Measuring Static Complexity in Mechatronic Products

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Abstract. The complexity present in products does not only affect development time, it also has impacts on production, for example: production costs, manufacturing lead times, quality and customer satisfaction. The complexity of the product will have a profound impact on the manufacturing organization and the product management style. A complex product generally consists of a large number of components, elements or agents, which interact with one another and with the environment. A system or product would be more complex, if there are more parts or components, and more connections between them. The main objective of this article is to propose a methodology to measure the complexity in a mechatronic product. In the course of proposing this methodology, several methodologies used by different authors to measure this variable are studied. The proposed methodology is applied to measure the complexity of four products manufactured and marketed by a Brazilian company. The proposed methodology uses tools such as the DSM (Design Structure Matrix) to support the calculation of the complexity between the interconnections of the subsystems of the products.

Keywords: Product complexity · Mechatronic product · Production systems

1 Introduction

The current economic environment is characterized by increasing customer requirements on product performance, quality, and price, leading to a highly dynamic product design environment with shortened development and product life-cycles [1]. Currently NPD (New Product Development) teams are in a constant struggle to reduce development times, because the product life cycles are becoming shorter. Shorter life cycles lead to greater complexity in the areas of product and process design, factory implementations and production operations [2].

Complexity is an inseparable aspect of complex products [3], particularly in mechatronic systems with a large number of components and interconnections, interactions,

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and interfaces [4, 5]. Modelling the complexity is increasingly challenging in these systems [6], being related to the number of product components/parts and their interaction [7–11], the number of different disciplines necessary for designing the product [12], the degree of innovation and the technology novelty [7, 13, 14], and the complexities involved on customer interfaces [4, 15]. A high product complexity can impact manufacturing, inventory and distribution areas and consequently production costs [16]. Given this scenario, this article provides a method to measure the complexity in a mechatronic product, as a first step to propose a methodology to manage the complexity in a mechatronic product and thus mitigate the impacts of these variables in the manufacturing or product development process.

The complexity of a product is usually determined by the number of components, elements or agents that interact with each other and with the environment [17]. This paper addresses elements to deepen the understating of the product static complexity. Next section presents a review of literature listing works that strive to find solutions for managing product complexity. In Sect. 3, the method for complexity determination is exposed. Section 4 presents the features of products studied here. Section 5 shows the application of method in four products, which are produced by the same company. Finally, Sect. 6 presents the conclusions and future works to give continuity to this research topic.

2 Theoretical Revision

To identify indicators for measuring complexity, the IEEE, SCOPUS and SCIENCE-DIRECT databases researched. The keywords of this research were Mechatronic Product and Complexity. These works are presented below.

According to Barbalho, Chapman, Novak and Danilovic in [8, 14, 18, 19, 20, 21], a mechatronic product complexity can be calculated on the basis of the number of product components, the extent of interaction, the degree of innovation embedded in the product, and the number of different kinds of technology employed.

In [22], Pugh uses math to calculate product complexity with the variables: number of parts, number of types of parts, number of interconnections and interfaces, and number of functions that the product must perform. With these variables, the authors calculate the product complexity for forecasting the production costs. Hobday in [23], presents an example of assessing the complexity of an air traffic control system, and a flight simulator, as a way to wonder about product costs. Hobday uses 16 indicators to evaluate the product complexity associated with the development cost.

McCarthy et al. [24] defined a range from one to five for a set of product complexity elements with the intention of numerically measuring the total complexity of a company. Likewise, Meysam et al. [25] presents a table to measure the complexity of a mechatronic product, explaining the concepts that are used to evaluate it. Moulianitis et al. [12] present the characteristics of a mechatronic product in terms of an indicator vector that contains variables of intelligence, flexibility and complexity. To assess complexity, Moulianitis uses the number of components, number of internal interconnections, number of design alternatives, number of feedback loops, number of knowledge base, degree of customization, and degree of intelligence. In [14], Danilovic represents a product by implementing the DSM (Design Structure Matrix) to manage the dependencies and relationships of the product components and the DMM (Domain Mapping Matrix) to compare two different products or projects. It is possible to observe that DSM and DMM matrices allow viewing the whole product with all components and interconnections, offering great support for estimating and visualizing the complexity of a mechatronic product.

