UDC 621
DOI: 10.15587/1729-4061.2023.267430

ASSESSMENT OF ASSEMBLY PROCESS COMPLEXITY USING MATERIAL COEFFICIENTS FOR HANDLING AND INSERTION

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Complexity principles are very important for reducing difficulty while at the same time continuously attaining the requirements of the product, process, and system. A crucial factor affecting the complexity of assembly is material selection. The material used for a product will be closely linked to the handling and insertion process. In a previous study, the methods used to select materials and assembly processes have been developed separately. In this study, those methods will be developed together into a single entity with respect to the complexity of each process. Scientific information about this matter has yet to be revealed, so it still requires intensive study. Hence, the study aims to promote a new way to measure the complexity of parts assembly by examining the material selection parameters. The proposed method involves material coefficients in establishing an assembly complexity index and consists of two phases. Numerical examples are provided to illustrate the suggested design comprehensively, which uses three material variants in piston products to calculate the complexity index of the assembly process. Variants with a small complexity index are ideal and facilitate the assembly process.

The study creates a material coefficient model to specify the assembly process, where each component has various coefficient values. The material coefficient describes the value of material characteristics related to the assembly method, namely the process of handling and insertion. The material selection requires a clear understanding of the assembly requirements for each component. The related material characteristics are density, fracture toughness, Young's modulus, elastic limit, tensile strength, elongation, and hardness. Assessment of the complexity index using methods from previous studies obtained 6.02. Using the present method, 5.777 were obtained for variant 1 and 5.769 for the second variant. The mean complexity value is compatible with the material coefficient and assembly time

Keywords: assembly, complexity index, material coefficient, material selection, handling, insertion, fastening

Received date 22.11.2022
Accepted date 24.01.2023
Published date 28.02.2023

How to Cite: *Muskita, N. D., Soenoko, R., Sonief, A. A., Choiron, M. A. (2023). Assessment of assembly process complexity using material coefficients for handling and insertion. Eastern-European Journal of Enterprise Technologies, 1 (1 (121)), 67–78. doi: https://doi.org/10.15587/1729-4061.2023.267430*

1. Introduction

During the last decade, the use and evolution of Information and Communication Technologies (ICT) in the industry have become unavoidable, mainly vital for increasing organizational efficiency and competitiveness. Nevertheless, the information available in real-time and in-line, gathered through systems, will increase management's decision-making efficiency and become more flexible and efficient shortly. Assembly work has a very long history. However, modern assembly processes aim to produce high-quality and low-cost products. Several essential ideas have been developed to facilitate assembly work. Another innovation in the history of assembly manufacturing is minimizing assembly time. Since each task has relatively limited content, skills can be developed quickly. Thus, the assembly speed can be increased, and the quality improved [1]. Assembly operation accounts for 53 % of the entire fabrication period and 20 % of the fabrication charge. It is well understood that this operation is an essential manufacturing process. For 20 % of the assembly, the price is attributed to the cost of setup 12 %, the middle process 24 %, the last assembly 24 %, and 40 % for promoting the process or operation as well as a system [2]. Low assembly complexity will reduce assembly time and costs. Therefore, studies on the complexity of assembly are of scientific relevance.

2. Literature review and problem statement

Assembly is joining two or more components, subassemblies, or groups to serve the desired functionality. Multiple sequences are generally available to complete a particular task from start to end. Still, not all sequences are feasible, as they cannot satisfy the given constraints. It is essential to select the optimal feasible sequence for an assembly to reduce factors affecting the overall cost. The factors such as total assembly time, number of workers required to complete the task, and inventory cost of the components, etc., affect the overall assembly cost [3].

A significant challenge for manufacturing companies today is managing a considerable amount of product variants and building options simultaneously in manufacturing engineering and production. The overall complexity and risk of quality errors in the manual assembly will increase, placing high demands on the operators who must manage many different tasks in current production. Low complexity criteria aid designers in preventing costly errors during assembly and create good primary assembly conditions in the early design phases of new manufacturing concepts [4].

Complexity principles are very important for reducing difficulty while simultaneously continually attaining the requirements of the product, process, and system. Its primary goal is to minimize complexity using a rational approach based on fundamental principles. The measured complexity is essential for increasing reliability, lowering production and development costs, and achieving productivity. This makes it possible to predict the system behavior and obtain solutions related to complex problems. A distinctive feature of the complexity of a system is the variation in the number of components and their types and the interrelationships between each part. The greater the number of parts and the interrelationships between parts, the greater the value of the system's complexity [5]. There are several theoretical methods for the assessment of assembly complexity. One of the methods, the complexity index, aims at assessing operators' perception of manual assembly complexity in running production for the predictive evaluation of fundamental manual assembly complexity in early product and production development [6]. Several things, i.e., type of material, design, specification, and the number of components affect the manufacturing process complexity. On the other hand, material cost accounts for over 50 % of total production cost, so designers must be deliberate in material selection. Therefore, the manufacturing part complexity model used to measure machining process complexity was modified and further developed for assembly. Moreover, to account for various attributes of part handling and insertion and to consider the effect of fasteners on product assembly complexity. Furthermore, combining the complexity index of multiple parts to get an overall index representing the complexity of the product assembly is done with the model [7]. A product designer can accurately calculate the material volume and cost from the material base. In the assembly process, material selection has a predetermined procedure; although the numbers in the reference can be used as rough tools, the planner would be able to get views that are more precise from material suppliers [8].

