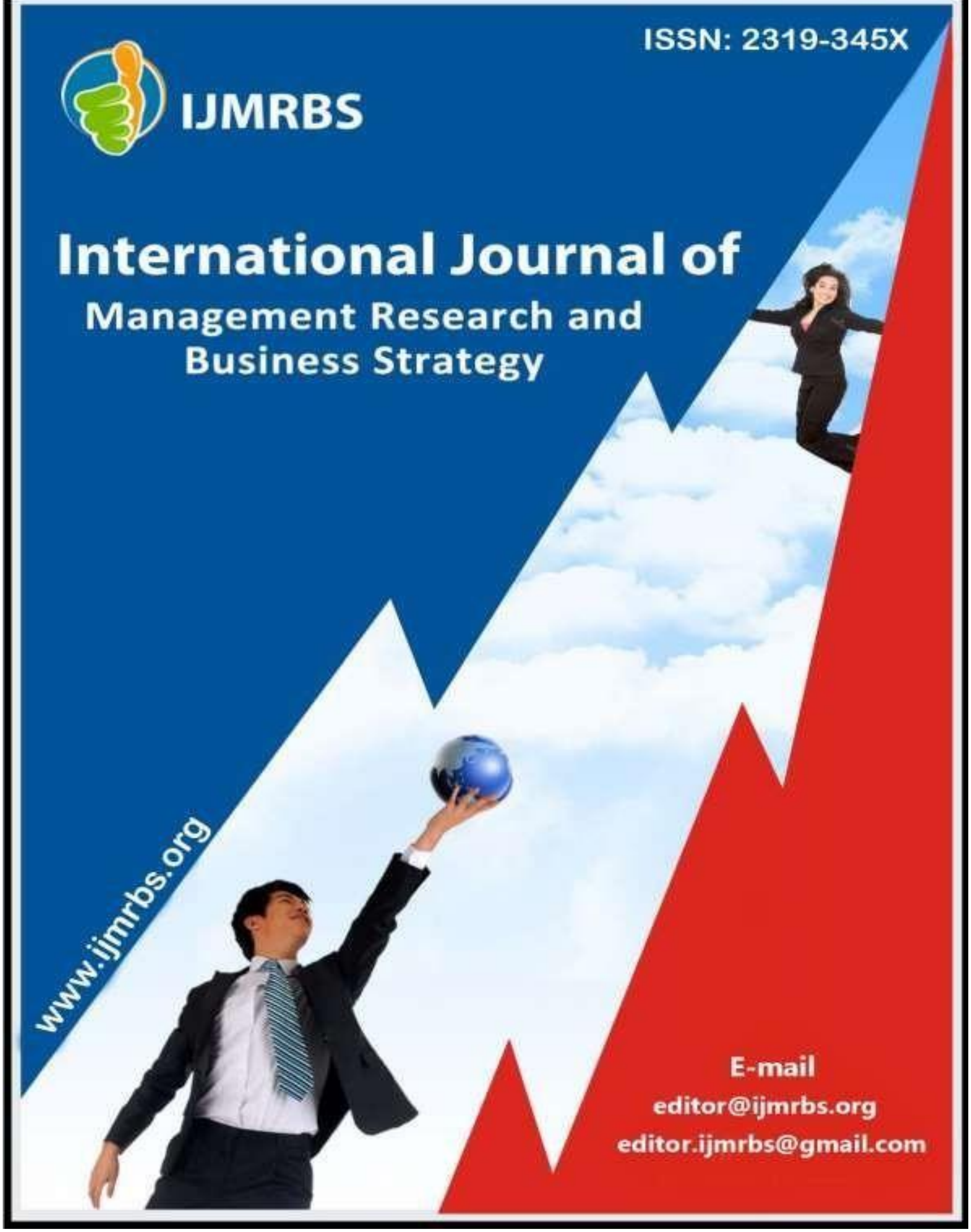
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Measuring the complexity of manufacturing system configurations based on operations

Karnati Raghavendra[1], Praveen Isuram[2],K.Durga Prasad[3],
Assistant Professor[1],Associate Professor [2],
Student[3],
Department of Mechanical,
BRILLIANT GRAMMAR SCHOOL EDUCATIONAL SOCIETY'S GROUP OF INSTITUTIONS-INTEGRATED CAMPUS
Abdullapurmet (V), Abdullapurmet (M), R.R Dt. Hyderabad-501505.

