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Measuring the complexity of manufacturing system configurations based on operations

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Abstract

Configuration determines the material flow pattern, which impacts production cost in a manufacturing system. The expanding diversity of commodities and the necessity for systems to be adaptable make the setup more complicated. We provide an operation-based approach to measuring the configuration complexity of a manufacturing system in this research. A mix of sequential and parallel approaches is used to develop complexity models for station layouts. Using the information entropy, a model of the whole system's operations is used to assess the configuration complexity of a manufacturing system. A quantitative depiction of the relationship between the degrees of complexity of operations and stations follows.

1. Introduction

Mass customisation is an approach to product development and manufacturing that uses assembly and modular interfaces to create and produce a wide variety of products at lower costs for individual customers. The cost is reasonable enough for mass production. On the other hand, production processes have issues because to the high diversity, including longer assembly times, reduced output, and worse quality [1]. Designing manufacturing systems that minimise production time and costs without sacrificing quality or flexibility is also becoming increasingly complex [2]. When designing a production line, there may be a number of possible configuration choices to consider. Finding a way to adapt to the changing conditions while limiting the

reducing the output quality, increasing the system's complexity, or both. In the setting of the highly changeable production environment, it could be difficult to predict how a choice would affect system performance [3]. Researching how various product types influence assembly and, by implication, system cost, product quality, and other system performances, might be one way to get around these problems. Assessing the production system's configuration complexity thoroughly could help decision-makers. A manufacturing system's complexity may be better investigated with the help of

The theory of complexity [1]. Figure 1 shows five main groups that similar

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approaches may be grouped into based on [4]. We begin with non-linear dynamics. One of the most important approaches in this class is the Lyapunov exponent. In addition to non-linear dynamics, additional tools from chaotic theory, like as bifurcation diagrams, have been used in the investigation and characterisation of complexity measurement. Theories like Shannon's and Kolmogorov's entropies, which are concerned with information, make up the second group. Shannon entropy is improved as a measure of disorder or unpredictability of behaviour by incorporating Kolmogorov entropy.

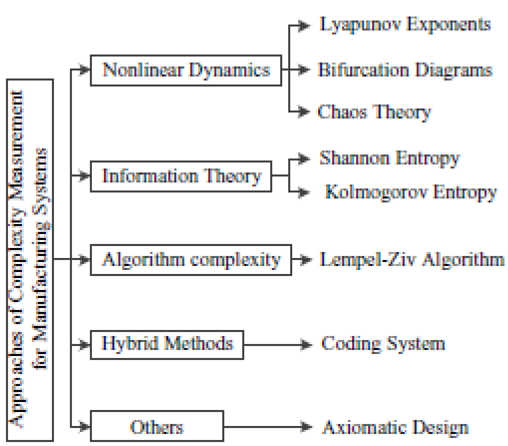

Figure 1: Various methods for gauging the complexity of industrial systems.

Thirdly, there is algorithmic complexity. You may say that the complexity of a system grows with the passage of time. Comments that provide a detailed description of its actions. When it comes to algorithms, the Lempel-Ziv algorithm is tops. It provides a numerical evaluation of the complexity according to the inner workings of the system. The coding method developed by ElMaraghy et al. [5] is one example of a hybrid approach to industrial equipment classification in the final category. There could be other relevant courses, such Axiomatic Design, outside the four already listed. (1), (2), and (7). The complexity of industrial processes has been described by academics like Papakostas et al. [8] using nonlinear dynamics approaches. A series of experiments were conducted to simulate and evaluate several manufacturing models. The models were identified by their unique production configurations and component routings. The workload patterns used in the studies were varied. Chryssolouris et al. [9] ran simulations of many manufacturing models with different schedules, production setups, and component routings. We use the results to measure the degree to which an industrial system can adjust to new requirements. In order to measure the structural and operational degrees of industrial complexity, Frizelle et al. [10] proposed entropy. The authors Deshmukh et al. [11] listed a number of potential reasons. Issues influencing static complexity, and suggested a metric for static complexity based on processing requirements of produced parts and capabilities of machines. There is no need to collect any further data beyond what is currently included in production orders and process plans in order to use the suggested static complexity measure in manufacturing systems. The complexity of managing and coordinating manufacturing processes throughout time may be measured by Brutal [12] and Arabic came up with a measurement.

Complexity is increased by both internal factors, such as the system's structure, and external factors, such as demand. In order to examine production-related unpredictability, Efthymiou et al. [13] used the Lempel-Ziv metric. Researchers examined the variance of important industrial performance parameters to determine the complexity of a

system.
To classify and code machines, buffers, and material handling equipment, ElMaraghy et al. [5] developed a complexity coding approach. The breadth and depth of the data are faithfully reflected in the code. Probability of successfully providing planned production capacity as a function of component availability is one way to assess a manufacturing system's ability to fulfil the projected anticipated production volume with its volatility. Samy and ElMaraghy [14] came up with a new metric to measure the fundamental structural complexity of machines, buffers, and material handling systems that are part of a production system. The complexity metric used to assess each module's contribution to the system's total structural complexity is based on the manufacturing systems categorisation code developed by ElMaraghy et al. [5], which is unrelated to the information theory technique. By delving into the idea of complexity outlined in axiomatic design theory, Lee et al. [6] sought to remove the uncertainty around the term "complexity" in engineering system design. The ability to identify the sources of complexity and devise a systematic approach to combating them.

