$$

$$Ctd(Gr3) = \frac{247.0}{2} \times 0.81 \times 0.659 = 73.3 \quad (10)$$

$$Ctd(Gr4) = \frac{343.1}{2} \times 0.87 \times 0.690 = 102.5 \quad (11)$$

Incidentally, this arranges the systems in order of increasing complexity identical to $Cx_{size\text{-}connec}$, because, in this case, the size-connectivity complexity has the most dominant effect on the complicatedness measures. But in other cases, the order of complicatedness indexes is not dominated by this factor. Before performing an experiment to validate this in a formal way, we analysed two additional sets of functionally equivalent systems.

The print stamping machines are referred to as “Set 1.” The next set of designs, referred to as “Set 2” contains only three designs. The last set of designs, “Set 3,” contains four designs.

The systems in Set 2 draw a square on an erasable or replaceable surface. Fig. 3 presents the systems in this set.

In this case, *NFR* = 1, since the only FR is “draw a square.” Analysing the size-connectivity complexity of these three systems yields the following results: $Cx_{size\text{-}connec}$(Gr1) = 285.6, $Cx_{size\text{-}connec}$(Gr2) = 315.5, and $Cx_{size\text{-}connec}$(Gr3) = 462.8.

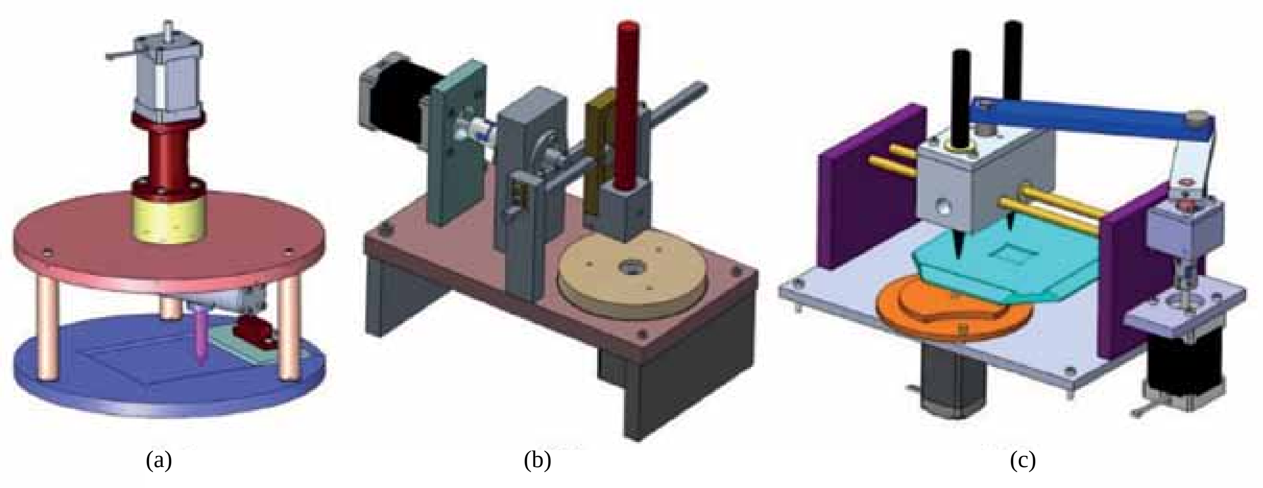
(a) (b) (c)

Fig. 3. Design Overview of Set 2, (a) Group 1, (b) Group 2, and (c) Group 3

Next, the average component complexity indexes are calculated based on the manufacturing costs. The average part complexity, in accordance with Equation (5), for Groups 1, 2, and 3 are 0.60, 0.66, and 0.63, respectively. The assembly complexity indexes are evaluated based on Samy and ElMaraghy's tables [20], and the results, along with the rest of the components of the model (calculated above), are plugged into the complicatedness model, resulting in complicatedness values of 114.0, 124.9, and 131.9, for Groups 1, 2, and 3, respectively.