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Abstract

A manufacturing system's production cost is affected by its configuration, which in turn defines the material flow pattern. The setup becomes more difficult due to the wide variety of goods and the ever-increasing need for adaptability in the systems. In this study, we offer an operation-based method for assessing a manufacturing system's degree of configuration complexity. Complexity models for station configurations are constructed using a combination of sequential and parallel procedures. The information entropy is then utilized to evaluate the configuration complexity of a manufacturing system that is based on a model of the whole system's operations. Then, a quantitative description of the connection between operations and stations' degrees of complexity is provided.

1. Introduction

Using a combination of assembly and modular interfaces, mass customization aims to develop and construct a broad range of items that can then be sold to individual consumers at a reduced cost. Affordable for a large scale manufacturing. However, the high variety causes problems for manufacturing systems, such as increased assembly time, decreased output, and lower quality [1]. In addition, it is becoming more difficult to design manufacturing systems that both save costs and production time while maintaining high quality and adaptability [2]. There might be several potential configuration options to think about during the design phase of a manufacturing line. The goal is to adjust to the new circumstances without significantly increasing thecomplexity or expense of the system or lowering the quality of the final output. A decision's impact on system performance might be hard to foresee in the context of the highly variable production environment [3]. One approach to overcoming these difficulties is to study the effects of different product categories on the assembly process and, by extension, on system cost, product quality, and other system performances. Decision-makers may benefit from doing a thorough analysis of the configuration complexity of the production system. The investigation of the complexity of a manufacturing system may benefit from the tools provided by

Complexity theory [1]. Figure 1 depicts five broad categories into which related methods may be placed according to [4]. In the first place, we have non-linear dynamics. Lyapunov exponents are one of the most influential methods in this class. Bifurcation diagrams and other approaches from chaotic theory have also been used for the study and identification of complexity measurement, following the non-linear dynamics. The second class consists of theories related to information, such as Shannon entropy and Kolmogorov entropy. By including Kolmogorov entropy, Shannon entropy becomes a more precise measure of behavior's unpredictability or disorder.

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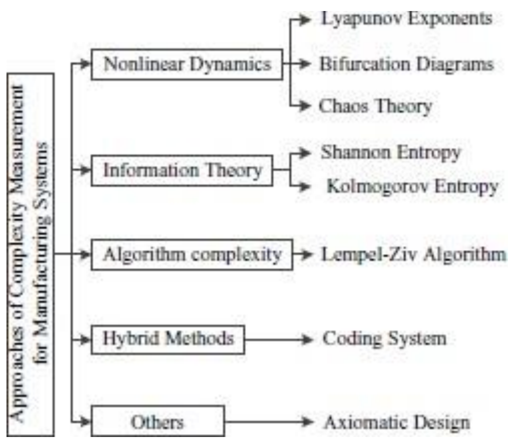

Figure 1: Various methods for gauging the complexity of industrial systems.

