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# DEVELOPMENT OF A PROCESS COMPLEXITY INDEX OF LOW PRESSURE DIE CASTING FOR EARLY PRODUCT DESIGN EVALUATION

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***The design of a product is key for the manufacturing industry to compete in the current era. Failure to plan a product design means losing in the market and falling behind competitors. One way to comprehensively evaluate one design is by analyzing its complexity. Complexity analyzes not only clear view parameters such as geometry and process time but also the whole design parameters, including its production process. This paper develops a process complexity index of low pressure die casting. A casting process is one unique process that depends on the melting and solidification of material in a die. A complexity analysis of low pressure die casting is yet to be done. Three different cylinder heads fabricated with low pressure die casting were used in the case study with the product's types of 3SZ, 1TR, and 2TR. A process complexity analysis is performed based on the LPDC process's physical and non physical parameters. The physical parameters are fixtures, tools, gauges, and machines. The non physical parameters are determined from the features and specifications of the low pressure die casting subprocess: setting, filling, solidification, and handling. The analysis successfully defines the complexity of each product, with 1TR having an index of 7.08, 2TR being 6.93, and 3SZ being 5.14. This developed complexity index can be utilized for early product design and cost estimation evaluation***

***Keywords: Design analysis, LPDC, process complexity index***

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## 1. Introduction

Product development is an important part of the business process of the manufacturing industry. The current era needs the product to be high quality, have a short lead time to introduce new products, and have low production costs. Effective and efficient product planning needs to be done to achieve those requirements. One core of product development is product design [1–3]. As reported in several works of literature, a good design can affect 70–80 % of product costs. The product design is not only the geometry but the whole production process of the product. Such information can be described in one value known as the process complexity index. Complexity in manufacturing can be explained as the complications value of the production process of a product [1–7]. The way to determine complexity can vary regarding the most important process in one manufacturing process. By analyzing the complexity of a product, the product's design can be described in one simple index. The higher index value correlates to a higher complexity one design had.

Complexity analysis has been utilized in many types of manufacturing processes, such as machining [4], additive manufacturing [5], and assembling [6]. Despite the mentioned facts, there is still limited report that practically analyzes the casting process's complexity, especially the low pressure die casting (LPDC) process. As part of manufacturing, casting is one important process that can mass-produce a product with complex geometry and a wide dimension range. LPDC is a type that uses pressure, rather than gravity, to fill permanent molds with casting molting metals [7–10]. The product usually developed using this method is the automobile parts, such as cylinder heads. Despite its importance, just a few reports still deeply discuss this process's complexity of LPDC. This research provides one practical way to analyze the complexity casting process, especially the LPDC. Complexity analysis depends on how we interpret the parameters surrounding one process. In the casting process, there are tools, machines, and dies in one part, but there are also things such as temperature, pressure, and other non-physical parts that construct the whole process. All those parameters should be considered and analyzed into one index, describing the complexity value of a low pressure die casting product.

Finally, this complexity index of an LPDC can be utilized for practical use in the manufacturing industry. First, it can be utilized as the design analysis of a product [1, 2, 11]. As mentioned, the index represents a combination of many parameters in constructing a product. When one new product design is planned, the complexity index will decide how complicated such a design is. The complexity index can be compared with other designs to decide which is better. The further utilization is to predict the cost of the product in the early stages [4, 12]. Cost estimation is a major issue in the manufacturing industry. An overestimated cost will make a product lose competitiveness when competing in the current market. An underestimated cost will result in financial loss for the company. A precise estimation is needed to ensure the company's business is healthy and competitive. Therefore, earlier cost estimation remains an interesting challenge for many researchers.

## 2. Literature review and problem statement

The casting process, as a part of the whole manufacturing process, is a crucial production process. Many products depend on casting as the main fabrication process, as it can develop products with complex geometry. LPDC used in this paper describes a process that utilizes low pressure to inject the cast metal into the mold. Although it is quite a mature process, many researchers are still improving this process overcoming many of its challenges [7–10].

This process's challenges lie in avoiding failures in the product after the casting process. In this case, the product design should be analyzed thoroughly before the fabrication is executed. The product's design can be measured by its complexity: the geometry and the whole process. By designing a less complex process to achieve a product, the failures and the production cost also can be minimized. There are many ways to perform a design analysis of a product. One common way is by its geometry. Several researchers are trying to add such analysis to LPDC-based products. One report tried to analyze the geometry based on computer-aided design (CAD) and analyze its complexity [7]. The geometry itself is a good approach to determining the complexity of such a product. Still, recent studies show that the quality of casting depends on several more parameters related to its in-production process.

