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An Appraisal of Manufacturing Structures Using Timeliness-Quality Entropy and Order Index Methods

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ABSTRACT A system's configuration plays a significant role in promoting its efficient functioning. This article addresses the problem of the deficiency of algorithms that can be employed to appraise the running performance of a system in diverse manufacturing structures. First, a timeliness-quality entropy concept is presented according to the mechanisms of information transmission. Based on the conditional entropy theory, a timeliness-quality entropy approach, jointed a structure order index developed, is then proposed to appraise the order degree of manufacturing structures quantitatively and screen manufacturing structure solutions appropriately. In an empirical study, we target the different facilities layout design of a job shop before and after conducting technological transformation and compute the order index under the different layout types. Eventually, the result obtained illustrates the applicability and effectiveness of the proposed approach. Therefore, this approach provides crucial theoretical support and practical guidance for appraising and screening manufacturing structures.

INDEX TERMS Manufacture structure appraisal, order index, timeliness-quality entropy, running performance.

I. INTRODUCTION

In a globally connected market, short lead time, demand fluctuations and high customization may result in an increase in the operating uncertainty of manufacturing systems [1]. The complexity of a system configuration may have a tremendous negative effect on the running and scheduling of the whole system [2]. A reasonable manufacture structure, on the other hand, is conducive to acquiring a high-efficiency production system and might save total cost by up to 60% [3]. The structural assessment of production systems has been a study focus over the years. Although researchers pay attention to assessing the structure of production systems, a path choice among multiple schemes - obtained by different optimized algorithms - has not been given much consideration yet. Manufacturing organizations frequently deal with the unavailability of manufacturing pattern with restrictive and partial fixes instead of carrying out costly and tedious system redesign [4], [5].

The agility of production systems involves the ability of an enterprise or company to operate profitably in a competitive environment with continuous and unpredictable user changing needs [6], [7]. Agile manufacturing can develop and manufacture high-quality products that meet market needs in the shortest time. It incorporates two factors to build a flexible production system in terms of information control: On the one hand, the information structure has a crucial impact on mapping to the systematic structure. On the other hand, the operating mechanism of information flow also plays a significant role in the reconfiguration and integration of system resources [8], [9].

Reconfigurable manufacturing system (RMS), for instance, is an advanced paradigm of agility production, aiming at offering the functions and strategies required by the system through accurate and timely information flow [10], [11]. Therefore, in the field of manufacturing systems, more and more attention has been paid to the assessment of

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manufacturing structures [12]–[14]. Currently, there are some intelligent algorithms to enhance manufacturing structures, which can be employed to achieve approximate optimal scheme - particle swarm optimization, genetic algorithms, and annealing algorithms, for example. These intelligent approaches, however, can only be used to design and enhance manufacturing structures. If multiple optimization schemes are obtained based on different algorithms, there is currently a lack of quantitative methods to compare these schemes and screen the most suitable one for the actual enterprises.

On the basis of information-theoretic entropy, we first put forward a timeliness-quality entropy algorithm, jointed a structure order index, to solve the problem of the deficiency of algorithms for appraising the running performance of production systems under diverse configuration environments. Then, we calculate the order index under the two different manufacture arrangements with the approach presented to appraise the running performance precisely in a case study. The main contributions of our work are three-fold: (1) We first present a timeliness-quality entropy approach with general characteristics to lay a theoretical foundation for screening manufacturing structure solutions. (2) We propose a structure order index, jointed the timeliness-quality entropy algorithm, as a useful tool, to appraise the running performance of diverse manufacture arrangements quantitatively. (3) Based on the approach raised, we conduct an empirical study to verify its rationality. Eventually, the results obtained demonstrate the scientificity as well as the applicability of this algorithm.

The remaining of this article is arranged as follows: Section II discusses related work. Moreover, Section III presents the timeliness-quality entropy concept. Section IV proposes the timeliness-quality entropy model and the structure order index. An empirical study is presented, and the calculation of the order index is analyzed in Section V. Section VI concludes the paper and states directions for future research.

II. LITERATURE REVIEW

Based on the features of the problem, we review the most relevant and recent literature on assessment of production structures and information-theoretic entropy approach of manufacturing systems.