For Zhang [26], the complexity of the product is determined by the analysis of its technology and size to optimize product design and evaluate design alternatives for different production systems. Hehenberger in [27], defines an equation that allows to calculate the probability of technical success by quantifying the complexity of the project. Ahmadinejad [28] used the DMM and DSM matrices to obtain the structural model of an intelligent gas meter. Tastekin [29] uses the Gray measurement methodology to measure the complexity of five software products. Medina [30] presents a study to measure design complexity (DC) in medical devices by using the device functions and components with their interactions and variations. Park an Kremer in [31] define metrics to correctly calculate the static complexity for both design and manufacture processes. These proposed complexity metrics are based on the concept of similarity of products and processes. Diagne in [32], proposes a methodology based on DSM matrix principles to evaluate the performance of a complex product.

According to Elmaraghy et al. [33, 34] the type of complexity may be classified as: (i) static or (ii) dynamic. Static complexity is time-independent complexity due to the product and systems structure and dynamic complexity is time-dependent and deals with the operational behavior of the system [35].

Park and Kremer [31] argue that since static complexity is based on a functional analysis of product design, it is useful to clearly identify the direct impact of complexity on manufacturing performance. Static complexity is made up of factors (a) structural, (b) computational and algorithmic, (c) size, volume, and quantity, and (d) network interaction [34]. Park focuses on static complexity, occurring from the structural configuration of a system, from the perspectives of both product design and manufacturing, and scrutinizes the impact of complexity on manufacturing performance.

Regarding the visualization of the internal interconnections between the subsystems of a product, a tendency to use the DSM tool and its derivatives can be observed. Therefore, it is proposed to use this tool to measure the complexity of the internal structure of the mechatronic product.

For the full product complexity determination, it is possible to observe the tendency to use tables, where a value is simply given to an indicator. These evaluations of the indicators are directed to count the number of components, knowledge bases and others. So, the challenge of this research becomes to unify a method that can express the complexity derived from the internal structure of the product (exchange of in-formation (software)-energy-material-space), the complexity derived from the physi-cal components (number of components, degree of customization and others) and the complexity derived from the interdisciplinary nature of the product (areas of knowledge and others involved).

In accordance with the main objective of this research, a methodology to measure product complexity should be used. Starting then from the literature review of the most used indicators to measure the complexity of a technological product, from the definition of static complexity and the similar to [31], in this proposition a time independent analysis is made (calculation of static complexity).The works presented in this section (fourteen papers) study the complexity from different points of view. Table 1 presents the mentioned indicators and the frequency with which they are used by the referenced authors.

Table 1 shows that the most frequent indicators to measure the complexity in a product, according to the bibliographic review of this section are the indicators 1, 2 and 9 that correspond to: (a) the quantity of the components, (b) the degree of complexity of the interconnections between components and (c) The degree of customization of the final system.

Table 1. Indicators of complexity in technological products.

Indicators	Referenced works	Percentage (%)
1. Quantity of components	13/14	92.86
2. Interconnections Complexity	9/14	64.29
3. Financial scale of the project	1/14	7.14
4. Product volume	2/14	14.29
5. Number of knowledge bases for product design	6/14	42.86
6. Degree of technological maturity of the process	5/14	35.71
7. Software complexity	1/14	7.14
8. Degree of variety of components	3/14	21.43
9. Degree of customization of the final system	7/14	50
10. Feedback cycles of later phases	1/14	7.14
11. Intensity of the client's participation in the design	1/14	7.14
12. Uncertainty/alteration in user requirements	1/14	7.14
13. Intensity of participation of suppliers	1/14	7.14
14. Regulatory standards	3/14	21.43
15. Quality of the staff	3/14	21.43
16. Number of departments to develop the product	1/14	7.14
17. Competition in the market	1/14	7.14
18. Transformation of information	1/14	7.14
19. Resource allocation	1/14	7.14
20. Number of suppliers and customers	1/14	7.14
21. Number of Product Functions	3/14	21.43
22. Complexity of manufacturing	1/14	7.14

To obtain better results in the evaluation of the complexity in a mechatronic product, the indicators found in the review should be taken into account, however this work was limited to choosing the indicators whose information was provided by the company. Nevertheless, the insight presented in this chapter provides the reader with indicators, tools and bibliography for determining the complexity of a product.

3 Proposal to Measure the Static Complexity in Products

Based on Table 1, Table 2 is proposed to measure the static complexity. The indicators listed on Table 2 were chosen according to the applicability (information provided by the company). The indicators were identified in the company documentation, and analyzed by an experienced engineer. In column 5 of Table 2 it is explained how the authors evaluated each indicator.

