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Operation-based configuration complexity measurement for manufacturing system

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Abstract

Configuration not only determines the material flow pattern but also influences the production cost in a manufacturing system. The diversity of the products and growing demands for system flexibility increases the complexity of the configuration. In this paper, an operation-based approach is proposed to measure the configuration complexity of a manufacturing system. The configuration complexity models of the stations are built with single operation, several operations and their parallel types. Subsequently, an operation-based configuration complexity model of the overall system is used to measure the configuration complexity of a manufacturing system using the information entropy. Then, the relationship of the complexity between operations and stations is quantitatively described. An assembly line example is presented to validate the model. The results show that the proposed complexity measurement may evaluate the configuration complexity of a manufacturing system.

Keywords: Manufacturing systems; complexity; information entropy

1. Introduction

The purpose of mass customization is to design and assemble a wide variety of products by combining assembly and modular interfaces to provide customized products at close to mass production costs. However, the high variety poses several challenges for manufacturing systems including complicating the assembly process, reducing productivity, and reducing product quality [1]. Besides, manufacturing systems that reduce cost and time without decreasing quality and flexibility are increasingly complex [2]. In the design stage of a production line, there might be several configuration alternatives to consider before selecting a new configuration. The objective is to adapt to the new conditions without unduly increasing the system cost or complexity or degrading the resulting product quality. However, the dynamic manufacturing environment makes it difficult to predict the effect of a decision on system performance [3]. One possible way to address these challenges is to investigate how product categories complicate the assembly process and, in turn, affect system cost, product quality and other system performances. An effective approach is to evaluate the complexity of the manufacturing system configuration to help decision makers compare alternatives.

Complexity theory provides useful approaches for the analysis of a manufacturing system's complexity [1]. The related approaches can be classified into five categories [4] as illustrated in Figure 1. The first category is non-linear dynamics. One of the most important approaches in this category is Lyapunov exponents. Following the non-linear dynamics, bifurcation diagrams and other methods from chaotic theory have also been employed for the analysis and identification of complexity measurement. The second category is information theory including Shannon entropy and Kolmogorov entropy approaches. Kolmogorov entropy makes Shannon entropy more accurate to quantify the randomness or disorder of behaviors.

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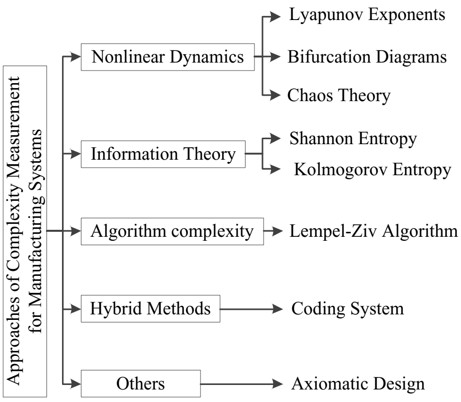

Fig. 1. Approaches of complexity measurement for manufacturing systems.

The third category is algorithm complexity. The basic premise is that a system becomes more complex with a longer number of statements that describe its behavior. The Lempel-Ziv algorithm is the most relevant algorithm. It provides a quantitative estimate of the complexity from the systems' internal structure and process. The fourth category contains hybrid methods including a coding system developed by ElMaraghy et al. [5] to classify the various types of equipment in a manufacturing system. Apart from the four categories above, other approaches like Axiomatic Design may also be relevant [6][7].

Referring to manufacturing system, researchers such as Papakostas et al. [8] modeled the complexity of manufacturing systems using nonlinear dynamics approaches. A set of manufacturing models, characterized by different production configurations and part routings, were simulated and evaluated through a series of experiments employing diverse workload patterns. Chryssolouris et al. [9] simulated a set of manufacturing models characterized by different production configurations and part routings and employing diverse workload patterns. The results are used to determine the sensitivity of a manufacturing system to workload changes.