Algorithm complexity is the third kind. The idea is that as time goes on, the complexity of a system increases. Remarks that characterize its behavior in detail. The Lempel-Ziv algorithm is the best option available. It offers a numerical assessment of the complexity based on the system's internal structure and operation. In the last group, we find hybrid approaches to classifying industrial machinery, such as the coding scheme created by ElMaraghy et al. [5]. In addition to the aforementioned four classes, there may be others that are more applicable, such as Axiomatic Design [6] [7]. Nonlinear dynamics techniques have been used by academics like Papakostas et al. [8] to describe the complexity of industrial processes. Several models of manufacturing were simulated and assessed through a battery of experiments using various workload patterns; these models were distinguished by their respective production configurations and part routings. Chryssolouris et al. [9] simulated a collection of manufacturing models with varying workload patterns, configurations of production, and component routings. The findings are used to gauge how easily an industrial system can adapt to shifting demands. Entropy was introduced by Frizelle et al.
[10] as a way to quantify manufacturing complexity across the structural and operational levels. Deshmukh et al. [11] listed several possible causes. Factors impacting static complexity, and proposed a static complexity measure based on the processing needs of manufactured components and machine capabilities. The proposed static complexity metric in manufacturing systems requires no additional data beyond what is already included in production orders and process plans. In order to measure the difficulty of coordinating and controlling production processes across time, Arabic and Brutal [12] created a metric. Both internal elements, like the structure of the system, and external ones, like demand, contribute to the complexity. Efthymiou et al. [13] used the Lempel-Ziv metric to analyze randomness in production. To gauge a system's complexity, researchers looked at the variation of key industrial performance metrics.
ElMaraghy et al. [5] created a complexity coding method to categorize and code production system components such machines, buffers, and material handling gear. The code accurately represents the depth and breadth of the data. A manufacturing system's ability to meet the targeted forecast production volume with its variation is measured in part by the probability that it will succeed in delivering the desired production capacity as a function of the availability of its components. In order to quantify the underlying structural complexity of production system components including machines, buffers, and material handling systems, Samy and ElMaraghy [14] developed a new metric. Each module's contribution to the overall structural complexity of the system is measured using a complexity metric unrelated to the information theory method, but based on the manufacturing systems categorization code created by ElMaraghy et al. [5]. To eliminate the ambiguity of the word "complexity" in engineering system design, Lee et al. [6] looked into the complexity notion described in axiomatic design theory. Understanding of complexity's root causes and the development of a methodical strategy for tackling it.
While other studies can serve as a guide toward creating a reliable complexity measurement, there are a few challenges unique to complexity assessments that need to be taken into account. Existing complexitymeasurement studies almost seldom take into account the connection between operational unpredictability and overall line design. In addition, the nonlinear connection between stations is hard to quantify. Many experts agree that information entropy theory provides a good description of complexity, and they also agree that operations, system architecture, workflow, and work time are all intimately connected to complexity characteristics. Therefore, in order to specify the meaning of complexity in manufacturing systems, it is necessary to construct a model that takes into account the connection between operations and configuration.

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2. Configuration complexity of manufacturing system

2.1. Problem description and assumption

Complex and nonlinear production systems are the result of using a wide variety of tools and machinery. Because of this, gauging the system's effectiveness is made much more challenging. The complexity of the system grows as a result of the unpredictability of its parts. Additionally, the complexity of the coupled system resources should not be calculated by linearly superimposing the complexity of the individual resources. The production system complexity cannot be accurately estimated by adding together the complexity of individual manufacturing cells. The technique also fails to capture the complexity of the system itself or its signature coupling connection. Given the adaptability of the machine, the configuration complexity has been addressed by a number of researchers. Greater functionality usually means greater complexity in machinery. Analyzing the adaptability of each production station might begin with a look at the system's current state of operation if dynamic system process is taken into account. Once the Shannon entropy is known, the station's complexity can be determined. According to Shannon entropy, information density may be used to measure the degree of system state uncertainty. The entropy enclosed is [3] [4] when there are m occurrences, each with independent probabilities p1 p2pm.