As mentioned in several research papers [8–10], the parameters crucial in the casting process, especially in LPDC, are the filling temperature, pressure, fast velocity, cooling, and holding time. Quantifying such parameters will provide a more reliable design analysis for an LPDC product. Several papers have tried to analyze part of those parameters, such as the pouring temperature and pressure. Three reported papers tried to optimize the LPDC process computationally by analyzing its pouring temperature and filling pressure based on historical data from experts' experience [8–10]. The reports successfully model such parameters and determine the optimum condition for the LPDC process to minimize the failure of the process. But as mentioned, the LPDC process also needs to consider all parameters that can quantify the process's whole complications.

Process complexity analysis is one possible method to analyze the LPDC design [1, 2]. As a tool to analyze one product design, complexity appears to be one powerful tool. The complexity originated from the theory introduced in a research paper [2]. Complexity can be a flexible but robust tool to analyze products comprehensively. Complexity observes and analyzes the whole production parameters of one product and provides an index that describes the complications of the product. Complexity has been successfully analyzed in various manufacturing processes, such as machining [4, 11], additive-based processes [5], and assembly [6]. However, there is still limited study of the complexity of the casting process, especially LPDC. Based on such fact, this study demonstrates the development of the complexity index in the LPDC-based product. This study will benefit the manufacturing industry in analyzing its casting product and fulfilling the current market requirement effectively and efficiently.

## 3. The aims and objectives of the study

The aim of the study is to develop an index describing the complexity of LPDC's based products.

To achieve this aim, the following objectives are accomplished:

– to analyze the crucial parameters to be analyzed on the LPDC process,

– to calculate a complexity index based on the observed parameters.

## 4. Materials and methods

### 4. 1. Theoretical methods

Process complexity is one of the tools that can be used to analyze the design features of a product from an early stage [1, 2]. It is a function of the product design, quantity, and process environment. To determine the precise process complexity of a product, each parameter that constructs the process should be addressed comprehensively. Process complexity ($pc_x$) is a function of the variety of information ratio of the process ($D_{Rprocess}$), the relative complexity coefficient ($c_{j,process}$), and the entropy of the information ($H_{process}$), as seen in (1) [2]:

$$pc_x=(D_{Rprocess}+c_{i,\,process})*H_{process}. \quad (1)$$

$D_{Rprocess}$ is determined from the ratio of the unique information ($n$) and the total quantity of the information ($N$). $H_{process}$ is calculated from the binary logarithm of $N+1$:

$$D_{Rprocess}=\frac{n}{N}, \quad (2)$$

$$H_{Rprocess}=\log_2(N+1). \quad (3)$$

The $c_{j,process}$ is defined as $x_f$ (percentage of $x^{\text{th}}$ dissimilar feature) times the $c_f$ (the relative feature complexity coefficient) (4):

$$c_{j,process}=\sum\nolimits_{f=1}^{F} x_f * c_{f,feature}, \quad (4)$$

$$c_{f,feature}=\frac{F_N * F_{CF}+S_N * S_{CF}}{F_N+S_N}, \quad (5)$$

where $F_N$ is the quantity of the features. $F_{CF}$ is the feature complexity factor. $S_N$ is the number of specification checks. $S_{CF}$ is the specifications complexity factor (5):

$$F_{CF}=\frac{\sum\nolimits_{j=1}^{J} factor\_level_j}{j}, \quad (6)$$

where $J$ is the number of categories and $factor\_level_j$ is the factor of $j^{\text{th}}$ category (6).

$$S_{CF}=\frac{\sum\nolimits_{k=1}^{K} factor\_level_k}{k}, \quad (7)$$

where $K$ is the number of specifications, and $factor\_level_j$ is the factor of $k^{\text{th}}$ specifications (7).

### 4. 2. Process complexity analysis of LPDC

There are two main parameters to determine the process complexity of a product [2]: the physical parameter (environment) and the non-physical parameter.

The physical parameter is based on components or tools used during a process, such as fixtures, tools, gauges, and machines.

The non-physical parameter is based on the value used during the process consisting of in-process features and in-process specifications.

Both explanations are:

– the in-process feature is a parameter to construct a product so that the shape, geometry, and tolerance are of standard quality;

– the in-process specification is a parameter to make a product has added value than the standard quality of the product.