Frizelle et al. [10] proposed a method using entropy to measure complexity in the structural and operational domains in manufacturing. Deshmukh et al. [11] enumerated factors influencing static complexity and defined a static complexity measure in terms of processing requirements of parts to be produced and machine capabilities. The measure suggested for static complexity in manufacturing systems only needs the information available from production orders and process plans. Vrabic and Butala [12] developed a metric for operational complexity that is concerned with the temporal aspects of coordination and control in manufacturing systems. The complexity is influenced by internal factors such as system structure as well as external factors such as demand.

Efthymiou et al. [13] assessed unpredictability in manufacturing via the Lempel-Ziv measure. The fluctuation of critical manufacturing performance indicators was studied to evaluate the complexity of a manufacturing system.

ElMaraghy et al. [5] developed a complexity coding system to classify and code machines, buffers, and material handling equipment that make up manufacturing systems. The code captures the amount and variety of information. The probability of a manufacturing system being successful in delivering the desired production capacity as function of the availability of its components is used as an additional measure of the system ability to meet the targeted forecast production volume with its variation as a measure of complexity. Samy and ElMaraghy [14] introduced a metric to measure the structural complexity of manufacturing systems based on the complexity inherent in the structure of its components: machines, buffers, and material handling systems. The model uses the manufacturing systems classification code developed by ElMaraghy et al. [5] to assess the contribution of each module to the overall system structural complexity even if the complexity metric is not related to the information theory approach.

Lee et al. [6] investigated the complexity concept defined in axiomatic design theory to avoid vague use of the term 'complexity' in engineering system design, to provide deeper insight into possible causes of complexity, as well as to develop a systematic approach to complexity reduction.

Other research provides a clue to develop an effective measurement for complexity, but several issues on the special features of complexity measurements must be noticed. The relationship between uncertainty of the operation and overall line configuration is rarely considered in existing complexity-measurement researches. Moreover it is difficult to measure the nonlinear relationship among each station.

Researchers generally think that information entropy theory effectively describes complexity, and the complexity features are closely related to operations, system layout, workflow, and work time. Thus, it is necessary to build a model that considers the relationship between operations and configuration to detail the inherent meaning of complexity in manufacturing systems.

Uneven loads, station blocks and rhythm disorders caused by uncertain factors increase the complexity of manufacturing systems. Complexity theory is an effective method to measure diversity and uncertainty and is used to measure the uncertainty of production system in manufacturing system. The traditional complexity measurement method emphasizes the differences in equipment types in manufacturing systems and divides the equipment into production equipment, buffer, and material handling system. The complexity of the manufacturing system is increased, and the difficulty of measurement arises. Parallel stations and sub-lines definitely influence the complexity of the overall line; it is necessary to also measure their complexity from the point of view of overall line.

In the following sections, we present an approach based on operations to measure and quantify simultaneously the configuration complexity of manufacturing system that contain parallel stations and sub-lines. A detailed description of our approach is introduced. Next, we apply it to an assembly line case study. The purpose is to develop the methodology for describing the complexity of relationship between the manufacturing processes with the system configuration, which can be applied to optimize the design of a manufacturing system configuration itself.

2. Configuration complexity of manufacturing system

2.1. Problem description and assumption

The use of many different pieces of equipment makes manufacturing systems complicated and nonlinear. This greatly increases the difficulty of measuring the system's complexity. The uncertainty of individual resources increases the system complexity. Besides, coupling the system resources should not be calculated by linearly superimposing the individual resources' complexity. If the manufacturing system complexity is obtained by accumulating the manufacturing cell complexity independently, then the results will be inaccurate. The method also does not reflect the system inherent complexity and the characteristic coupling relationship.