Choosing an appropriate material for a particular product is one of the critical tasks for the initial stage of product design. Material selection aims to classify material based on its specification or characteristic. Material selection in the assembly process has a predetermined procedure and influences the first stage of product design. Material selection procedures classify materials based on certain specifications or material characteristics. A substance selection is considered independent of the fabrication way that can be used, while suitability with the process and material is crucial. Various ways can be used to justify and found compatible parts to apply in the first steps of the output pattern [9]. Therefore, designers need to identify materials with specific functionalities to eliminate assembly operations' failures that can significantly reduce productivity to optimize the geometry of complex additive manufacturing components to minimize assembly requirements [10]. There is a significant correlation between assembly complexity, assembly time, and cost. This indicates that complex assembly has to be avoided to make the potential saving in production time and cost [11, 12]. Besides, in terms of assembly cost, complexity plays a crucial role in achieving the best product design regarding manufacturing processes and the quality of the end product [13]. Therefore, measuring assembly complexity is a vital step in product development.

However, complexity is due to difficulties in assembly operations [9]. Difficulty factors are the difference in a material that its material coefficient can know, and this coefficient is part of the material base and is employed in assembly complexity determination. The difficulty level is presented in nominal called the complexity index. Measurement of complexity index uses either entropy information content approach, heuristics approaches, or indices [14].

On the other hand, the material selection requires a clear understanding of the functional requirements for each component and various essential criteria considerations. Therefore, some researchers conducted a study of optimal [15] and straightforward methods for material selection [16–20]. However, these studies have not involved a relationship between material selection and the assembly process. Based on the previous studies, the research on developing methods to determine the effect of the material selection process and its relationship with the assembly process on a product is a significant factor [21–31]. However, scientific information about this matter has not been revealed, so it still requires intensive study. Therefore, this is the focus and attention of our present study.

3. The aim and objectives of the study

The aim of the study is to develop a method for assessing the complexity of the assembly process and material selection as represented by the material coefficient.

To achieve this aim, the following objectives are accomplished:

– to measure and analyze the complexity of the assembly process, which is influenced by the type of material used in each component;

– to analyze the interconnection between assembly complexity and related materials of the proposed model.

4. Materials and methods of research

To implement the method developed in this research, piston products use three material variants. The three variants refer to material ratings based on material coefficients related to the assembly process: handling, insertion, fastening, and material characteristics.

Of the three variants used, the variant with a small complexity index value will be easier to assemble; in other words, the assembly time will be short.

The percentage of material costs can exceed 50 % of the total production costs, so estimation must be done carefully. Designers can determine the volume of material needed for natural objects and can easily predict material costs. Although the numbers in references can sometimes be used as rough guides, designers can obtain more accurate figures from material suppliers [32]. Thus, the material selection stage is crucial in the assembly process; for this reason, using material coefficients in calculating the complexity index of the assembly process is very necessary.

To measure and analyze the material coefficient, a new method is needed, which is a mechanism to use material coefficient values to determine the complexity index of the assembly process. Material is one of the factors that cause difficulties in assembling in the handling and insertion process. Each material has its characteristics, which describe its properties and identities. This research's optimization in the material selection process aims to identify materials with specific features appropriate to the process requirements. Three material properties, which give difficulties in handling operations, are considered, i.e., density, fracture toughness, and Young's modulus. The selection of properties is based on the fundamental properties of characteristics for each material. While there are four material properties in the insertion process, i.e., elasticity, strength, stiffness, and tenacity, involved in the proposed model. These characters are selected from each material property's definition and primary parameter.

A new methodology is introduced to link the influence of material selection within assembly operation, including a material coefficient index in determining assembly complexity indices. This section describes the proposed methods composed of two main phases, i.e., (1) this phase deals with the selection of material and measurement of the complexity index for each component. It starts with the identification of each component shape into a matrix. Next, a relation matrix between process and material is established. This is done by referring to typical uses of material, i.e., based on the relationship of the component and material used, which must be adjusted with material classification [29]. Once material identification is complete, the used material candidate for each part is obtained. In the next step, the material properties data (mechanical and general properties) related to the handling, insertion, and fastening process, is identified. These processes are essential parameters of the assembly operation. The material ranking is acquired based on the assumption that the material with the most negligible density is placed in the first position, as it is known that a smaller density makes the material easier to be assembled. Furthermore, the material coefficient index for each material candidate is calculated, and its result is employed to determine the part complexity index of each material candidate. This step generates the ranking list of material candidates for each assembled component.

Furthermore, (2) this phase involves applying the selected material to a product. Initially, the number and unique assembled components are identified, and its result is connected with the material candidates acquired from the first phase. Next, the assembly complexity is calculated using a material coefficient. This step is followed by calculating the product complexity index that incorporates two-part complexity attributes, the handling complexity attributes as well as the insertion complexity attributes. The insertion resistance value is multiplied by a material coefficient to obtain the insertion complexity attributes. The product complexity index is calculated for three material variants, i.e., general material, selected material in the first position, and ideal material, which is economical from a complexity viewpoint.

Lastly, the assembly complexity index is determined using the three material variants above.

The output of this phase is the proposal of ideal/economic material for each component, which will be used for assembling a product.

The methodology to generate the assembly complexity that includes the material coefficient index is developed, as shown in Fig. 1. Whereas to test the modeling accuracy, the outcomes of the proposed method are compared with the results of the previous study [4].

Fig. 1 shows an illustration for developing a methodology by incorporating material coefficient values into the calculation of the assembly process complexity index created previously by the author. In addition, from Fig. 1, it can be explained that $CI_{Assembly\ Process}$ is the complexity of the assembly process of the product, and $D_R\ (h, i)$ is the ratio of diversity for handling and insertion. However, $CI_{Product}$ is the output assembly complexity value, $H_{(h,\ i)}$ is entropy for handling and insertion, $D_{R(f)}$ is the ratio of diversity to fastening, and $H_{(f)}$ is entropy for fastening. Furthermore, C_{Part} is part complexity, X_P is, C_h is the handling complexity parameter, and $C_{h,\ f}$ is the relative handling complexity value. Moreover, C_i is the insertion complexity value, f is the inclusion complexity value, and J is the number of handling attributes of every component. K is the number of insertion attributes of each component, C_m is the value of the material coefficient, and Weight is the weight attribute value by considering the type of material used. The material characteristics used in this calculation are those that affect the handling and insertion processes, namely Density (D), Fracture Toughness (FT), Young's Modulus (M), Elastic Limit (EL), Tensile Strength (TS), Hardness (H) and Elongation (E).