There are a number of specific difficulties associated with complexity evaluations that must be considered, even while previous research might provide direction towards developing a trustworthy complexity measurement. Researchers in the field of complexity measurement have mostly ignored the correlation between operational unpredictability and line architecture in their existing literature. The nonlinear relationship between stations is also difficult to measure. Information entropy theory, according to many experts, gives a decent explanation of complexity. They also believe that complexity features are closely related to operations, system design, workflow, and work time. Consequently, building a model that considers the relationship between configuration and operations is essential for defining complexity in manufactured systems.

2. Configuration complexity of manufacturing system

2.1. Problem description and assumption

The use of several machines and equipment leads to production systems that are complex and nonlinear. This makes it far more difficult to determine the system's efficacy. Because its components are unpredictable, the system's complexity increases. Furthermore, it is not appropriate to linearly superimpose the complexity of individual resources in order to determine the complexity of the connected system resources. It is not possible to acquire a good idea of the complexity of the production system only by adding up the complexity of the manufacturing cells. Neither the system's inherent complexity nor its distinctive coupling relationship are captured by the method. The configuration complexity has been tackled by several researchers, thanks to the machine's versatility. Machinery tends to be more complicated when it has more functions. Considering the dynamic system process, it may be helpful to start by examining the present status of the system in order to assess the adaptability of each production station. The complexity of the station may be calculated when the Shannon entropy is established. Information density may be used to assess the degree of uncertainty in the system state, according to Shannon

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entropy. When m events occur, each with its own probability p1 p2pm, the contained entropy is [3] [4].

$$I = -\sum_{i=1}^{m} p_i \log p_i \qquad (1)$$

It is possible to build the production system's configuration complexity model by modelling the complexity of each station separately. Stations in a production system often fall into one of four types: those that execute a single operation, two or more operations, all four operations simultaneously, or none at all. Figure 2 and Table 1 both show the different kinds of stations. A sub-line is a line that runs parallel to the main line. Building a model that accounts for the relationship between configuration and operations is necessary for comprehending the complexity of a production system. This model might provide a critical theoretical basis for future configuration optimisation efforts. Table 1 lists the many kinds of stations that make up 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

Structure of the organisation How much a manufacturing system's configuration affects the success chance of a certain manufacturing activity is a measure of its complexity. Detailed assignment of responsibilities at each station as well as the number of stations listed in Section 2.1. The it procedure has a pi chance of succeeding and a 1 I p chance of failing, according to real data, practical measurements, or previous experience.

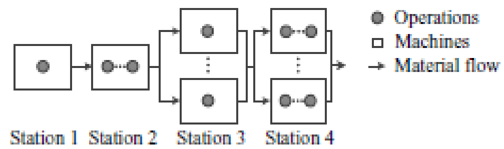

Fig. 2. Several kinds of station representations.

(1) Station 1

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

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

Where, *pri* = success probability of operation *i* in station *r*.

(2) Station 2

The complexity of a station with more than one operation is has if and only if there are m operations in the station.

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

where, *psi* = success probability of operation *i* in station *s*;
m = number of the operations in station *s*.

(3) Station 3

The complexity of the machines at a station is ht if there are at least two identical ones there.

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

Where, *pti* = success probability of operation *i* in station *t*;
k = number of the machines in station *t*.

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(4) Station 4

This represents a situation when there are many machines operating in tandem at a single station. Given the current state of affairs, this station's complexity is HD. If there is just one machine type f at station d, the probability is given by pdf.

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

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

(5) Overall system

We next envision a production line where u stations carry out a single operation, v stations execute several operations, and w parallel stations each carry out a single operation. Equipment and (e) stations with numerous functions running in parallel. The visual representation of the setup is shown in Figure 3.

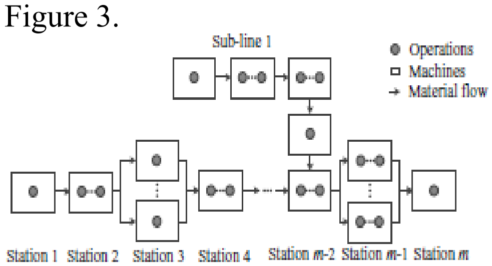

Figure 3: Graphical depiction of the production system.

Hcms is the measure of the whole manufacturing system's configuration complexity.

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

3. Case study

In Table 2, you can see the likelihood of the tasks performed at each of the 35 main line stations on a gearbox assembly line for one particular automaker. Points 1, 2, 3, 4, and 5 are the five offshoots of this central line. their locations on the main assembly line are 8, 14, 17, 22, and 24. The 26th and 33rd stations are similar. Figure 2 shows the proportion of full-capacity operations that were successful at the main line station. Two of the many stations that serve many purposes are Station 2 and Station 4. For each operation in the branching sequence, the probability of success is shown in Table 3. The overall layout of the assembly line is shown in Figure 4.