Several researchers have addressed the configuration complexity considering the flexibility of the machine. A more flexible machine is often more complex. If the dynamic system process is considered, then the state of operation is an effective starting route for analyzing the flexibility to each station in the manufacturing system. The Shannon entropy can then calculate the complexity of the station. Shannon entropy suggests that the amount of information can be used to evaluate the uncertainty degree of the system state. When there are m events with individually occurring possibilities p_1, p_2, $\cdots$, p_m, then the contained entropy is [3] [4]:

$$I = -\sum_{i=1}^{m} p_i \log p_i \tag{1}$$

If it is possible to model the complexity of each station starting from its type, the configuration complexity model of the manufacturing system can be built. Usually, the manufacturing system consists of the following station types: the station to complete one operation, the station to complete at least two operations, the parallel stations including one operation each, and the parallel stations including at least two operations each. The station types are shown in Table 1 and Figure 2. A sub-line is similar to the main line. Thus, it is necessary to build a model that considers the relationship between operations and configuration to draw out the inherent meaning of the manufacturing system complexity. This model can provide an important theoretical basis to implement further configuration optimization.

Table 1. The station types in a manufacturing system.

Station type	Station description
Station 1	One station including one operation
Station 2	One station including several operations
Station 3	Parallel stations including one operation each
Station 4	Parallel stations including several operations each

2.2. Operation-based configuration complexity model

Operation-based configuration complexity describes the extent of the manufacturing system's configuration related to the success probability of a manufacturing operation, the distribution of operations among the stations, and the diversity of the station types as described in Section 2.1. The success probability p_i of the *i-th* operation is estimated on practical measurement data, empirical data, or experience, while $1-p_i$ is the failure probability of the operation.

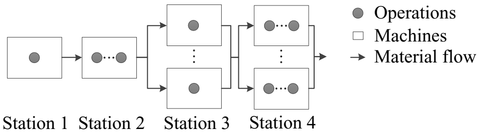

Fig. 2. Several kinds of station representations.

(1) Station 1

The complexity of station has just 1 operation, which is h_r.

$$h_r = p_{ri} \log_2 \frac{1}{p_{ri}} + (1-p_{ri}) \log_2 \frac{1}{(1-p_{ri})} \tag{2}$$

where, p_{ri} = success probability of operation i in station r.

(2) Station 2

If there are m operations in a station, then the complexity of station that has more than 1 operation is h_s.

$$h_s = \prod_{si=1}^{m} p_{si} \log_2 \frac{1}{\prod_{si=1}^{m} p_{si}} + (1-\prod_{si=1}^{m} p_{si}) \log_2 \frac{1}{(1-\prod_{si=1}^{m} p_{si})} \tag{3}$$

where, p_{si} = success probability of operation i in station s;
m = number of the operations in station s.

(3) Station 3

If there are two or more than two machines without any difference in a single station, then their complexity is h_t.

$$\begin{aligned} h_t = &\binom{0}{k} p_{ti}^k \log_2 \frac{1}{p_{ti}^k} + \binom{1}{k} (1-p_{ti}) p_{ti}^{k-1} \log_2 \frac{1}{(1-p_{ti}) p_{ti}^{k-1}} + \cdots \\ &+ \binom{k-1}{k} (1-p_{ti})^{k-1} p_{ti} \log_2 \frac{1}{(1-p_{ti})^{k-1} p_{ti}} \\ &+ \binom{k}{k} (1-p_{ti})^k \log_2 \frac{1}{(1-p_{ti})^k} \end{aligned} \tag{4}$$

where, p_{ti} = success probability of operation i in station t;
k = number of the machines in station t.

(4) Station 4

This describes two or more than two machines in a single station where every machine needs to complete several operations. In this situation, the complexity of this station is h_d. The probability of the single machine f in the station d is p_{df}.

$$p_{df} = \prod_{fi=1}^{b} p_{fi} \tag{5}$$

where, f = number of machine in station d;
p_{df} = success probability of machine f in station d;
p_{fi} = success probability of operation i in machine f;
b = total number of the operation in machine f;
g = total number of the machines in station d.