The indicators 2 and 6 (Table 2) represent the complexity provided by the mechatronic nature. The mechatronic nature refers to the interaction and integration of different disciplines that involve a mechatronic product. Indicator 2 lists the number of areas involved in the design of the mechatronic product and indicator 6 evaluates the degree of interaction of these areas within the mechatronic product. These areas are found in the structure of the product represented by subsystems, modules or others. The degree of integration is directly proportional to the degree of interaction of the areas and the number of areas.

Table 2. Complexity determination table

Indicators (I)	Evaluation (E)	Maximum limit (ML)	Complexity (C)	How to calculate
I.1. Number of Fuctions				Counting the number of primaries functions for which the prototype is designed
I.2. Number of knowledge bases				Listing the number of areas of knowledge that are necessary for the implementation of the main functions of the prototype
I.3. Components number				Counting all the components of the prototype

(*continued*)

Table 2. (*continued*)

Indicators (I)	Evaluation (E)	Maximum limit (ML)	Complexity (C)	How to calculate
I.4. Degree of variety of components				Counting the total number of components without repetition in the prototype
I.5. Degree of customization of the final system				Counting the number of components, the company had to design and manufacture (unique components)
I.6. Degree of complexity of the interconnections between components				Dividing a prototype into its main subsystems and calculating the strength of the interconnection from 1 to 5 in space dependencies, information exchange, material ex- change and energy exchange, based on [36]. In order to analyze the ex- change of information, it was necessary to study the algorithms of each product, thus addressing the complexity of the software
Total complexity (TC)				Adding all values in column 4

For the measurement of complexity, the maximum values (column 3) were calculated as the *maximum (Indicator1.Product1, Indicator1.Product2, Indicator1.Product3, Indicator1.Product4)* and so on for each indicator: (I.1) 1, (I.2) 4, (I.3) 2474, (I.4) 927, (I.5) 475 and (I.6) 374. These maximum values correspond to the highest data in the evaluation of the indicators in the products studied.

In the bibliographic review carried out in this section, it was observed that the works [14, 32, 36, 37], used the DSM (Design Structure Matrix) to visualize and understand the operation of a complex product. In the evaluation of the complexity proposed in this work, DSM is used to evaluate the indicator "Degree of complexity of interconnections between subsystems". Figure 1 presents an example of the DSM of a product having 4 subsystems (a, b, c and d). Each evaluation of the complexity of an interconnection is evaluated considering the interaction guidelines defined in [36] as: *Spatial,* associations of physical space and alignment between the components or subsystems, *Energy, t*he interaction of the Energy type identifies needs of a physical phenomenon between two elements, *Information*, the interaction of the type of information identifies the need to exchange information or signal between two subsystems or components and *Material, t*he interaction of the type of material identifies needs of interfaces or components between two elements.

The interconnections represented by each position of the matrix receive a rating from 1 to 5 depending on their complexity (0 represents a null value of relations between subsystems and 5 the maximum value of relation between subsystems). At the end, the values of each position of the matrix are added and the result of this sum is the value of complexity of the interconnections of the product. To fill the DSM, specifically the Information Exchange (Information) item, it is necessary to study the algorithms of each product, which considers the software complexity as an influential indicator in the complexity determination.

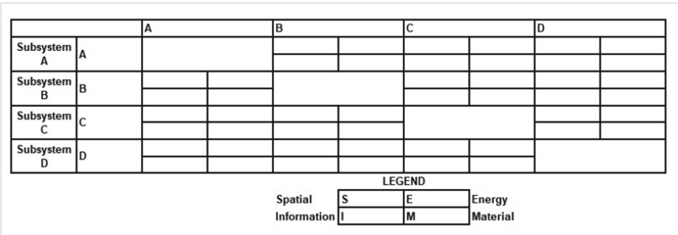

Fig. 1. DSM for the evaluation of the complexity of interconnections between product components.

4 Products Features

The company studied is a Brazilian company in the field of optics, which operates in medical, industrial, optical components, aerospace and defense. The structural and functional characteristics of the products were extracted through the analysis of the documentation provided by the company. Table 3 was filled with the characteristics of the products and shows the values of the indicators of each product, necessary for the calculation of the static complexity.

Table 3. Indicators information for the complexity evaluation

Indicators	Product 1	Product 2	Product 3	Product 4
I.1. Product functions number	1	1	1	1
I.2. Number of knowledge bases for product design	4	4	2	4
I.3. Number of components	2474	1515	46	2340
I.4. Degree of variety of components	927	404	30	750
I.5. Degree of customization of final system	475	150	25	400
I.6. Interconnections Complexity	324	374	72	345

5 Methodology Application

This section presents the application of the methodology for the measurement of static complexity, specifically for product 1 to exemplify the step-by-step process. By analyzing the internal structure and identify the product 1 subsystems, the DSM was designed and filled to determination of (I.6). This matrix is shown in Fig. 2. According to Fig. 2, the complexity of the interconnections for product 1 is 324, based in the methodology proposed to evaluate this indicator. Then, total complexity of product 1 is then calculated according to the indicators used in this article. Table 4 shows the values obtained to calculate the product 1 complexity.