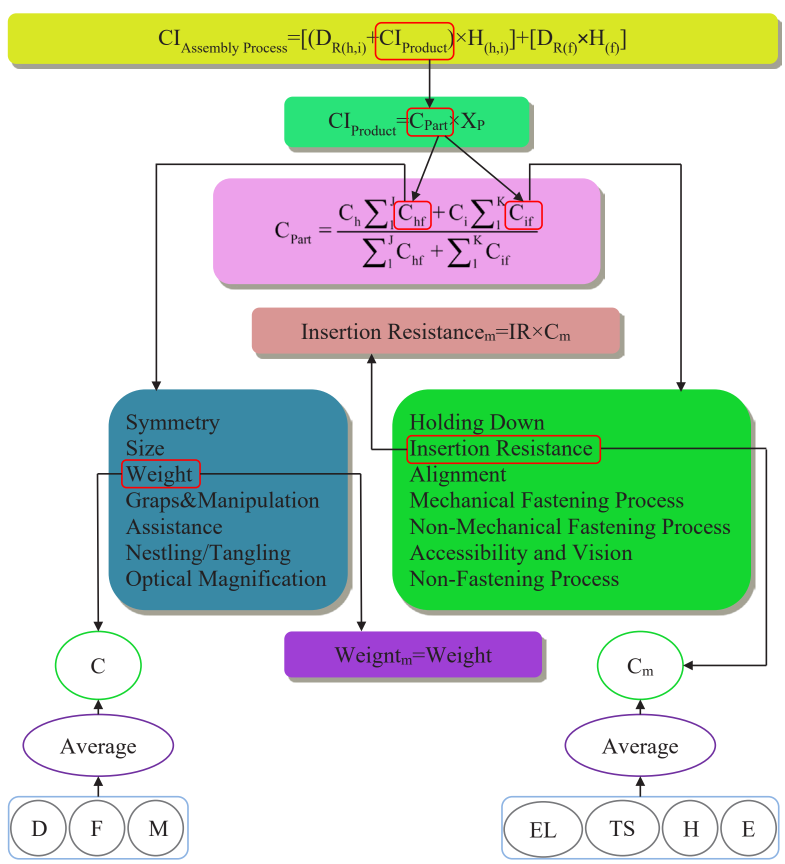


Fig. 1. An illustrative diagram for the proposed methodology

5. Results of the assessment of assembly complexity with material coefficients for handling and insertion in piston products

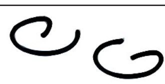
5. 1. Selection of materials for piston products used to determine the complexity index of the assembly process

In this study, an automotive piston assembly [7] is considered to demonstrate the computation of the proposed methodology.

Details of piston products regarding parts and number of components in this study refer to previous researchers [5], and the detailed results can be seen in Table 1.

Table 1

Components of the piston product [5]

Part name	Component figure	Number
Compression ring		2
Oil ring		1
Piston		1
Piston pin		1
Snap ring		2
Connection rod shaft		1
Connection rod cap		1
Bearing		2

This component is a part of the exchange machine, which is used to remove energy from expanding gas in the cylinder to the crankshaft through a piston rod and connecting rod. The material ranking can be obtained based on the density and complexity of each engine piston component. The thickness and other material characters, i.e., fracture toughness, Young's modulus, elasticity, strength, stiffness, and tenacity, are taken from each material database, allowing each engine piston component. In this calculation, the value of the used material characters has been normalized.

Normalization of material characteristic values can be calculated using the formula [10]:

$$N = \frac{100 \log\left(\frac{P}{P_{\min}}\right)}{\log\left(\frac{P_{\max}}{P_{\min}}\right)}, \quad (1)$$

P is the data used (mean value), $P_{\min}$ is the smallest range of data, $P_{\max}$ is the most extensive range of data, and 100 is the scale used for weighting.

(1) is used to calculate the density value. Then, the value of product complexity is calculated using equation (2) [7]:

$$CI_{product} = C_{Product} \times X_p, \quad (2)$$

where C_{Part} is part complexeity, X_p is the percentage of the x dissimilar parts.

After performing complex calculations for each component, Table 2 shows the results of the material rating based on the density and complexity values for each element.

From the results above, the process complexity index was calculated using three variants.

Furthermore, the material coefficients are obtained from Table 2 as follows to enumerate the complexity index.

Moreover, the value of these material characteristics is calculated using the normalization formula because each aspect has a different unit.

The material coefficient values obtained for materials in piston products can be seen in Table 3.