It follows:

$$h_d = \binom{0}{g} p_{df}^{g} \log_2 \frac{1}{p_{df}^{g}} + \binom{1}{g}(1-p_{df})p_{df}^{g-1} \log_2 \frac{1}{(1-p_{df})p_{df}^{g-1}} + \cdots + \binom{g-1}{g}(1-p_{df})^{g-1} p_{df} \log_2 \frac{1}{(1-p_{df})^{g-1} p_{df}} + \binom{g}{g}(1-p_{df})^{g} \log_2 \frac{1}{(1-p_{df})^{g}} \tag{6}$$

(5) Overall system

We then consider a production line that contains u stations having one operation, v stations having more than one operation, w parallel stations having one operation in each machine, and e parallel stations having more than one operation. The configuration representation is shown in Figure 3.

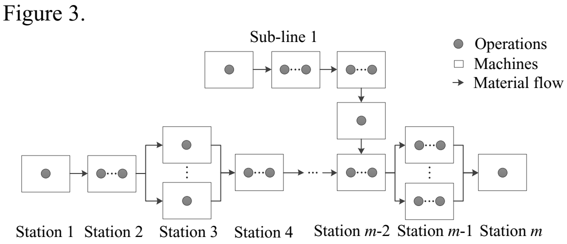

Fig. 3. Manufacturing system representation.

The configuration complexity of overall manufacturing system is H_{cms}:

$$H_{cms} = \sum_{r=1}^{u} h_r + \sum_{s=1}^{v} h_s + \sum_{t=1}^{w} h_t + \sum_{d=1}^{e} h_d \tag{7}$$

3. Case study

An assembly line for a gearbox in a certain vehicle company includes 35 stations in main line, whose operations' probabilities are shown in Table 2. This line has 5 sub-lines, named 1, 2, 3, 4 and 5. They merge into the main assembly line respectively at station 8, 14, 17, 22 and 24. The 26th and 33th stations are parallel. Table 2 shows the success probability of the operations at good capacity in the main line's station. Many stations implement 2 or 3 operations such as station 2 and station 4. The success probability of the operations in the sub-lines is shown in Table 3. The layout of the overall assembly line is shown in Figure 4.

3.1. The result of using operation-based configuration complexity model

Using the model in section 2.2, the complexity of stations is evaluated as shown in Table 4 and Table 5.

Table 2. The probability of the operations in main line's station.

Station 1-9	***p***	**Station 10-18**	***p***	**Station 19-27**	***p***	**Station 28-35**	***p***
1	1	**10**	0.9975	**19**	0.984	**28**	0.9975
2	0.994 0.995 0.995	**11**	0.99 0.994	**20**	0.996	**29**	0.9975
3	0.9975	**12**	0.984	**21**	0.995	**30**	0.9975
4	0.992 0.992	**13**	0.995	**22**	0.995	**31**	0.984
5	0.993 0.995 0.994	**14**	0.995	**23**	0.995	**32**	0.995
6	0.996	**15**	0.998 0.9995	**24**	0.999 0.996	**33**	0.995
7	0.998 0.998 0.999	**16**	0.9975	**25**	0.9975	**34**	0.995
8	0.998 0.9995	**17**	0.998 0.997	**26**	0.998 0.997	**35**	0.995
9	0.9975	**18**	0.999 0.998 0.998	**27**	0.9975		

Table 3. The probability of the operation in sub-line's station.

Stations	**Sub-1**	**Sub-2**	**Sub-3**	**Sub-4**	**Sub-5**
1	0.984	0.999, 0.996	0.995	0.995	0.995
2	0.997, 0.998	0.9975, 0.9975		0.995	0.996
3	0.992, 0.992	0.995		0.9975	0.992, 0.992
4	0.9975	0.992, 0.992		0.995	0.995
5		0.996		0.984	

Table 4. The complexity of the stations (S) in main line.

S 1-7	**S 8-14**	**S 15-21**	**S 22-28**	**S 29-35**
0	0.025203	0.025203	0.045415	0.025212
0.117845	0.025212	0.025212	0.045415	0.025212
0.025212	0.025212	0.045369	0.045384	0.11835
0.11797	0.117993	0.045354	0.025212	0.045415
0.129442	0.11835	0.11835	0.090738	0.090829
0.037622	0.045415	0.037622	0.025212	0.045415
0.045354	0.045415	0.045415	0.025212	0.045415

Table 5. The complexity of the stations in sub-lines.