A. ASSESSMENT OF PRODUCTION STRUCTURES

With the ever-changing market demand and the pursuit of product diversification by enterprises, the complexity of the manufacturing structure has become a challenging issue. In the academic literature, the evaluation of the complexity of manufacturing structure is one of the themes of many studies in the last decade. For a complete review of the complexity assessment of manufacturing structure in production systems, the reader is referred to [15]–[17]. Chu *et al.* [18] published a pioneering paper on the comprehensive evaluation of complex manufacturing structures. They firstly presented a production plan arrangement model with an entropy assessment method, containing manufacturing facilities and manufacturing procedures for the technological manufacturing structure. They appraised the reliability of the system structure, the adaptability of structural components and the interrelationship between the system structure and its internal elements with the proposed approach. Then D'Addonat [19] solved a class III integrated problem related to tool inventory management in a complex production environment. He put forward the characteristics of bounded rationality as an agent and proved the uncertainty in the perception, behavior and internal structure of production systems by introducing limited rationality into the agent characteristics and the possible conversion of historical data. Also, Patel [20] raised an assumption: environmental uncertainty can mitigate the compatibility between formalization and production flexibility, and he used a fuzzy mathematical method to evaluate the developed framework. The final results verified that the structure with production flexibility could promote the running efficiency of production rooms. Fortunet *et al.* [21] presented a production structure design method based on entropy modeling to enhance the complexity of the manufacturing process by considering the design of a more reasonable manufacturing structure.

When screening and evaluating the production structures, it is of great significance to find the core indicators and visualize these indicators and the production structures. Some approaches are proposed to evaluate the production structure in the planning phase. For instance, Huan *et al.* [22] studied various factors that may affect their safety status for improving the accuracy of the evaluation results of wooden buildings. In the process, they set up a monitoring and evaluation system for the building system. In addition, they also built a dynamic entropy model to appraise the rationality of the building structure. Peukert *et al.* [23] designed an original alternative product of traditional machine tool framework through integrating microsystem technology and lightweight modules. According to the general geometric requirements of machine tool frame, they formulated a set of rules to show the three different polyhedral building set methods and assess their advantages based on geometric function and sustainability criteria. To cope with selecting a manufacturing system configuration that meets the requirements of production functions and is apt to run and manage, Kuzgunkaya and Elmaraghy [15] proposed a new index to assess the structural complexity of production system configuration. By using the index derived from the newly developed production system classification code, they solved the inherent complexity of each module in the production system. The established metrics would help to choose the most straightforward production system configuration that satisfies the demands. In visual program and modelling aspect, Caggiano *et al.* [24] proposed a visualized production program that can be used to evaluate the feasibility of the production process. Based on the theory of information entropy, the program integrated related intelligent production platforms to appraise the reliability of each production link and the rationality of the manufacturing structure. Based on an intelligent and visual integrated platform, Bahadir and Bahadir [25] used a hybrid entropy modeling approach to realize the convenience of a structure selection process. They employed the developed approach to choose the appropriate manufacturing structures.

The model and approach raised in this paper are linked to these studies in an attempt to integrate the screening and planning functions. The reviewed articles mainly involve in those that apply information entropy approach as well as operations research theory and take into account the following aspects of products structure, production schedules and equipment and facilities layout. The models mentioned above hypothesize that the conditions that affect design decisions are deterministic. Many decision-making procedures in the real world, however, involve in an environment where restrictions or constraints cannot be accurately known. In addition, as far as the research of manufacturing structure assessment is concerned, most of the current methods are to build a more reasonable manufacturing structure or design a new structure to replace the initial one. If there are multiple alternatives using different algorithms after structural optimization, there is a lack of a quantitative approach to screen the optimal solution.