All the parameters needed in an LPDC process should be determined and added to the process complexity calculation. The flow to analyze the process complexity in an LPDC can be seen in Fig. 1.

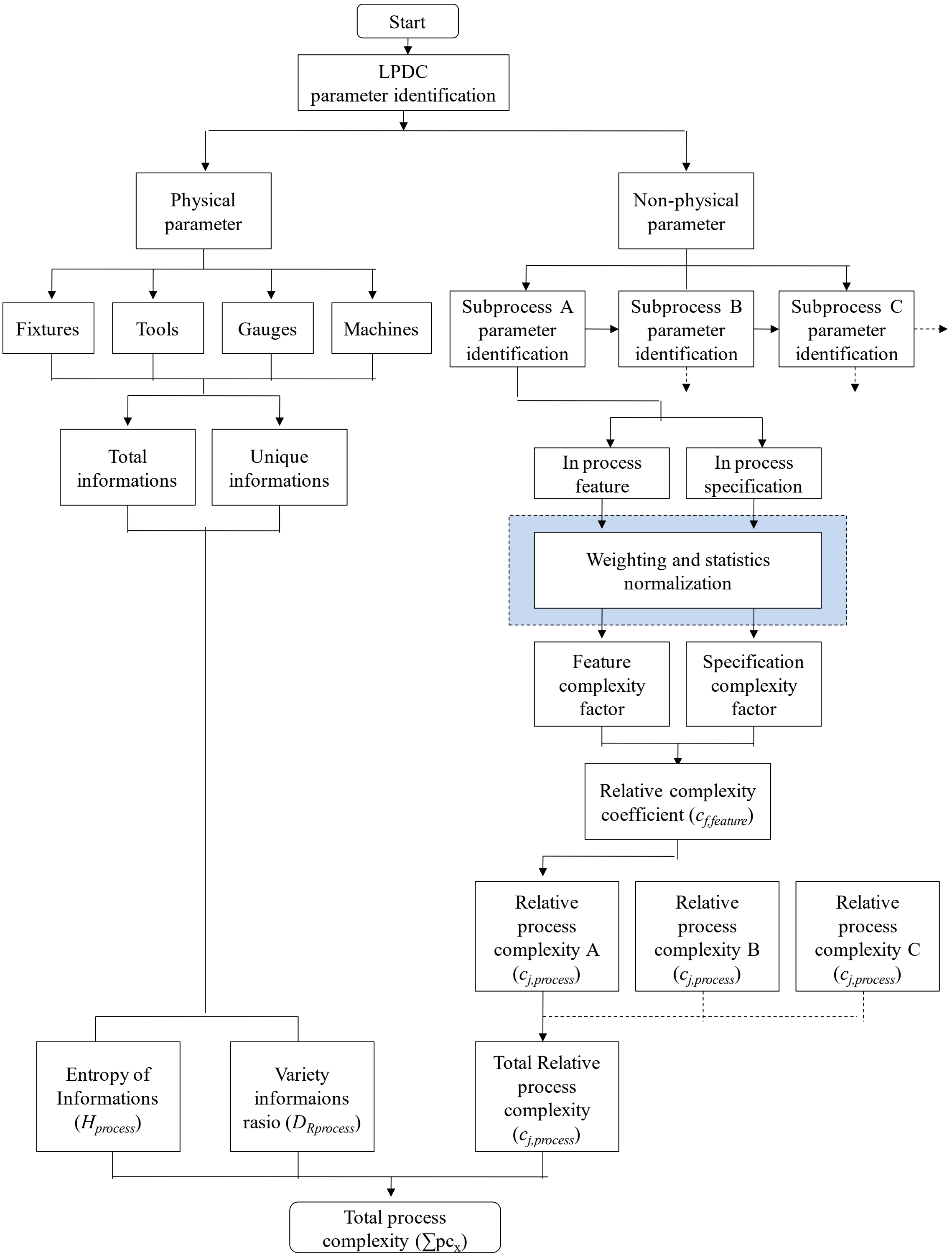

Fig. 1. Process complexity flow chart

In Fig. 1, physical parameters analysis collects physical information such as fixtures, tools, gauges, and machines.

The total information and unique information are analyzed in this step to calculate the $H_{process}$ and $D_{Rprocess}$.

The non-physical parameters analysis includes the in-process feature and in-process specification.