Table 2

Summary of the complexity product (C), density (D), and material rating calculation (R)

Material used	Components for piston products																							
	Compression ring			Oil ring			Piston			Piston pin			Snap ring			Connection rod shaft			Connection rod cap			Bearing		
	C	D	R	C	D	R	C	D	R	C	D	R	C	D	R	C	D	R	C	D	R	C	D	R
Cast iron	0.10	50.35	2	0.05	50.35	3	0	0	0	0	0	0	0.10	50.35	2	0	0	0	0	0	0	0.10	50.35	1
High carbon steel	0.11	50.16	4	0.05	50.16	4	0	0	0	0.05	50.16	2	0.11	50.16	6	0.05	50.16	3	0.05	50.16	4	0.11	50.16	2
Low alloy steel	0.12	50.16	5	0.06	50.16	5	0	0	0	0.06	50.16	3	0.12	50.16	7	0.06	50.16	4	0.06	50.16	5	0	0	0
Low carbon steel	0.10	50.16	3	0.05	50.16	4	0	0	0	0.05	50.16		3	50.16	5	0.05	50.16	4	0.05	50.16	6	0	0	0
Medium carbon steel	0.12	50.16	5	0.06	50.16	5	0	0	0	0.06	50.16	3	0.12	50.16	7	0.06	50.16	4	0.06	50.16	5	0	0	0
Stainless steel	0.11	50.80	2	0.06	50.80	2	0.06	50.80	2	0.06	50.80	2	0.11	50.80	2	0.06	50.80	3	0.06	50.80	3	0	0	0
Aluminium alloy	0.11	51.85	1	0.05	51.85	1	0.05	51.85	1	0.05	51.85	1	0.11	51.85	1	0.05	51.85	2	0.05	51.85	2	0	0	0
Titanium alloy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.05	54.87	1	0.05	54.87	1	0	0	0

Table 3

The material coefficients of the assembly process

No.	Material	Material coefficient (C_m)
1	Cast iron	0.13
2	High carbon steel	0.18
3	Low alloy steel	0.19
4	Low carbon steel	0.13
5	Medium carbon steel	0.16
6	Stainless steel	0.18
7	Aluminium alloys	0.05
8	Copper alloys	0.12
9	Lead alloys	0.11
10	Magnesium alloys	0.04
11	Nickel alloys	0.15
12	Titanium alloy	0.14
13	Tungsten alloys	1.06
14	Zinc alloys	0.08

Then we can calculate C_{Part} of the component used by including the material coefficient parameters using the following formula [7]:

$$C_{Part}=\frac{C_h\sum_1^J C_{hf}+C_i\sum_1^K C_{if}}{\sum_I^J C_{hf}+\sum_I^K C_{if}}. \quad (3)$$

After the complexity part value is obtained, it is continued with $CI_{product}$ calculation using the formula:

$$CI_{product}=C_{Part}\times X_p. \quad (4)$$

Then the $CI_{product}$ value is used to calculate $CI_{Assembly\ Process}$:

$$CI_{Assembly\ process}=$$

$$=\left[\left(D_{R(h,i)}+CI_{Product}\right)\times H_{(h,i)}\right]+\left[D_{R(f)}\times H_{(f)}\right], \quad (5)$$

where $H=\log_2(N+1)$; N is the amount of information. $D_R=n/N$; n is the amount of unique information. Furthermore, in previous studies, the calculation of the complexity value of the handling factor did not use the type of material parameters, so this is a fundamental difference from the development of our present method.

5. 2. Determination of the assembly process complexity index for three variants

The first variant with the common material used.

Tables 4, 5 show the results of the process complexity index calculation for handling and insertion, respectively. While the calculation of the result complexity index is presented in Table 6.

Table 4

Components handling complexity attributes matrix for the first variant

Part name	Material	Number	Handling complexity factor								J	Ch,f	Ch	Ch * Ch,f
			Sym	Size	Thckns	Weight	Grps & manpl	Asstnc	Nest/tang	Optcl mgnfctn				
Compression ring	Medium carbon steel	2	0.7	0.74	0.27	0.28	1	0.34	0.58	0	7	3.91	0.56	2.18
Oil ring	Cast iron	1	0.7	0.74	0.27	0.26	1	0.34	0.58	0	7	3.885	0.56	2.16
Piston	Cast aluminum alloy	1	0.7	0.74	0.27	0.22	0.91	0.34	0.58	0	7	3.755	0.54	2.01
Piston pin	Cast aluminum alloy	1	0.7	0.74	0.27	0.22	0.91	1	0.58	0	7	4.415	0.63	2.78
Snap ring	High carbon steel	2	0.7	0.81	0.5	0.28	1	1	0.58	0	7	4.87	0.70	3.39
Connection rod shaft	Low alloy steel	1	0.7	0.74	0.27	0.28	1	0.34	0.58	0	7	3.91	0.56	2.18
Connection rod cap	Low alloy steel	1	0.7	0.74	0.27	0.28	1	0.34	0.58	0	7	3.91	0.56	2.18
Bearing	Cast iron	2	0.7	0.74	0.27	0.26	0.91	1	0.58	0	7	4.455	0.64	2.84

Table 5

Components insertion complexity attributes matrix for variant 1

Part name	Material	Number	Handling complexity factor							K	Ci,f	Ci	Ci * Ci,f
			Hld. Dwn.	Insrt. Rest.	Align	Mch. Fst.	Non mch. Fst.	Acsblty. & Visn.	Non fstn. prcs.				
Compression ring	Medium carbon steel	2	0.54	0.73	1	0	0	0	0	3	2.27	0.76	1.72
Oil ring	Cast iron	1	0.54	0.62	1	0	0	0	0	3	2.16	0.72	1.56
Piston	Cast aluminium alloy	1	0.54	0.61	0.86	0	0	0	0	3	2.009	0.67	1.35
Piston pin	Cast aluminium alloy	1	0.54	0.50	1	0	0	0	0	3	2.04	0.68	1.39
Snap ring	High carbon steel	2	0.54	0.64	1	0	0	0	0	3	2.18	0.73	1.58
Connection rod shaft	Low alloy steel	1	1	0.61	1	0	0	0	0	3	2.609	0.87	2.27
Connection rod cap	Low alloy steel	1	1	0.61	1	0.42	0	0	0	4	3.029	0.76	2.29
Bearing	Cast iron	2	1	0.62	1	0	0	0	0	3	2.62	0.87	2.29