B. ENTROPY MODELLING APPROACH IN MANUFACTURING STRUCTURES

Concerning the study of entropy modelling approach, there are three branches underway, which can be divided into the following categories:

The first approach is through Shannon entropy modelling. In this method, entropy model is used to measure the uncertainty and complexity of different operational structures, service hierarchy and assembly process of manufacturing systems to help enterprises improve operation efficiency and make correct decisions. For instance, Wang *et al.* [26] proposed the information criterion of mean entropy skewness to figure out the uncertainty of resource cost for scheduling optimization in a flexible manufacturing system. Due to the possible limitations of the existing measures, the third-order information standard was integrated to be more general and more reliable to represent the schedule dispersion under uncertainty. They also constructed a dynamic entropy algorithm to achieve an accurate probability distribution that is generally unknown in an application. Finally, a practical stamping industry case study was conducted to demonstrate the practical applicability of the model. On the basis of maximizing profit and bounded rational expectation rule, Li *et al.* [4] put forward a dynamic game model by the system entropy diagram to prove that the higher the service hierarchy and the profit distribution rate, the smaller the stability region of the system. Also, they also offered a proposal to assist manufacturers and retailers in making better decisions in multiple layer supply chain. Using the conditioned entropy modelling theory, Thomé and Rui [27] built a new method to define the manufacturing selection complexity for effectively controlling them in mix model assembly lines. The proposed model considered both the selection combination and the similarity between the choices, and it can be used to quantitatively evaluate the efficiency of overall system performance on the selection complexity.

In addition, the direct Shannon entropy model is also used to combine with other methods, such as heuristic algorithms, regression model method, dynamic function method, etc., to achieve the improvement and optimization of the production process. Liu *et al.* [28], for example, put forward a new heuristic algorithm to promote process planning on the basis of establishing an information entropy model of process planning optimization. At the same time, they also presented a new sample generation mechanism, and derived an updated expression of probability distribution parameter. Finally, they compared the proposed method with genetic algorithm and genetic programming in a case study, and the results demonstrated that the method based on cross-entropy is scientific and practical. Rodríguez-Picón [29] proposed the uncertainty method considering that the behavior of the function needs and procedure coefficients follow a normal distribution. The uncertainty is acquired through the continuous way of the information entropy. He used regression modelling as an approach to relate the function needs of the procedure to their corresponding coefficients, such that the multiple regression models can be established and expanded as a time function to determine a model to handle uncertainty. Kuznetsov [30] raised a dynamic approach to solve operational stability of production processes. Besides, the functional expression of the complexity between operations and stations was raised. The structure entropy and operational entropy of cellular production systems were constructed to quantitatively measure the complexity and the states of manufacturing facilities by Zhang [31]. He also used an example to prove the availability of the proposed approach.

Shannon entropy modelling approach is also applied to the production system to measure and monitor the operation efficiency and state of the system. Representative studies, for instance, are as follows: Jha *et al.* [32] used an entropy model transformed to monitor the standardized production of an enterprise. Eventually, they proved the feasibility of the approach established by a case study. Smunt and Ghose [33] introduced a specific approach of flow dominance through cross-entropy and tested its efficacy in forecasting the operational efficiency of production systems. They aggregated messages embedded in the routing of all parts within a system to a single measure in calculating entropy flow dominance (EFD). The final results indicate that EFD is a statistically significant determinant of manufacturing system's operation. Villecco and Pellegrino [34] extended Shannon axiom to non-probabilistic events and introduced the information theory of non-repetitive functions to measure the reliability of complex mechanical system data. Therefore, they designed an engineering solution which is consistent with the value of design constraints to analyze the correlation between entropy functions and restriction conditions. Also, Zhang [35] established a dissipative structure entropy model by controlling the alterability of related factors. Finally, the model proposed was used to measure the manufacturing complexity of production systems quantitatively in an empirical research.

The second method is through Boltzmann entropy modelling. In Boltzmann's entropy research, it's mainly used to measure the configuration complexity of different types of products and manufacture. Guenov [36], for example, employed Boltzmann's statistical concept entropy to measure the complexity of the size and the distribution of couplings in the system's decomposition for helping decision makers screen alternatives during the early complex systems design stage. Modrak and Bednar [37] used the Boltzmann's entropy theory to measure and compute the configuration complexity of the realistic mass customized manufacture of washing machines. They contrasted the results with product configuration values obtained through a combinatorial method and finally draw the conclusion. In addition, Boltzmann entropy is also employed to landscape mosaics and landscape gradients to measure and compare the disorder of real landscapes. The reader can be referred to [38] for a comprehensive review of this research area.