According to these results, the order of the designs from the least complicated to the most complicated is as follows:

Group 1's Design
Group 2's Design
Group 3's Design

This order makes sense, since Group 1 fulfils the task using only one motor and mechanism, whereas Groups 2 and 3 each use two motors and two mechanisms. Group 3 further complicates the design by using the Geneva mechanism for translating the rotation from the motor to a partial rotation of the surface.

In a similar fashion, a third set of functionally equivalent systems is assessed using the complicatedness model. Set 3 is different from Sets 1 and 2, because it emphasizes both mechanical and industrial designs. The FRs were to do the following: raise a ball on one path, lower it (or drop it) on a separate path, and have the ball skip every fifth cycle, while the elevator mechanism runs a blank cycle. The designs for this set can be seen in Fig. 4.

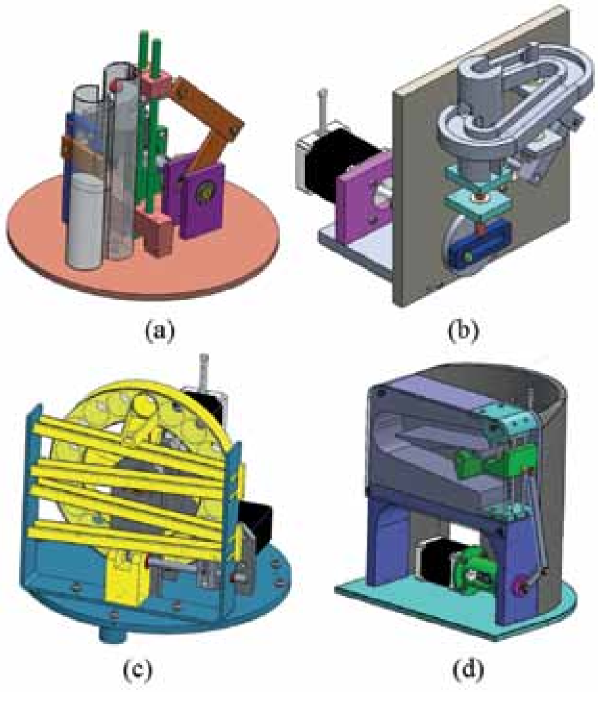

Fig. 4. Design overview of Set 3, (a) Group 1, (b) Group 2, (c) Group 3, and (d) Group 4

In this Set, the calculations for the individual variables in the complicatedness model are carried out in the same way as for Sets 1 and 2. The results are summarized below:

Group 1's design (*Ctd* = 49.9)
Group 2's design (*Ctd* = 50.3)
Group 4's design (*Ctd* = 66.1)
Group 3's design (*Ctd* = 52.5)

The complicatedness index for Groups 1, 2, and 4 are very close, while Group 3's design is noticeably more complicated. This is not surprising when examining the design solutions. Group 3 makes several sacrifices, in terms of complicatedness, in favour of a visually appealing machine. This group has the highest part count and the most complex assembly. Therefore, the scores received for the designs in this set, together with the analyses of Sets 1 and 2, verify the consistency of the complicatedness model. But to formally validate the model, a validation experiment is performed as described in the next section.

3. Validation Experiment, Results and Findings

In addition to the verification process, a validation experiment was conducted. During the experiment, 30 experienced mechanical engineers reviewed the design of the system assessed in the study, and they evaluated the complicatedness of each design. After reviewing the designs thoroughly, participants graded the complicatedness of each design using a seven-point Likert scale. This experiment was executed individually to prevent discussion among participants and to enable the operator to help with any technical questions. The design of each system was presented in a thorough but unbiased fashion, which did not direct the user towards the system properties used in the model. Instead, participants were able to scroll through exploded views, section views, and overall views, as well as assembly animations and videos of the final design during operation. The experiment was programmed in LabView Software [28], and the layout of modules was intuitive and user-friendly to enable participants to really understand the mechanical design in detail. Before submitting the scores for each system, the participants were able to view all systems in a set, compare the scores they assigned to each system, and change them without limitations.

The results were analysed using one-way ANOVA and Kendall Correlation coefficients. The results for Sets 1 and 2 illustrated a perfect match with the model's prediction with a statistical significance of $p < .0001$.[1] The results are summarized in Tables 1 and 2.