Each parameter in the subprocess is then weighted and normalized by statistics to get $F_{CF}$ and $S_{CF}$.

Those factors are then used to calculate the $c_{f,feature}$, and finally get the $c_{j,process}$. The sum of each $c_{j,process}$ from each subprocess is the total relative process complexity.

From the $H_{process}$, $D_{Rprocess}$, and $c_{j,process}$, the $pc_x$ of a product can be calculated.

Then, each product's $pc_x$ is compared to see which product has the highest complexity.

### 4. 3. Product and LPDC process description

The product used for the base of the study is provided in Fig. 2.

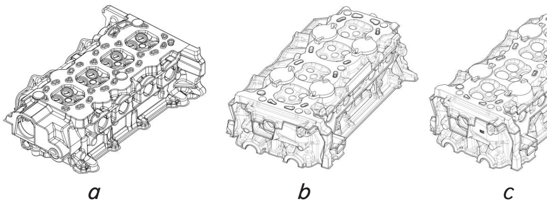

Fig. 2. Cylinder head with a product type: *a* – 3SZ; *b* – 1TR; *c* – 2TR

The LPDC products analyzed for complexity are three different types of cylinder heads fabricated in PT. Astra Daihatsu Motor. The drawings of the cylinder heads can be seen in Fig. 2.

By the volume of the cylinder head, 3SZ has a volume of around 0.0135 m$^3$, 1TR is 0.0221 m$^3$, and 2TR is 0.0210 m$^3$. From these three cylinder heads, the process complexity analysis will be done.

The subprocesses of the whole LPDC process should be identified for the process complexity analysis. The subprocesses are divided sequentially into four subprocesses: setting, filling, solidification, and handling.

Fig. 3 shows the historical data of pressure and time during the filling and solidification subprocesses of all three cylinder head types in PT. Astra Daihatsu Motor, Indonesia.

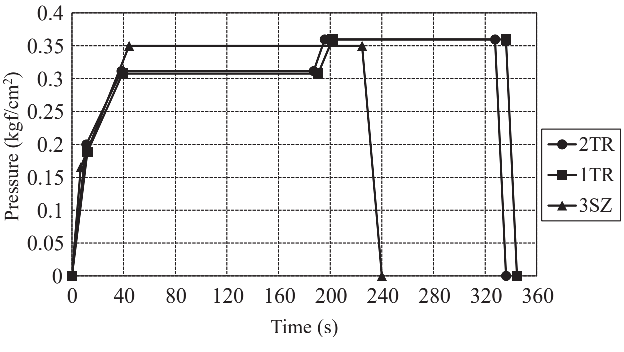

Fig. 3. Pressure and time of the filling and solidification subprocesses

The pressure will be one of the non-physical parameters deciding the cylinder head's process complexity.

## 5. Results of complexity analysis of LPDC

### 5. 1. Parameter analysis

### 5. 1. 1. Physical parameters

The physical parameters consist of components used during the LPDC process, including fixtures, tools, gauges, and machines. All three cylinder heads mentioned in Fig. 3 have the same physical components. The complete list of physical components can be seen in Table 1.

Table 1

Physical parameters of the cylinder heads

| Physical parameters | Total information ($N$) | Unique information ($n$) |
|---|---|---|
| Fixtures | 1 | 1 |
| Tools | 9 | 6 |
| Gauges | 3 | 3 |
| Machines | 6 | 5 |
| Total | 19 | 15 |

The uniqueness of the information is based on which tools and machines are used specifically in the LPDC process. All the identified physical parameters are utilized to calculate $H_{process}$ and $D_{Rprocess}$ based on (1)–(3).

### 5. 1. 2. Non-physical parameters

The non-physical parameters are identified for each subprocess (setting, filling, solidification, and handling). The non-physical parameters are confirmed from the observation in PT. Astra Daihatsu Motor. All the parameters for in-process feature of each sub-process are die cavity and core for setting; pressure, temperature, velocity, and material for filling; temperature for solidification; and again, die cavity and core for handling. For the in-process specification, the parameters are die cavity and core for setting; pressure and die cavity for filling; cooling for solidification; product for handling.

Then, following (4)–(7), each in-process feature and specification is calculated to get the $c_{j,process}$ of the cylinder head. The full weighting and normalizing process of each cylinder head type can be seen in Tables 2–10. Tables 2–4 cover the calculations for the 3SZ cylinder head. Tables 5–7 covers the calculations for the 1TR cylinder head. Finally, Tables 8–10 cover the calculations for the 2TR cylinder head.