Table 6

Calculation of product complexity index for the first variant

Part name	Material	Number	C_{Part}	X_p	CI
Compression ring	Medium carbon steel	2	0.631	0.182	0.115
Oil ring	Cast iron	1	0.614	0.091	0.056
Piston	Cast aluminium alloy	1	0.583	0.091	0.053
Piston pin	Cast aluminium alloy	1	0.646	0.091	0.059
Snap ring	High carbon steel	2	0.705	0.182	0.128
Connection rod shaft	Low alloy steel	1	0.683	0.091	0.062
Connection rod cap	Low alloy steel	1	0.645	0.091	0.059
Bearing	Cast iron	2	0.724	0.182	0.132
$CI_{product}$		0.663			

On the basis of the product complexity index obtained from Table 5, the assembly process complexity index for variant 1 can be computed as follows:

$$CI_{assembly\ processs}=\left[\left((8/11)+0.663\right)*\log_2(11+1)\right]+ +\left[(1/2)*\log_2(2+1)\right]=5.777.$$

The complexity index value of piston products with commonly used materials is 5.777.

The second variant with the material on the first ranking of the material selection.

Using the same procedures, the computations of the process complexity index for handling and insertion of the selected material are presented in Tables 7, 8, respectively. Cast aluminum alloy is the best-suited material for five of the eight piston components.

Table 9 shows the product complexity index calculation for the selected material.

Table 7

Components handling complexity attributes matrix for variant 2

Part name	Material	Number	Handling complexity factor								J	Ch,f	Ch	Ch * Ch,f
			Sym	Size	Thckns	Weight	Grps & manpl	Asstnc	Nest/ tang	Optcl mgnfctn				
Compression ring	Cast aluminium alloy	2	0.7	0.74	0.27	0.22	1	0.34	0.58	0	7	3.845	0.55	2.11
Oil ring	Cast aluminium alloy	1	0.7	0.74	0.27	0.22	1	0.34	0.58	0	7	3.845	0.55	2.11
Piston	Cast aluminium alloy	1	0.7	0.74	0.27	0.22	0.91	0.34	0.58	0	7	3.755	0.54	2.01
Piston pin	Cast aluminium alloy	1	0.7	0.74	0.27	0.22	0.91	1	0.58	0	7	4.415	0.63	2.78
Snap ring	Cast aluminium alloy	2	0.7	0.81	0.5	0.22	1	1	0.58	0	7	4.805	0.69	3.30
Connection rod shaft	Titanium alloy	1	0.7	0.74	0.27	0.27	1	0.34	0.58	0	7	3.895	0.56	2.17
Connection rod cap	Titanium alloy	1	0.7	0.74	0.27	0.27	1	0.34	0.58	0	7	3.895	0.56	2.17
Bearing	High carbon steel	2	0.7	0.74	0.27	0.28	0.91	1	0.58	0	7	4.48	0.64	2.87

Table 8

Parts insertion complexity attributes matrix for the second variant

Part name	Material	Number	Handling complexity factor							K	Ci,f	Ci	Ci * Ci,f
			Hld. Dwn.	Insrt. Rest.	Align	Mch. Fst.	Non tmch. fst.	Acsblty. & Visn.	Non fstn. prcs.				
Compression ring	Cast aluminium alloy	2	0.54	0.70	1	0	0	0	0	3	2.24	0.75	1.67
Oil ring	Cast aluminium alloy	1	0.54	0.70	1	0	0	0	0	3	2.24	0.75	1.67
Piston	Cast aluminium alloy	1	0.54	0.61	0.602	0	0	0	0	3	1.751	0.58	1.02
Piston pin	Cast aluminium alloy	1	0.54	0.70	1	0	0	0	0	3	2.24	0.75	1.67
Snap ring	Cast aluminium alloy	2	0.54	0.70	1	0	0	0	0	3	2.24	0.75	1.67
Connection rod shaft	Titanium alloy	1	1	0.62	1	0	0	0	0	3	2.6177	0.87	2.28
Connections rod cap	Titanium alloy	1	1	0.62	1	0.294	0	0	0	4	2.9117	0.73	2.12
Bearing	High carbon steel	2	1	0.64	1	0	0	0	0	3	2.64	0.88	2.32

Table 9

Calculation of components complexity index for variant 2

Part name	Material	Number	C_{part}	X_p	CI
Compression ring	Cast aluminium alloy	2	0.622	0.182	0.1131
Oil ring	Cast aluminium alloy	1	0.622	0.091	0.0565
Piston	Cast aluminium alloy	1	0.551	0.091	0.0501
Piston pin	Cast aluminium alloy	1	0.670	0.091	0.0609
Snap ring	Cast aluminium alloy	2	0.706	0.182	0.1283
Connection rod shaft	Titanium alloy	1	0.683	0.091	0.0621
Connection rod cap	Titanium alloy	1	0.630	0.091	0.0573
Bearing	High carbon steel	2	0.729	0.182	0.1325
$CI_{product}$		0.661			

Employing the same formula, the assembly process complexity index for variant 2 can be enumerated as follows:

$$CI_{assembly\ process} = \left[\left((8/11)+0.661\right)*\log_2(11+1)\right]+$$
$$+\left[(1/2)*\log_2(2+1)\right]=5.769.$$

The complexity index value of the piston product using the material that ranks first in material selection is 5.769.

Third variant with the ideal material.

Some materials of parts must be replaced because the type of these materials does not enable mass production. As shown in Tables 10, 11, the material of the two connecting rod parts is changed by cast aluminum alloy. Previously, based on the material selection process, the best-suited material for these components was titanium alloy. Based on the complexity attributes matrix, the index of the product complexity is obtained (Table 12).