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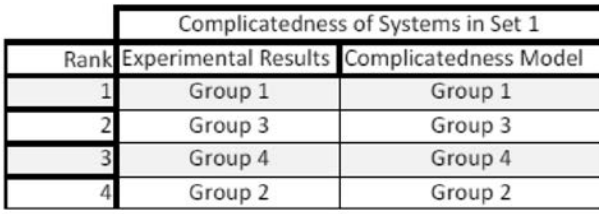
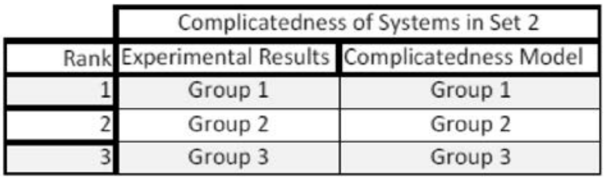
[1] For Set 1, we also used the Glimmix Model to prove statistical significance of the conformation to model.

Table 1. Comparison of Ranking of Designs' Complicatedness for Set 1



	Complicatedness of Systems in Set 1	
Rank	Experimental Results	Complicatedness Model
1	Group 1	Group 1
2	Group 3	Group 3
3	Group 4	Group 4
4	Group 2	Group 2

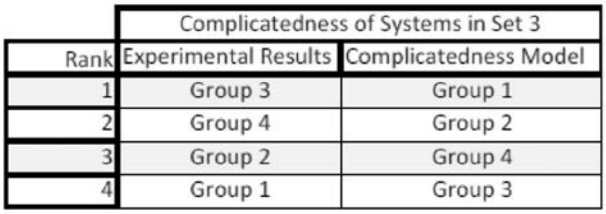
Table 2. Comparison of Ranking of Designs' Complicatedness for Set 2



	Complicatedness of Systems in Set 2	
Rank	Experimental Results	Complicatedness Model
1	Group 1	Group 1
2	Group 2	Group 2
3	Group 3	Group 3

In Set 3, there was no match between the scores of the participants in the experiment and the model's prediction. Table 3 compares the experimental results to the model.

Table 3. Comparison of Ranking of Designs' Complicatedness for Set 3



	Complicatedness of Systems in Set 3	
Rank	Experimental Results	Complicatedness Model
1	Group 3	Group 1
2	Group 4	Group 2
3	Group 2	Group 4
4	Group 1	Group 3

The design approach for Set 3 is briefly mentioned above (integrating mechanical & industrial designs), and it is a dominant factor in this discrepancy. But before analysing the differences between the sets, we present the Kendall Correlation analysis, which yields important findings (Fig. 5).