Table 2

$F_{CF}$ calculation of 3SZ cylinder head

| Sub-Process | Number | $J$=Variable | | *SUM* | *SUM/J* ($F_{CF}$) |
|---|---|---|---|---|---|
| | | Aspect feature | Weight | | |
| Setting | 2 | Die Cavity | 0.20 | 0.54 | 0.27 |
| | | Core | 0.33 | | |
| Filling | 1 | Pressure | 0.36 | 1.99 | 0.50 |
| | | Temperature | 0.58 | | |
| | | Velocity | 0.50 | | |
| | | Material | 0.55 | | |
| Solidification | 1 | Temperature | 0.58 | 0.58 | 0.58 |
| Handling | 2 | Die Cavity | 0.20 | 0.54 | 0.27 |
| | | Core | 0.33 | | |

Table 3

$S_{CF}$ calculation of 3SZ cylinder head

| Sub-Process | Number | $K$=Variable |  | $SUM$ | $SUM/K$ ($S_{CF}$) |
|---|---|---|---|---|---|
|  |  | Aspect Specification | Weight |  |  |
| Setting | 2 | Die Cavity | 0.76 | 1.07 | 0.54 |
|  |  | Core | 0.31 |  |  |
| Filling | 1 | Pressure | 0.13 | 0.50 | 0.25 |
|  |  | Die Cavity | 0.37 |  |  |
| Solidification | 1 | Cooling | 0.43 | 0.43 | 0.43 |
| Handling | 2 | Product | 0.39 | 0.39 | 0.39 |

Table 4

Process complexity calculation of 3SZ cylinder head

| Sub-Process | Feature complexity | Weighted feature complexity |
|---|---|---|
| Setting | 0.40 | 0.13 |
| Filling | 0.37 | 0.06 |
| Solidification | 0.50 | 0.08 |
| Handling | 0.33 | 0.11 |
| $c_{j,process}$ |  | 0.39 |

Table 5

$F_{CF}$ calculation of 1TR cylinder head

| Sub-Process | Number | $J$=Variable |  | $SUM$ | $SUM/J$ ($F_{CF}$) |
|---|---|---|---|---|---|
|  |  | Aspect feature | Weight |  |  |
| Setting | 2 | Die Cavity | 1.00 | 1.96 | 0.98 |
|  |  | Core | 0.96 |  |  |
| Filling | 1 | Pressure | 0.37 | 1.94 | 0.49 |
|  |  | Temperature | 0.58 |  |  |
|  |  | Velocity | 0.44 |  |  |
|  |  | Material | 0.55 |  |  |
| Solidification | 1 | Temperature | 0.58 | 0.58 | 0.58 |
| Handling | 2 | Die Cavity | 1.00 | 1.96 | 0.98 |
|  |  | Core | 0.96 |  |  |

Table 6

$S_{CF}$ calculation of 1TR cylinder head

| Sub-Process | Number | $K$=Variable |  | $SUM$ | $SUM/K$ ($S_{CF}$) |
|---|---|---|---|---|---|
|  |  | Aspect Specification | Weight |  |  |
| Setting | 2 | Die Cavity | 0.76 | 1.07 | 0.54 |
|  |  | Core | 0.31 |  |  |
| Filling | 1 | Pressure | 0.50 | 1.50 | 0.75 |
|  |  | Die Cavity | 1.00 |  |  |
| Solidification | 1 | Cooling | 0.75 | 0.75 | 0.75 |
| Handling | 2 | Product | 1.00 | 1.00 | 1.00 |

Table 7

Process complexity calculation of 1TR cylinder head

| Sub-Process | Feature complexity | Weighted feature complexity |
|---|---|---|
| Setting | 0.76 | 0.25 |
| Filling | 0.62 | 0.10 |
| Solidification | 0.66 | 0.11 |
| Handling | 0.99 | 0.33 |
| $c_{j,process}$ |  | 0.80 |

Table 8

$F_{CF}$ calculation of 2TR cylinder head

| Sub-Process | Number | $J$=Variable |  | $SUM$ | $SUM/J$ ($F_{CF}$) |
|---|---|---|---|---|---|
|  |  | Aspect feature | Weight |  |  |
| Setting | 2 | Die Cavity | 0.90 | 1.86 | 0.93 |
|  |  | Core | 0.96 |  |  |
| Filling | 1 | Pressure | 0.36 | 2.15 | 0.54 |
|  |  | Temperature | 0.75 |  |  |
|  |  | Velocity | 0.43 |  |  |
|  |  | Material | 0.60 |  |  |
| Solidification | 1 | Temperature | 0.58 | 0.58 | 0.58 |
| Handling | 2 | Die Cavity | 0.90 | 1.86 | 0.93 |
|  |  | Core | 0.96 |  |  |