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

The configuration complexity model of the production system may be constructed if the complexity of each station can be modeled independently of its kind. As a rule, the stations in a production system may be classified into the following categories: those that do a single operation, those that perform at least two, those that perform all four, and those that perform all four in parallel. Table 1 and Figure 2 both display the various station types. Similar to the main line is the sub-line. In order to understand the complexity of a manufacturing system, it is required to construct a model that takes into account the connection between operations and configuration. If additional configuration optimization is to be implemented, this model may serve as a crucial theoretical foundation.

Station types in a production system are listed in Table 1.

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

Organizational configuration the complexity of a manufacturing system is the degree to which its configuration influences the likelihood that a given manufacturing activity will be successful. Station-by-station division of duties and the variety of stations indicated in Section 2.1. Based on actual facts, practical measurements, or past experience, we may estimate that the likelihood of success for the it operation is pi, whereas the probability of failure is 1 I p.

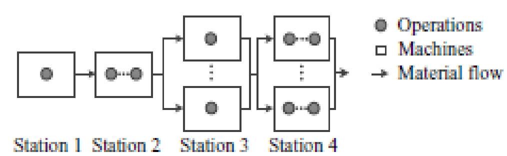

Fig. 2. Several kinds of station representations.

(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.

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

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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.

$$h_t = \binom{0}{k} p_{ti}^k \log_2 \frac{1}{p_{ti}^k} + \binom{1}{k}(1-p_{ti})p_{ti}^{k-1}\log_2 \frac{1}{(1-p_{ti})p_{ti}^{k-1}} + \cdots + \binom{k-1}{k}(1-p_{ti})^{k-1}p_{ti}\log_2\frac{1}{(1-p_{ti})^{k-1}p_{ti}} + \binom{k}{k}(1-p_{ti})^k \log_2 \frac{1}{(1-p_{ti})^k} \quad (4)$$

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

(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.

$$p_{df} = \prod_{fi=1}^{b} p_{fi} \quad (5)$$

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

(5) Overall system

Next, we think about a manufacturing line with u stations doing a single operation, v stations performing several operations, and w parallel stations performing a single operation each. Machine and (e) multiple-function parallel stations. Figure 3 depicts the graphical depiction of the arrangement.

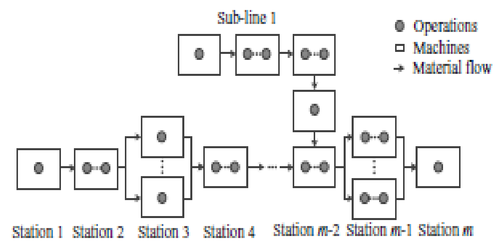

Figure 3: Graphical depiction of the production system.

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

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

3. Case study

Table 2 displays the probability of the activities at each of the 35 major line stations on a gearbox assembly line at a certain car manufacturer. There are five branches off of this main line: listed items 1, 2, 3, 4, and 5. they join the main production line at stations 8, 14, 17, 22, and 24. There is a parallel between the 26th and 33rd stations. The percentage of successful operations at full capacity at the main line station is shown in Table 2. There are a lot of stations that do double or triple duty, including Station 2 and Station 4. Table 3 displays the likelihood that each operation in the branching sequences will be successful. Figure 4 depicts the total assembly line arrangement.

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.

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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	