Stations	**Sub-1**	**Sub-2**	**Sub-3**	**Sub-4**	**Sub-5**
1	0.11835	0.045384	0.045414	0.045415	0.045415
2	0.045369	0.045367		0.045415	0.037622
3	0.11797	0.045415		0.025212	0.11797
4	0.025212	0.11797		0.045415	0.045415
5		0.037622		0.11835	

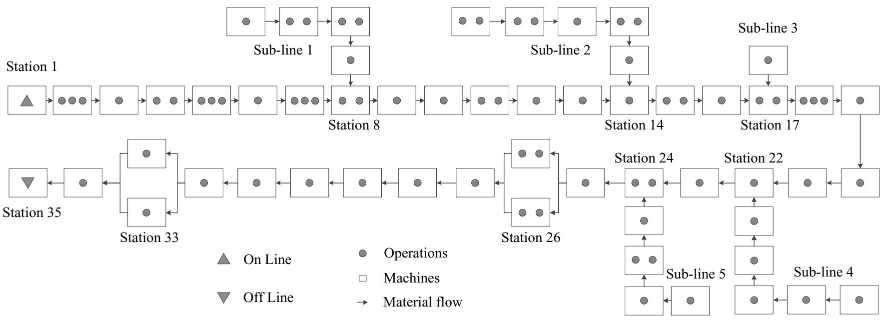

Fig. 4. The layout of the manufacturing system in the case

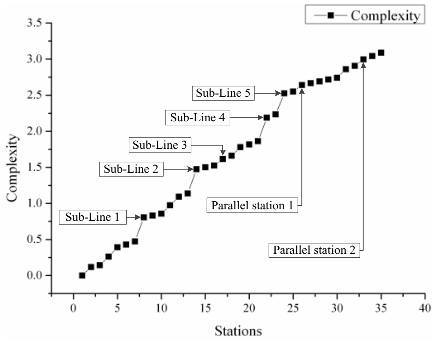

Fig. 5. The complexity index of stations along with material flow.

Figure 5 shows the cumulative complexity index of the stations along with the material flow in the main line. The results in Figure 5 indicate that the configuration complexity increases as the number of the stations along with the material flow. There will be a value step in the station in which the sub-line is inserted. The complexity of overall system is 3.088.

3.2. Comparison of the case with "The Coding System"

To validate the proposed approach, the configuration complexity of the considered case study was also calculated using the coding system proposed by Kuzgunkaya and ElMaraghy [5]. Most gearbox processing involves several operations that can be performed on three different machine types: tightening machine, compressing machine and measuring machine. These machines consist of five kinds of codes. There are 23 automatic stations and 31 human-based stations in this line. There are 2 machines in station 26 and station 33. The symbols and the maximum value of the type code are shown in Table 6. The type code string for automatic stations is shown in Table 7. Using Eq. (9) in [5], the machine type complexity index of each automatic station is evaluated as shown in Table 8.

Table. 6. The symbols and the maximum value of the type code.

Digit	Structure	Axes	Heads/Spindles	Fixed tool	Adjustable tool
Symbol	St	Ax	He	Fi	Ad
MAX	4	9	20	2	40

Table. 7. The type code string for automatic stations.

S	St	Ax	He	Fi	Ad	S	St	Ax	He	Fi	Ad
3	1	3	9	1	18	**30**	1	2	1	1	2
6	1	1	1	1	1	**31**	1	2	2	2	
7	1	1	1	1	1	**33**	1	1		1	
9	1	2	3	1	26	**34**	1	5	1	1	1
11	1	2	4	1	4	**1.1**	1	1	2	1	2
12	1	1	3	1	3	**1.2**	1	2	2	1	2
14	1	7	1	2	1	**1.3**	1	1	2	1	2
16	1	2	9	1	38	**1.4**	1	1	1	1	2
20	1	1	1	1	1	**2.2**	1	1	1	1	1
24	1	1	1	1	16	**2.3**	1	1	1	1	1
25	1	2	5	1	10	**5.3**	1	1	1	1	1
28	1	2	7	1	14						

Table. 8. The machine type complexity index.