Table 9

$S_{CF}$ calculation of 2TR cylinder head

| Sub-Process | Number | $K$=Variable |  | $SUM$ | $SUM/K$ ($S_{CF}$) |
|---|---|---|---|---|---|
|  |  | Aspect Specification | Weight |  |  |
| Setting | 2 | Die Cavity | 0.76 | 1.07 | 0.54 |
|  |  | Core | 0.31 |  |  |
| Filling | 1 | Pressure | 0.50 | 1.20 | 0.60 |
|  |  | Die Cavity | 0.70 |  |  |
| Solidification | 1 | Cooling | 0.75 | 0.75 | 0.75 |
| Handling | 2 | Product | 0.95 | 0.95 | 0.95 |

Table 10

Process complexity calculation of 2TR cylinder head

| Sub-Process | Feature complexity | Weighted feature complexity |
|---|---|---|
| Setting | 0.73 | 0.24 |
| Filling | 0.57 | 0.09 |
| Solidification | 0.66 | 0.11 |
| Handling | 0.94 | 0.31 |
| $c_{j,process}$ |  | 0.76 |

Fig. 4 summarizes the feature complexity of all three cylinder head types from the previous calculations in Tables 2–10.

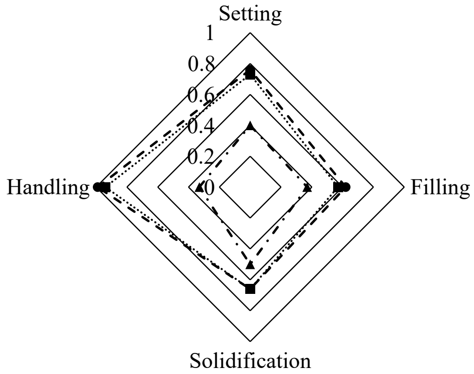

Fig. 4. Comparison of feature complexity of all three cylinder head types

The cylinder heads 1TR and 2TR are similar in the graph, where the subprocess with the highest complexity is the handling and setting process. Both are manual processes that depend on the product, die, and core geometry. As mentioned before, the dimension of 1TR and 2TR is far larger than the 3SZ. As for the 3SZ, the process with the highest relative complexity is solidification. The 3SZ has a relatively small dimension for the cylinder head, so the manual process is not as complex as the other two types. The solidification process depends on the temperature of the die and liquid, the coolant's type, and the processing time.

### 5. 2. Process complexity index calculations

Table 11 provides the calculation results of $H_{process}$, $D_{Rprocess}$, $c_{j,process}$, and the $pc_x$ of all three cylinder heads based on (1). The process complexity index obtained shows how complex a product is.

Table 11

$pc_x$ calculation of all three cylinder head types

| Product Type | $H_{process,x}$ | $D_{Rprocess,x}$ | $c_{j,process,x}$ | $\sum p_{cx}$ |
|---|---|---|---|---|
| 3SZ | 4.32 | 0.79 | 0.39 | 5.14 |
| 1TR | 4.32 | 0.79 | 0.80 | 7.08 |
| 2TR | 4.32 | 0.79 | 0.76 | 6.93 |

From calculations in Table 11, the 1TR has the highest complexity index of 7.08, followed by 2TR at 6.93 and 3SZ at 5.14, Table 11. This index distinguishes which product is more complicated to be produced than the others.

The calculated index mentioned in Table 11 can be utilized for design analysis. Aside from the product's complexity comparison, the complexity index can be used for complexity prediction of future LPDC based product design. For example, Fig. 5–7 compares the $pc_x$ and parameters of LPDC, such as the product's volume, the production process time, and the maximum pressure used. These comparisons are meant to easily plot the complexity of a future LPDC product based on the design's data.

Dimension plays an important role in the process complexity of a product. As seen in Fig. 5, Cylinder head 3SZ, which has the least $pc_x$ value, also has the smallest dimension. Therefore, it can be considered in the design process to minimize the dimension while maintaining the product's performance. The relation also can be seen as linear, with $R^2$ being 0.9977. The volume of products can be seen directly during the design process with computer-aided design (CAD) software. As such, the process complexity of a product can be seen early in the initial design process.