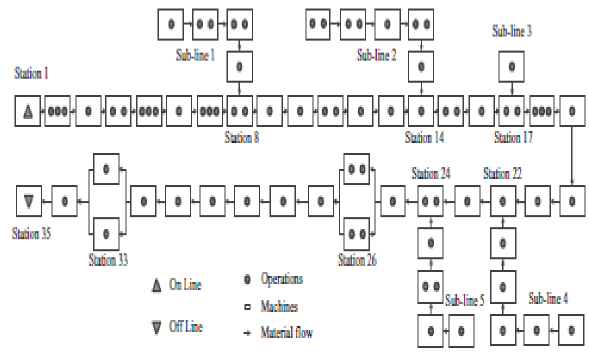

Fig. 4. The layout of the manufacturing system in the case

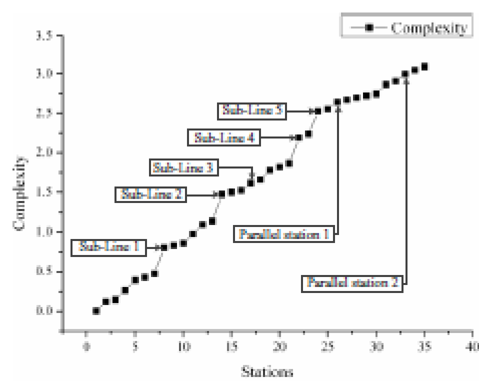

Figure 5: The material flow and station complexity index.

Figure 5 depicts the main line material flow and the cumulative station complexity index. Figure 5 shows that the material flow and the complexity of the setup both grow with the number of stations. At the station where the branch line is added, a new value step will be implemented. Overall system complexity is estimated to be 3.088. 3.2. A comparison to "The Coding System" The configuration complexity of the case study was also estimated using the coding technique suggested by Kuzgunkaya and ElMaraghy [5] to verify the proposed method. Tightening machines, compressing machines, and measurement

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machines are the three main kinds of gearbox processing machinery. There are five distinct code structures in these devices. On this route, you'll find 23 self-service stations and 31 staffed stops. Station 26 and 33 each has their own machine. Table 6 displays the possible symbols and their maximum type code values. Table 7 displays the station type code string used for automated stations. Table 8 displays the results of an evaluation of each automated station's machine type complexity index using Eq. (9) from [5].

Type codes and their maximum possible values are shown in Table 6.

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		

Using the formula Eq. (3) in [5] (Table 9), one may determine the complexity of stations on the main line based on the dependability of the machine in an automated station. Table 10 displays the sub-line station complexity. Since the human-based station is ignored by the encoding system, the human operator's experience is used to determine how complex the station needs to be. This, however, is but one interpretation among many. Station complexity (S) on the main line is tabulated 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	

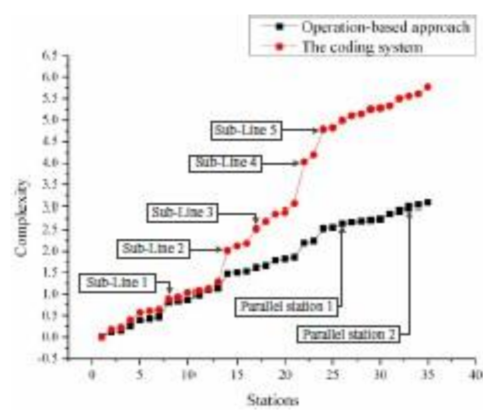

Figure 6: The material flow and station complexity index.

Using the machine complexity expression given in [5], we can calculate the overall station complexity. Figure 6 depicts the material movement together with the process. The entire system complexity was calculated to be 5.776. Both methodologies provide consistent results when comparing the complexity of manufacturing systems, even if the coding scheme places more emphasis on the sub-lines.

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4. Discussion and conclusions

The sub-lines and parallel stations in a production system are taken into account in a new configuration complexity model. The suggested model takes system measurements. Information-theoretic measure of complexity. It is also feasible to simultaneously assess the complexity of human-based stations and automated stations, and the impact of operations on the complexity of system setup is taken into account in full. To prove the model's worth, a case study was suggested. This proves that the suggested methodology may be used to assess the configuration complexity of a production system. What's more, the operation-based approach evaluates the connection between processes and the overall line. In contrast to the coding system method, the suggested method may be implemented from the outset of setting up the production system. There is no need for elaborate planning with regards to the code structure. When dealing with automated systems during the detailed design phase, the coding system remains a relevant method to state the manufacturing system complexity. To create a technique for improving the configuration design of a manufacturing system, researchers will combine configuration optimization with process planning to determine the connection between process planning and system architecture.

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