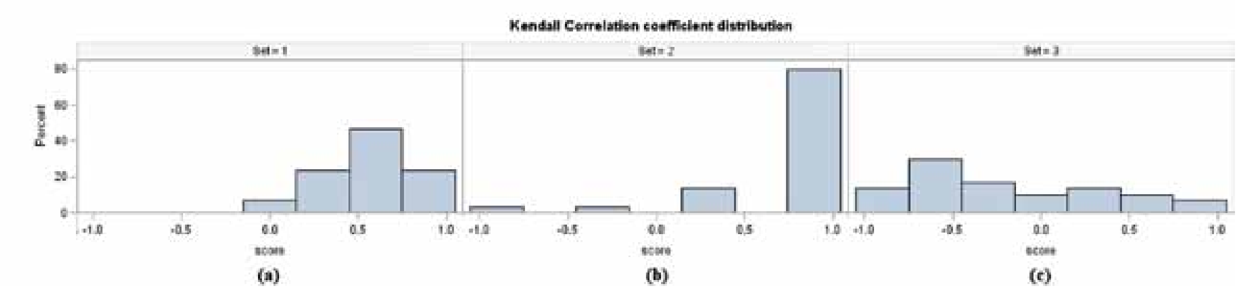


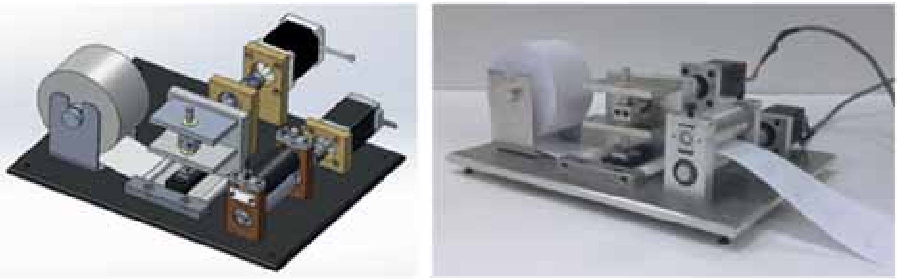
Fig. 5. Kendall Correlation Coefficient Results for (a) Set 1, (b) Set 2, and (c) Set 3

Two major findings from this analysis may help clarify the difference in results between the first two sets and the third one. First, the results from Sets 1 and 2 show a high agreement among participants, with more than 50% of participants receiving a Kendall Correlation above 0.67 for Set 1, and 80% of participants receiving a correlation of 1 for Set 2. But in Set 3, the Correlation distribution is almost even throughout the scale, showing no agreement among the participants. Second, the significance test of correlation between the experimental results and the model evaluation result in *p* values less than .0001 for Sets 1 and 2, but a *p* value of .075 for Set 3, which is insufficient. This shows that the disagreement among participants for Set 3 is more significant than their "average" scores compared to the model's predictions.

4. Discussion

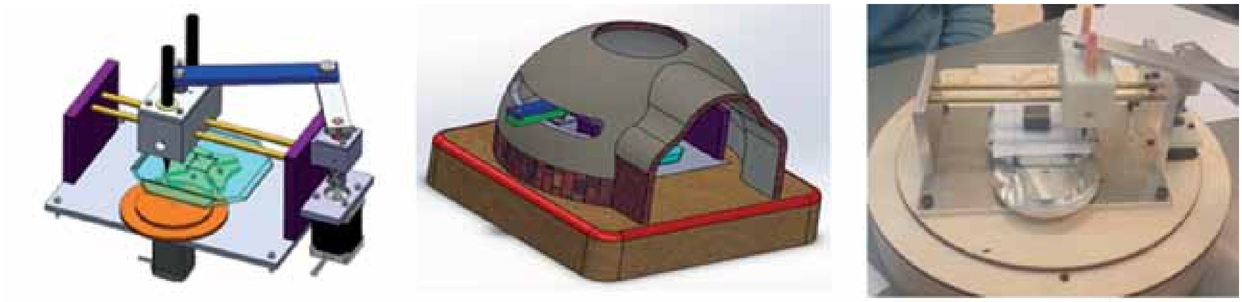
As mentioned above, the experiment findings present a significant fit of the model for Sets 1 and 2, but not for Set 3. Also, the systems in Set 3 are different from the systems in Sets 1 and 2, in that the mechanical design and the industrial design are integrated. In fact, in Set 1, the design approach may be referred to as *exposed* design, and in Set 2 as *enveloped* design, while in Set 3 the mechanical design and the industrial design are *embedded*. To understand these terms, the conceptual designs must be compared to the physical systems. In *exposed* design, the CAD models are identical to the physical system, as illustrated in Fig. 6.

In *enveloped* design, the mechanical design goes into a decorative covering, which hides the mechanical design from the user. Such is the case in most consumer products, from coffee makers to automobiles. But when assessing the complicatedness of *enveloped* design, as required in the experiment, the decorative covering can easily be removed to expose the mechanisms themselves (Fig. 7).



(a) (b)

Fig. 6. Comparison of (a) CAD Model and (b) Design Product for *Exposed* Design



(a) (b) (c)

Fig. 7. Comparison of the (a) CAD model of Mechanical Design, (b) Mechanical Design *Enveloped* with Industrial Shell and (c) Mechanical Design with Covering Removed for *Enveloped* Design

(a) (b)

Fig. 8. Comparison of (a) CAD Model and (b) Design Product for Embedded Design

But in *embedded* design, as seen in Set 3, some of the mechanical components also serve as industrial design decorative elements. Thus, when evaluating the complicatedness of the mechanical design, it is not possible to completely eliminate the industrial design elements and effects (Fig. 8).