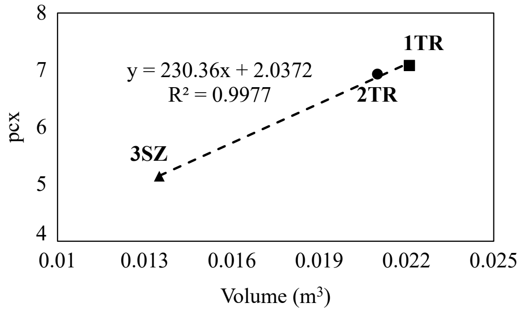

Fig. 5. Comparison of product dimension and $pc_x$

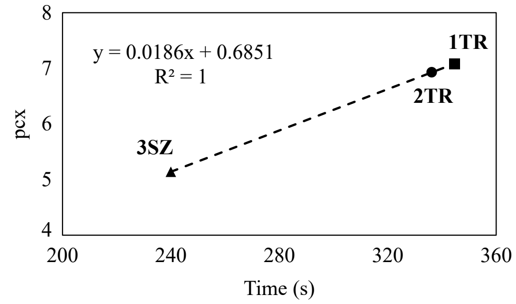

Fig. 6. Comparison of process time and $pc_x$

In Fig. 6, the processing time is compared to the calculated $pc_x$. The processing time can be identified in Fig. 3. The $pc_x$ and the processing time can be seen as the linear relation with the linearity $R^2$ is 1. This graph can roughly estimate the complexity of design in the LPDC process. Shorter process time will result in lower process complexity.

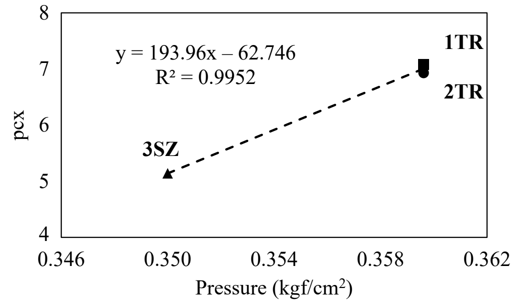

Fig. 7. Comparison of process pressure and $pc_x$

In a die casting process, one important non-physical parameter is pressure. Fig. 7 shows the relation of the maximum pressure of a cylinder head casting process with the $pc_x$. The linear relation shown with the $R^2$ is 0.9952. The graph in Fig. 7 shows that the casting process's complexity can also be roughly estimated.

The whole process of casting can be estimated in the early design process. Then, the design for manufacture and assembly (DFMA) will be performed in the system-level design. The time to finish one manufacturing process can be estimated in this process. The estimated process time can then be plotted to see the rough value of the process complexity of a product.

The pressure of the process also can be estimated early during the design process. The product's geometry and material have specific casting conditions which can be estimated in the early phase, for example, the pressure. The rough value of process complexity can also be estimated by plotting such value.

Another utilization of the index is estimating a product's cost, shown in Fig. 8. The early design process contributes 70–80 % of the product cost. The product's geometry and the production process's design can be estimated in this phase. In Fig. 5–7, a simple complexity model has been developed based on the historical manufacturing process. The relations of process complexity are shown either with product volume, process time, or pressure. Data from the early design process can be plotted to estimate the estimated process complexity of the design.