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

Tables 4 and 5 provide the results of an analysis of the stations' complexity using the model presented in Section 2.2.

Probability of Main Line Station Operations Table 2.

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.

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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	

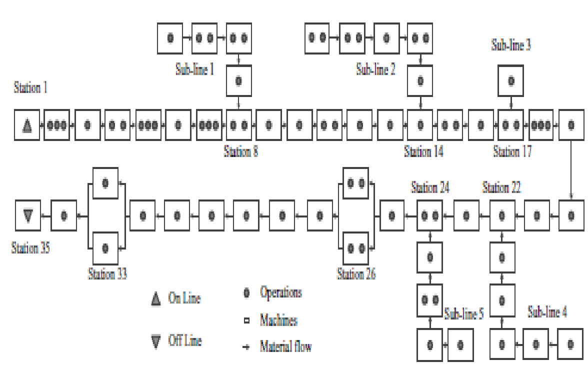

Fig. 4. The layout of the manufacturing system in the case

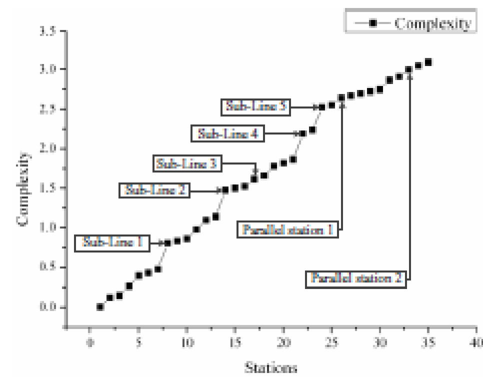

Figure 5: The material flow and station complexity index.

The material flow on the main line and the cumulative station complexity index are shown in Figure 5. As shown in Figure 5, the setup complexity and material flow both increase as the number of stations increases. A new value step will be introduced at the station where the branch line is installed. An estimated 3.088. 3.2 is the total system complexity. Relating to "The Coding System" In order to confirm the provided strategy, we also assessed the case study's configuration complexity using the coding methodology described by Kuzgunkaya and ElMaraghy [5]. There are primarily three types of gearbox processing machinery: machines that tighten, compress, and measure. In these gadgets, you'll find five different code structures. A total of 31 stops with attendants and 23 self-service stations are located along this route. There is a separate machine at Station 33 and Station 26. The maximum type code values for each potential symbol are shown in Table 6. The code string for automated stations is shown in Table 7. Table 8 shows the outcomes of evaluating the machine type complexity index for each automated station using Eq. (9) from [5]. Table 6 displays the type codes together with their maximum allowable values.

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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		

You may find out how complicated the main line stations are depending on the reliability of the equipment at an automated station by using the formula Eq. (3) in [5] (Table 9). Table 10 shows the complexity of the sub-line stations. The complexity of the station is determined by the operator's expertise, since the encoding system disregards the human-based station. But this is just one possible reading. The main line station complexity (S) is shown in table 9.

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	

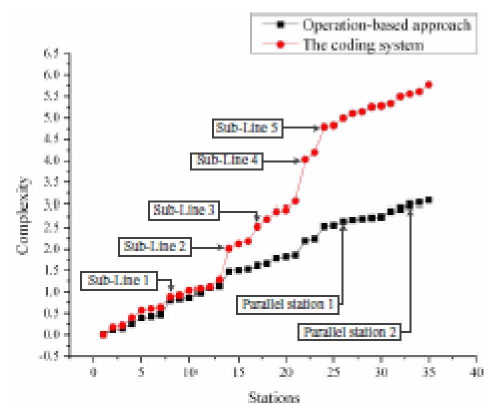

Figure 6: The material flow and station complexity index.

The total station complexity may be determined by using the machine complexity formula provided in [5]. The method and the material's movement are shown in Figure 6. An overall complexity of 5.776 was determined for the system. Comparing the complexity of manufacturing systems using either methodology yields identical findings, regardless of whether the coding scheme prioritises sub-lines or not.

4. Discussion and conclusions

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A novel model for configuration complexity accounts for the sub-lines and parallel stations that make up a manufacturing system. The proposed model collects data from the system. A measure of complexity based on information theory. The effect of operations on the difficulty of system setup is fully considered, and it is also possible to evaluate both automated and human-based stations at the same time. A case study was proposed as a means of demonstrating the model's value. This establishes the feasibility of using the proposed approach to evaluate the configuration complexity of a production system. The operation-based methodology also considers the total line in its evaluation of process connectivity. The proposed approach may be put into place right from the start of the production system setup, unlike the coding system technique. Concerning the organisation of the code, much preparation is unnecessary. Complexity of the production system may still be expressed using the coding system, which is important when working with automated systems in the detailed design phase. By fusing configuration optimisation with process planning, researchers will find the link between system architecture and process planning, and then use that knowledge to improve manufacturing system configuration design.

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