Table 10

Components handling complexity attributes matrix for the third variant

Part name	Material	Number	Handling complexity factor								J	Ch,f	Ch	Ch * Ch,f
			Sym	Size	Thckns	Weight	Grps & Manpl	Asstnc	Nest/tang	Optcl mgnfctn				
Compression ring	Cast aluminium alloy	2	0.7	0.74	0.27	0.22	1	0.34	0.58	0	7	3.845	0.55	2.11
Oil ring	Cast aluminium alloy	1	0.7	0.74	0.27	0.22	1	0.34	0.58	0	7	3.8465	0.55	2.11
Piston	Cast aluminium alloy	1	0.7	0.74	0.27	0.22	0.91	0.34	0.58	0	7	3.755	0.54	2.01
Piston pin	Cast aluminium alloy	1	0.7	0.74	0.27	0.22	0.91	1	0.58	0	7	4.415	0.63	2.78
Snap ring	Cast aluminium alloy	2	0.7	0.81	0.5	0.22	1	1	0.58	0	7	4.805	0.69	3.30
Connection rod shaft	Cast aluminium alloy	1	0.7	0.74	0.27	0.22	1	0.34	0.58	0	7	3.845	0.55	2.11
Connection rod cap	Cast aluminium alloy	1	0.7	0.74	0.27	0.22	1	0.34	0.58	0	7	3.845	0.55	2.11
Bearing	Cast iron	2	0.7	0.74	0.27	0.26	0.91	1	0.58	0	7	4.455	0.64	2.84

Table 11

Parts insertion complexity attributes matrix for the third variant

Part name	Material	Number	Handling complexity factor							K	Ci,f	Ci	Ci * Ci,f
			Hld. Tdwn.	Insrt. Rest.	Align	Mch. fst.	Non mch. fst.	Acsblty. & Visn.	Non fstn. prcs.				
Compression ring	Cast aluminum alloy	2	0.54	0.70	1	0	0	0	0	3	2.24	0.75	1.67
Oil ring	Cast aluminum alloy	1	0.54	0.70	1	0	0	0	0	3	2.24	0.75	1.67
Piston	Cast aluminum alloy	1	0.54	0.61	0.60	0	0	0	0	3	1.75	0.58	1.02
Piston pin	Cast aluminum alloy	1	0.54	0.70	1	0	0	0	0	3	2.24	0.75	1.67
Snap ring	Cast aluminum alloy	2	0.54	0.70	1	0	0	0	0	3	2.24	0.75	1.67
Connection rod shaft	Cast aluminum alloy	1	1	0.61	1	0	0	0	0	3	2.61	0.87	2.27
Connection rod cap	Cast aluminum alloy	1	1	0.61	1	0.29	0	0	0	4	2.90	0.73	2.11
Bearing	Cast iron	2	1	0.63	1	0	0	0	0	3	2.63	0.88	2.31

Table 12

Calculation of component complexity index for variant 3

Part name	Material	Number	C_{part}	X_p	CI
Compression ring	Cast aluminium alloy	2	0.62	0.18	0.11
Oil ring	Cast aluminium alloy	1	0.62	0.09	0.06
Piston	Cast aluminium alloy	1	0.55	0.09	0.05
Piston pin	Cast aluminium alloy	1	0.67	0.09	0.06
Snap ring	Cast aluminium alloy	2	0.71	0.18	0.13
Connection rod shaft	Cast aluminium alloy	1	0.68	0.09	0.06
Connection rod cap	Cast aluminium alloy	1	0.63	0.09	0.06
Bearing	Cast iron	2	0.73	0.18	0.13
$CI_{product}$			0.659		

The result of the assembly process complexity index calculation for variant 3 is given by:

$$CI_{assembly\ process}=\left[\left((8/11)+0.659\right)*\log_2(11+1)\right]+$$
$$+\left[(1/2)*\log_2(2+1)\right]=5.764.$$

The complexity index value of the piston product using the material that ranks first in material selection is 5.764.

The results from previous studies.

To compare the results of the proposed model, we present the assembly process complexity calculation of past research.

Tables 13–15 show the computation of the process complexity index for handling and insertion, respectively, and the product complexity index without including the material coefficient.

Table 13

Parts handling complexity attributes matrix excluding the material coefficient

Part name	Material	Number	Handling complexity factor								J	Ch,f	Ch	Ch * Ch,f
			Sym	Size	Thckns	Weight	Grps & Manpl	Asstnc	Nest/ tang	Optcl mgnfctn				
Compression ring	Medium carbon steel	2	0.7	0.74	0.27	0.50	1	0.34	0.58	0.8	8	4.93	0.62	3.04
Oil ring	Cast iron	1	0.7	0.74	0.27	0.50	1	0.34	0.58	0.8	8	4.93	0.62	3.04
Piston	Cast aluminium alloy	1	0.7	0.74	0.27	0.50	0.91	0.34	0.58	0.8	8	4.84	0.61	2.93
Piston pin	Cast aluminium alloy	1	0.7	0.74	0.27	0.50	0.91	1	0.58	0.8	8	5.5	0.69	3.78
Snap ring	High carbon steel	2	0.7	0.81	0.5	0.50	1	1	0.58	0.8	8	5.89	0.74	4.34
Connection rod shaft	Low alloy steel	1	0.7	0.74	0.27	0.50	1	0.34	0.58	0.8	8	4.93	0.62	3.04
Connection rod cap	Low alloy steel	1	0.7	0.74	0.27	0.50	1	0.34	0.58	0.8	8	4.93	0.62	3.04
Bearing	Cast iron	2	0.7	0.74	0.27	0.50	0.91	1	0.58	0.8	8	5.5	0.69	3.78