Product 1	A		B		C		D		E		F		G		H	
Client A			0	0	2	0	0	0	5	0	5	0	3	0	1	0
			0	0	5	0	5	0	5	0	0	0	4	0	2	0
Subsystem B	0	0			1	3	2	3	0	0	0	0	0	0	0	0
	0	0			5	0	5	0	0	0	0	0	0	0	0	0
Subsystem C	4		2	2			5	4	5	5	3	3	4	0	2	1
	5		5	0			5	0	2	0	2	0	3	0	2	0
Subsystem D	0	0	2	2	5	5			2	0	3	0	3	2	0	0
	5	0	5	0	5	0			2	0	5	0	5	0	0	0
Subsystem E	5	0	0	0	5	5	2	0			5	5	0	0	5	5
	5	0	0	0	2	0	2	0			0	0	0	0	0	0
Subsystem F	5	0	0	0	3	3	2	0	5	5			0	0	0	5
	4	0	0	0	2	0	5	0	0	0			0	0	0	0
Subsystem G	4	0	0	0	4	0	3	2	0	0	0	0			0	5
	5	0	0	0	4	0	5	0	0	0	0	0			0	0
Subsystem H	4	2	0	0	2	2	0	0	5	5	0	5	0	5		
	5	0	0	0	2	0	0	0	0	0	0	0	0	0		

Legend

Spatial	S	E	Energy
Information	I	M	Material

Fig. 2. DSM to evaluate the complexity of the internal interconnections for product 1.

For the Number of Product Functions indicator (I.1), the main function of product 1 is to allow the physician to quickly and clearly visualize the background of the eye, allowing accurate examination of the retina. For the indicators Number of Knowledge bases (I.2), Number of components (I.3), Degree of variety of components (I.4), and Degree of customization of final system (I.5), it is only necessary to count the components of the product. As can be seen in Table 4, the static complexity of the product 1 is 587. Tables 5, 6 and 7 show the complexity tables for Product 2, Product 3 and Product 4, respectively.

Table 4. Complexity of product 1

I	E	M	C
I.1	1	1	100
I.2	4	4	100
I.3	2474	2474	100
I.4	927	927	100
I.5	475	475	100
I.6	324	374	87
TC	$\sum$C		587

In this investigation, each Indicator is evaluated from 0 to 100, with respect to the highest values assigned to the indicator. Therefore, if a more complex product is added to the study, the limit values of the table will be modified. For further studies, tools will be implemented to visualize the weight in greater detail of each indicator in the design of a mechatronic product. In this investigation, the complexity of 4 products produced in the same company was measured, with the future objective of evaluating the effect of complexity on factors such as manufacturing time, development time, quality and costs, to propose predictive models that support the *Decision Making*.

6 Conclusions

This article proposes a methodology to measure complexity in mechatronic products, but it can be used in other types of products. The methodology addresses a structural and functional study of the designs of each product. Indicators found in the bibliographic review were not taken into account because there was no information the indicators from the company. The methodology to measure the complexity in a mechatronic product presented in this article contributes to investigating the effects of the products complexity in their respective manufacturing processes. For future work, it is planned to analyze the dynamic complexity in a manufacturing process of mechatronic products starting from the determination of the static complexity presented here. It is also important to consider adding to the methodology the component of complexity that provides connectivity and the insertion of enabling technologies of industry 4.0.

Table 5. Complexity of product 2.

I	E	ML	C
I.1	1	1	100
I.2	4	4	100
I.3	1515	2474	61
I.4	404	927	44
I.5	150	475	32
I.6	374	374	100
TC	∑C		***437***

Table 6. Complexity of product 3.

I	E	ML	C
I.1	1	1	100
I.2	2	4	50
I.3	46	2474	2
I.4	30	927	3
I.5	25	475	5
I.6	72	374	20
TC	∑C		***180***

Table 7. Complexity of product 4.

I	E	ML	C
I.1	1	1	100
I.2	4	4	100
I.3	2340	2474	95
I.4	750	927	80
I.5	400	475	84
I.6	345	374	93
TC	∑C		***552***

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