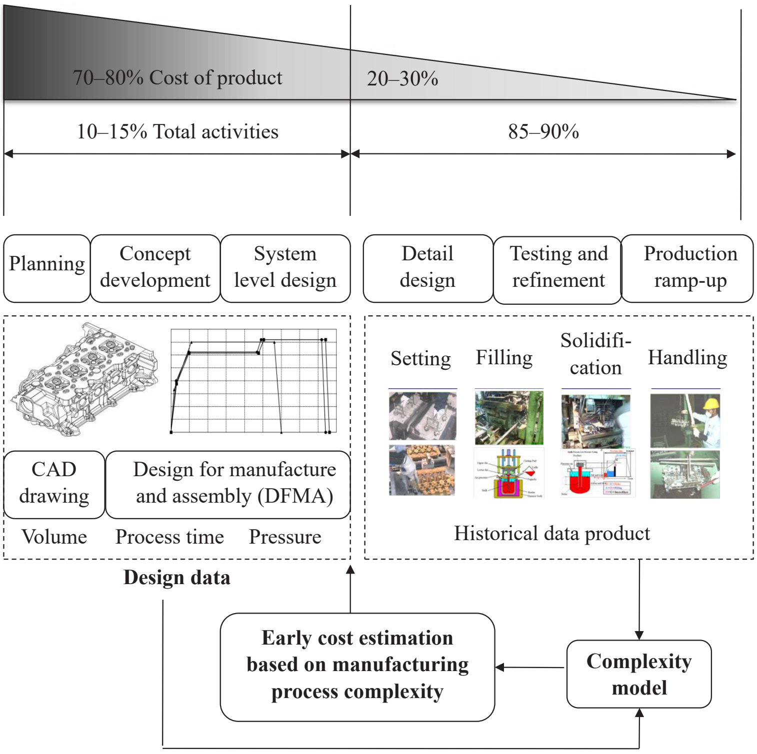

Fig. 8. Early cost estimation, which considers the manufacturing process complexity analysis [4]

The product cost tends to increase with the increment of process complexity value, as mentioned in previous work [4].

## 6. Discussions of complexity index development of the LPDC

Complexity index development is meant to add a new word in the manufacturing dictionary that can explain a product's complication. This paper shows the practical way to develop the index in the LPDC process that has yet to be developed.

The discussion starts with deciding the crucial parameters of an LPDC process. As mentioned, the parameters are divided into physical and non-physical parameters. Table 1 shows the physical parameters of this study. The products used for this study are all cylinder heads; therefore, they share the same physical components. The difference can be seen in Tables 2–10 where the non-physical parameters are described. Each of the products has specific in-process features and specifications. From Fig. 4, it is possible to see how each product can be distinguished by its complexity. The 3SZ product is far different in complexity from the others. That can be seen simply that the 3SZ product has the smallest geometry and the least pressure and process time. The complexity analysis then proves its reliability by comparing two almost similar products. From the calculations, it can be considered that the 1TR product has the highest complexity. The complexity index of the three products is 7.08 for 1TR, 6.93 for 2TR, and 5.14 for 3SZ.

These practical calculations of complexity show that the index can distinguish a product's complications even if the products are similar. In terms of future design, the index can be decided even from the early phase. The future design contains parameters planned to be used during the production process. From those parameters, the complexity index can be calculated. For example, the complexity index can be estimated by developing a simple linear model such as Fig. 5–7. By doing so, the manufacturing industry can choose the design with the least complexity as long as it complies with the requirement. It will lead to another utilization of early cost estimation. When the complexity is low, it tends to have lower production costs [4]. The whole of this concept can be seen in Fig. 8.

One advantage of design analysis using complexity is that the index shows the product complications in one index. As mentioned, it adds to the manufacturing dictionary how a product can be distinguished from its whole complications, not only geometry or just part of its parameter. Another advantage of this study is the limited analysis of LPDC based product design provided here. This study could be one of the benchmarks for how the design analysis of LPDC products should be carried out.

Although it has tried to cover all the parameters of the LPDC process, different manufacturing environments might have different parameters of LPDC. Furthermore, the new invention of technology to the LPDC also can add to or decrease the complexity index of a product. Another limitation, this study is also limited in that it only covers the study until the complexity index calculations.

For example, adding a model between complexity index and the product cost will benefit this study as it could reach the early cost estimation of an LPDC's product which will benefit more industries in the future.

The future approach of this research is to complete the complexity index of other manufacturing processes and build the complexity index database of those processes. This database will be essential for developing a comprehensive analysis of the whole manufacturing process, which will benefit the industry in the future.

## 7. Conclusions

1. Important parameters of LPDC for process complexity have been identified based on the historical data of PT. Astra Daihatsu Motor. The parameters are:

– physical parameters: fixtures, tools, gauges, and machines;

– non-physical parameters: product's specifications (*f*) and features (*s*):

a) setting: die cavity (*f* and *s*) and core (*f* and *s*);
b) filling: temperature (*f*), die cavity (*s*), and core (*s*);
c) solidification: temperature (*f*) and cooling (*s*);
d) handling: die cavity (*f*), core (*f*), and product (*s*).

2. Process complexity analysis has been analyzed. The complexity index has been identified with product 1TR having the highest complexity of 7.08, followed by 2TR at 6.93 and 3SZ at 5.14. The complexity index successfully identified which product has the most complex production parameters.

## 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.

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## Data availability

Manuscript has no associated data.

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