Table 14

Parts insertion complexity attributes matrix excluding the material coefficient

Part name	Material	Number	Handling complexity factor							K	Ci,f	Ci	Ci * Ci,f
			Hld. dwn.	Insrt. rest.	Align	Mch. fst.	Non mch. fst.	Acsblty. & Visn.	Non fstn. prcs.				
Compression ring	Medium carbon steel	2	0.54	1	1	0	0	0	0	3	2.54	0.85	2.15
Oil ring	Cast iron	1	0.54	1	1	0	0	0	0	3	2.54	0.85	2.15
Piston	Cast aluminium alloy	1	0.54	0.87	0.86	0	0	0	0	3	2.27	0.76	1.72
Piston pin	Cast aluminium alloy	1	0.54	1	1	0	0	0	0	3	2.54	0.85	2.15
Snap ring	High carbon steel	2	0.54	1	1	0	0	0	0	3	2.54	0.85	2.15
Connection rod shaft	Low alloy steel	1	1	0.87	1	0	0	0	0	3	2.87	0.96	2.75
Connection rod cap	Low alloy steel	1	1	0.87	1	0.42	0	0	0	4	3.29	0.82	2.71
Bearing	Cast iron	2	1	1	1	0	0	0	0	3	3	1.00	3.00

Table 15

Calculation of product complexity index excluding the material coefficient

Part name	Material	Number	C_{part}	X_p	CI
Compression ring	Medium carbon steel	2	0.69	0.18	0.13
Oil ring	Cast iron	1	0.69	0.09	0.06
Piston	Cast aluminium alloy	1	0.65	0.09	0.06
Piston pin	Cast aluminium alloy	1	0.74	0.09	0.07
Snap ring	High carbon steel	2	0.77	0.18	0.14
Connection rod shaft	Low alloy steel	1	0.74	0.09	0.07
Connection rod cap	Low alloy steel	1	0.70	0.09	0.06
Bearing	Cast iron	2	0.80	0.18	0.15
$CI_{product}$		0.73			

From Tables 14, 15, the assembly process complexity index is given by:

$$CI_{assembly\ process} = \left[\left((8/11)+0.73\right)*\log_2(11+1)\right]+$$
$$+\left[(1/2)*\log_2(2+1)\right]=6.02.$$

The index value of piston product complexity from previous studies was 6.02.

The results reveal that the three variants' assembly process complexity index differs. The first variant has a higher assembly process complexity than the other two variants, with the third variant having the lowest process complexity (Fig. 2).

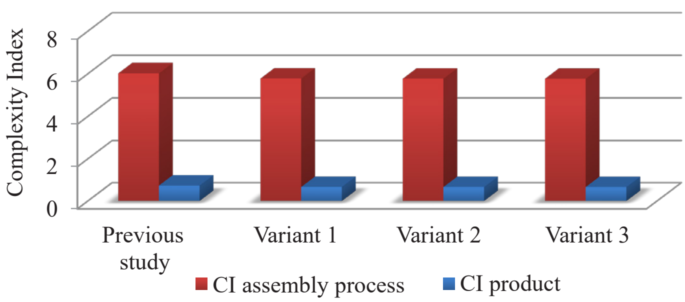


Fig. 2. Summary and difference of the product and assembly process complexity index results

After obtaining the results of the third variants used and from previous research, a variant with a small complexity index value will be recommended. Assuming the smaller the complexity index value, the assembly process will be faster [7].

6. Discussion of assessment of assembly method complexity with material coefficients for handling and insertion in piston products

The use of the three variants in this study takes into account the type of material used by each component of the piston product, and the results obtained will be compared between these three variants as well as with the results from previous studies, where the first variant uses materials commonly found in piston products. Furthermore, the second variant uses material that ranks first in material selection, and the third variant uses ideal material.

The first variant uses materials generally applied and easily found in the markets, such as medium carbon steel for producing compression rings and cast iron for oil rings and bearings. In addition, cast aluminum alloy for pistons, high carbon steel for the snap ring, and low alloy steel for the connection rod (Table 6). While the second variant employs a material that ranks first in the material selection process, and this material is the best or the most ideal for manufacturing these parts. Five of the eight parts use cast aluminum alloy, two parts of the connection rod apply titanium alloy, and only one bearing uses high carbon steel (Table 9).

The smallest complexity index is for the third variant, which uses the ideal material, which enables mass production.

From an economic perspective, titanium alloy and high-carbon steel are relatively expensive, so these materials are only allowed for custom production or only meet a particular demand. In this study, cast aluminum alloy and cast iron occupy the second rating in the material selection. However, it is excellent for mass production by considering material costs. Table 15 also shows the study's results differ from previous research. The differences between the four assembly process complexity indices are minor; the reason for these differences can be explained as follows. Based on Table 16 [31], the insertion resistance attribute can be categorized into no resistance and resistance to insertion, where the average difficulty factor (C_f) value for its detail is 0.87 and 1, respectively.

Furthermore, the calculation of the complexity index using material coefficients has a small value compared to the results of previous studies without using material coefficients. Here it is seen that the type of material will affect the complexity of the assembly process. Besides, those material costs are still considered, especially for products that will be mass-produced. Therefore, the use of material coefficients in calculating the complexity index of the assembly process is constructive for the planning stage of the assembly process. The assembly process complexity index will be directly proportional to the assembly time. In addition, the assembly process accounts for 53 % of the entire fabrication period and 20 % of the fabrication cost, so using the right and ideal material for each component will affect the process. The stages of material selection for each element need to be done correctly so that the difficulty level of the assembly process can be minimized. The use of the three variants in this study considers the type of material used by each component in the piston product. The first variant uses materials commonly found in piston products, such as medium carbon steel for the manufacture of compression rings and cast iron for oil rings and bearings. In addition, cast aluminum alloy for the piston, high carbon steel for the snap ring, and low alloy steel for the connecting rod (Table 6). Furthermore, the second variant uses a material that ranks first in the material selection process, and this material is the best or most ideal for making this part. Five of the eight sections use cast aluminum alloy, two link rod sections use titanium alloy, and only one bearing uses high carbon steel (Table 9).