S	a_{ij}	S	a_{ij}	S	a_{ij}	S	a_{ij}
3	0.396667	**14**	0.420555	**30**	0.214444	**1.3**	0.202222
6	0.187222	**16**	0.474444	**31**	0.314444	**1.4**	0.192222
7	0.187222	**20**	0.187222	**33**	0.172222	**2.2**	0.187222
9	0.354444	**24**	0.262222	**34**	0.276111	**2.3**	0.187222
11	0.254444	**25**	0.294444	**1.1**	0.202222	**5.3**	0.187222
12	0.217222	**28**	0.334444	**1.2**	0.224444		

The complexity of stations in the main line can be calculated according to the reliability of the machine in automatic station using the formula Eq. (3) in [5] (Table 9). The complexity of the stations in the sub-lines is shown in Table 10. Because the coding system does not consider the human-based station, the complexity of a human-based station is calculated by the reliability of the human operator, i.e., their experience. However, this is just one possible interpretation.

Table 9. The complexity of stations (S) in main line.

S 1-7	S 8-14	S 15-21	S 22-28	S 29-35
0	0.113325	0.113325	0.168989	0.113325
0.175483	0.040167	0.053766	0.168989	0.024302
0.044952	0.113325	0.168989	0.044313	0.055180
0.175483	0.044651	0.168989	0.033368	0.168989
0.175483	0.038119	0.175483	0.168989	0.058207
0.032854	0.168989	0.032854	0.113325	0.046660
0.031638	0.142138	0.168989	0.037901	0.168989

Table 10. The complexity of stations in sub-lines.

Stations	Sub-1	Sub-2	Sub-3	Sub-4	Sub-5
1	0.035487	0.168989	0.168989	0.168989	0.168989
2	0.037929	0.031638		0.168989	0.175483
3	0.035487	0.031638		0.113325	0.032854
4	0.021784	0.175483		0.168989	0.168989
5		0.175483		0.175483	

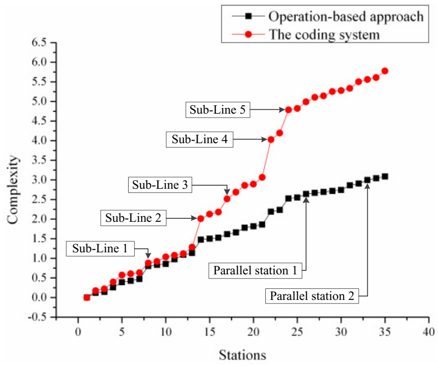

Fig. 6. The complexity index of stations along with material flow.

Based on the equation that expresses the complexity due to the machine in [5], the cumulative complexity of the stations along with material flow is shown in Figure 6. As shown, the complexity of overall system is 5.776. The complexity values of the manufacturing systems given by the two methods are coherent even if the coding system gives higher relevance to the sub-lines.

4. Discussion and conclusions

A new configuration complexity model of manufacturing system is built considering both sub-lines and parallel stations simultaneously. The proposed model measures the system complexity based on the information entropy. Moreover, the influence of operations on the complexity of system configuration is fully considered, and it is possible to measure the complexity of both human-based stations and automatic stations at the same time. A case study was proposed to validate the model. The result shows that the proposed method can evaluate the configuration complexity of a manufacturing system. Furthermore, the operation-based method measures the relationship between operations and the overall line.

Versus the coding system approach, the proposed approach can be used at the very beginning of the manufacturing system configuration. In fact, it does not require a detailed design of coding system needs. The coding system remains a relevant method to state the manufacturing system complexity when dealing with automated systems at the detailed design stage.

Further research activities will be devoted to incorporate the configuration optimization with process planning to find the relationship between process planning and layout of system to develop a methodology for optimizing the configuration design of a manufacturing system.

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