In Set 3, Group 3 exhibits the most elaborate industrial design, while Group 1 has the dullest design, shown in Fig. 9.

The operation of Group 3's system is also very smooth and visually appealing, compared to that of Group 1, whose operation seems non-elegant, though the two systems fulfil the FRs equally. It is not surprising that several participants grade the more elegant designs as "less complicated." If it were possible to ignore the industrial design, one would realize that Group 3 uses unnecessary zig-zagging ramps that do not affect the fulfilment of the FRs, requires a more complex assembly

Fig. 9. Set 3 – Group 1 Final Design

with additional tooling, and uses a disproportionate number of parts and interfaces. Yet, the industrial design apparently "tricks" the engineers who participate in this experiment. This issue was pointed out by at least one engineer as a feedback comment at the end of the experiment. Maeda [29] explains this phenomenon in his book *The Laws of Simplicity*: "anything that can make the medicine of complexity go down easier is a form of simplicity, even when it is an act of deceit" (p. 5). These results do not mean that the complicatedness model is not usable for *embedded* design, as the design for Group 3 is objectively the most expensive, most time consuming, and most difficult to assemble and disassemble for maintenance. The disagreement between the model and experimental results, and among participants for Set 3, indicates that the current validation experiment is less suitable for this type of design. Perhaps this can be the subject of future research. However, the model applies well to *exposed* and *enveloped* designs, where the aesthetic features of the design are either negligible, or can be removed to expose the mechanical design to the engineers.

Summary and Conclusion

This study addresses the emerging need to quantify and evaluate complicatedness and highlights the differences between complexity and complicatedness in mechanical design. We explain that complexity is a system property that stems from the nature of the project, and it is not a negative trait on its own. Complicatedness, on the other hand, is a derived property of the design, and can be identified and minimized.

Some of the most advanced methods for evaluating system complexity were illustrated on functionally equivalent systems. These methods evaluate complexity in both the functional domain (based on the system's function structure) and the physical domain (based on the number of parts, interfaces and types of interfaces), although separately. It was then concluded that, in order to evaluate complicatedness, both the physical and functional domains must be considered, as the physical complexity depends on and should be evaluated in relation to the number of functions the system performs.

A model was developed to evaluate complicatedness in mechanical design, based on the connectivity complexity method [5], the number of functions performed by the system, the average complexity of parts, and an index of the assembly complexity of the system [20]. The use of the model was demonstrated on three sets of functionally equivalent systems. In an experiment carried out for validating the model, 30 experienced mechanical engineers assessed the complicatedness of the three sets of systems. After these experts graded the systems, an open-ended question allowed them to discuss design properties that affect complicatedness. Finally, these participants rated the effects of predetermined design properties on the complicatedness of the design.

The findings of the experiment reveal that the complicatedness model works as predicted for *exposed* and *enveloped* designs, at least for relatively simple systems. For *embedded* design – where there is high integration of the industrial design within the mechanical solution – the correlation between the model and the experimental results is unclear. For this type of design, the model may still be valid, but proving it by using experienced engineers poses a certain challenge.

Thus the main conclusions of the research are as follows:

1. Complexity and complicatedness in mechanical design are different and non-interchangeable, which is not recognized in the mechanical design context today.
2. According to our study, complicatedness in mechanical design depends on the ratio of physical connectivity to number of functional requirements, on the average complexity of parts manufacturing, and on assembly complexity.
3. The model is validated with statistical significance for relatively simple mechanical systems that utilize the *exposed* and *enveloped* design approaches.

Further research into the model and its applications is recommended. Ideally, the model can be used for evaluating the complicatedness of mechanical designs as part of the design process or as part of the design review process. Both uses may help lead to less complicated designs. Creating a software program to automate the calculations by using data from the CAD models may help the model become more practical and user friendly.

Preferably, this software can be integrated into the mainstream CAD programs. Such software can also highlight the portion of the model that causes “the most” complicatedness. This would help the designer make better design decisions.

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