The basis for determining material ratings is the relationship between material characteristics that affect the assembly process (handling, insertion, and fastening). Material coefficients are the part developed in this study; each material has a different coefficient. The assembly process complexity index obtained will be different if we use another type of material for the same component. In previous research, the difference in the kind of material was not so influential. Material types are generally grouped; this can be seen in Table 16.

The smallest complexity index is for the third variant, which uses ideal materials and allows for mass production. From an economic point of view, titanium alloys and high-carbon steels are relatively expensive, so these materials are only allowed for unique production or only to meet specific demands. In this study, cast aluminum and cast iron alloys ranked second in material selection. However, it is perfect for mass production, considering the material cost. Table 15 also shows the results of previous studies, which are different from the results of this study.

The determination of the complexity index using material coefficients has a small value compared to the results of previous studies without using material coefficients. Here it can be seen that the material type affects the assembly process complexity. In addition, material costs are still taken into account, especially for products that will be mass-produced. So that the use of material coefficients in calculating the complexity index of the assembly process is constructive for the planning stage of the assembly process so that the complexity index will be directly proportional to the assembly time.

The material data is sourced from the material database with the help of software. In the future, it will be better if it comes from the results of material sample tests so that the material characteristic values are more accurate for each component in a product and are in line with technological developments.

Table 16

Assembly attributes for manual assembly [7]

Group	Attribute	Description	Average difficulty factor, C_f
Handling attributes	Symmetry (α+β)	α+β<360	0.70
Handling attributes	Symmetry (α+β)	360≤α+β+<540	0.84
Handling attributes	Symmetry (α+β)	360≤α+β+<720	0.94
Handling attributes	Symmetry (α+β)	α+β=720	1.00
Handling attributes	Size	>15 mm	0.74
Handling attributes	Size	6 mm<size≤15 mm	0.81
Handling attributes	Size	6 mm	1
Handling attributes	Thickness	2 mm	0.27
Handling attributes	Thickness	0.25 mm<size≤2 mm	0.5
Handling attributes	Thickness	≤0.25 mm	1
Handling attributes	Weight	<10 lb (light)	0.5
Handling attributes	Weight	>10 lb	1
Handling attributes	Grasping and manipulation	Easy to grasp and manipulate	0.91
Handling attributes	Grasping and manipulation	Not easy to grasp and manipulate	1
Handling attributes	Assistance	Using one hand	0.34
Handling attributes	Assistance	Using one hand with grasping aids	1
Handling attributes	Assistance	Using two hands	0.75
Handling attributes	Assistance	Using two hands with assistance	0.57
Handling attributes	Nesting and tangling	Parts do not severely nest or tangle and are not flexible	0.58
Handling attributes	Nesting and tangling	Parts severely nest or tangle or are flexible	1
Handling attributes	Optical magnification	Not necessary	0.8
Handling attributes	Optical magnification	Necessary	1
Insertion attributes	Holding down	Not required	0.54
Insertion attributes	Holding down	Required	1
Insertion attributes	Alignment	Easy to align or position	0.86
Insertion attributes	Alignment	Not easy to align or position	1
Insertion attributes	Insertion resistance	No resistance	0.87
Insertion attributes	Insertion resistance	Resistance to insertion	1
Insertion attributes	Accessibility and vision	No restrictions	0.57
Insertion attributes	Accessibility and vision	Obstructed access or restricted vision	0.81
Insertion attributes	Accessibility and vision	Obstructed access and restricted vision	1
Insertion attributes	Mechanical fastening processes	No additional material required	0.58
Insertion attributes	Mechanical fastening processes	Soldering processes	0.67
Insertion attributes	Mechanical fastening processes	Chemical processes	1
Insertion attributes	Non-fastening processes	Manipulation of parts or sub-assemblies (Fitting or adjusting of parts, ...)	0.75
Insertion attributes	Non-fastening processes	Other processes (liquid insertion, ...)	1

The method developed in this study helps facilitate the assembly process at the planning stage to predict the difficulty and time of the assembly process. To obtain accurate material characteristic values, it is necessary to carry out several tests, which require a lot of time and costs, so that the planning stage becomes longer.

Furthermore, in this study, the application of the method developed was used for piston products. Moreover, this method can also be used for other products if several different types of materials are used for each component in one product. Furthermore, this does not rule out the possibility that this method can be used for products other than machine parts as long as the product consists of several components, uses a different material for each component, and goes through the assembly process.

7. Conclusions

1. Each component can use a different material. Therefore, the material selection will affect the assembly process, so if there is a change in the type of material in the component, it will affect the complexity of the assembly process ($CI_{assembly\ process}$). Material selection is influenced by handling attributes, such as density, fracture toughness, and Young's modulus, and insertion attributes, i. e., elasticity, strength, rigidity, and flexibility, of these components leading to lower complexity of product assembly and process.

2. The use of the material coefficient (C_m) in determining the assembly process complexity index is essential because the proposed model uses an information content approach related to material characteristics that affect the product assembly process. Therefore, more information will affect the accuracy of the developed model.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing

This research was funded by the Ministry of Research, Technology and Higher Education of the Republic of Indonesia through a doctoral grant program, with grant number 453/K14/KL/2022.

Data availability

Data cannot be made available for reasons disclosed in the data availability statement.

Acknowledgments

The Ministry of Research, Technology and Higher Education, the Republic of Indonesia, funded this research under the program of Graduate Education Scholarships and Universitas Brawijaya as the organizer of the mechanical engineering doctoral program, which has supported this work.

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