The approach of information-theoretic entropy modelling with production systems is mostly used to solve the particular uncertainty problems generated by the variety of market environments, equipment arrangement and components categories, etc. Through the paper survey, we notice that there are no papers that use entropy modeling method to assess the running performance of diverse manufacturing structures quantitatively. Moreover, most relevant entropy modeling approaches set certain assumptions and scope of application, which results in significant limitations on its practicability.

III. TIMELINESS-QUALITY ENTROPY DEFINITIONS

Since this study involves the mechanism of messages sending and feedback, the definitions of timeliness-quality entropy are, therefore, firstly introduced.

Timeliness and accuracy are the two principal elements affecting information stream [39], and there is a negative correlation between them. As a result, the longitudinal information stream increases with the increase of the systematic hierarchy, while the information furcation decreases on account of the decrease of the systematic span. Although the speed of the information stream is put off, and the accuracy of the information can be enhanced, and vice versa.

We first introduce the conditional entropy definition of as a prerequisite of entropy modelling.

According to Shannon entropy concept, information entropy is to consider all possible values of the random variable, namely, the expectation of the amount of information brought by all possible events. The formula is as follows:

$$H(X|y_j) = -\sum_{i=1}^{m} P(x_i|y_j)\log_2 P(x_i|y_j) \tag{1}$$

Assuming there are random variables (X, Y), the joint probability distribution is:

$$p(X = x_i, Y = y_j) = p_{ij}, i = 1\cdots m = j = 1\cdots n$$

Therefore, we can define the conditional entropy $H(Y|X)$ as the mathematical expectation of Y for the entropy of the conditional probability distribution of X under the given condition Y. It can be provided by:

$$\begin{aligned} H(X|Y) &= -\sum_{x\in X} p(x)H(Y|X = x) \\ &= -\sum_{x\in X} p(x)\sum_{y\in Y} p(y|x)\log_2 p(y|x) \\ &= -\sum_{x\in X}\sum_{y\in Y} p(x, y)\log_2 p(y|x) \end{aligned} \tag{2}$$

Suppose there is a hierarchy exhibited in the following schematic. It contains n nodes, w levels and k intermediate layers. According to information theory, U_i is the party sending the information, and U_j is the other party returning the feedback information.

After the sender sends out the requesting messages within a time interval, the uncertainty that it can acquire the messages fed back by the corresponding receiver within this interval is considered as timeliness.

Definition 1: As U_i gives requesting messages to other members of the system in t_i period, it is considered as timeliness entropy that the indeterminacy of whether the corresponding response messages can be acquired in the same period.

Definition 2: As U_i provides requesting messages to other members of the system for a while, whether the messages received by the corresponding receiver meets the indeterminacy of the requesting messages is called quality entropy.

IV. TIMELINESS-QUALITY ENTROPY ALGORITHM AND ORDER INDEX

We will investigate the construction of the related entropy algorithm and an order index in this section.

A. TIMELINESS-QUALITY ENTROPY MODELING

Suppose that $A(t_i,1)$ is an information set provided by U_i in a time period t_i, which can be expressed in the following way:

$$\begin{aligned} A(t_i, 1) &= \{a_1(t_i, 1), \ldots, a_l(t_i, 1), a_{l+1}(t_i, 1), \\ &\quad \ldots a_m(t_i, 1), \ldots, a_n(t_i, 1)\} \\ &= \{a_i(t_i, 1)\,|i = 1, \ldots, l, \ldots, m, \ldots, n\} \end{aligned} \tag{3}$$

Assume $A(t_i,1,2), A(t_i,1,3), \ldots, A\ (t_i,1, k)$ to be a group of requesting information transmitted by U_1 to $U_2, U_3, \ldots, U_k$, and

$$A(t_i, 1) = A(t_i, 1, 2) \cup A(t_i, 1, 3) \cup \cdots \cup A(t_i, 1, k) \tag{4}$$

According to the principle of equal probability, if we know nothing about the frequency of different states in the set of States, we should consider that the frequency or probability of each state is equal. Therefore, $A(t_i,1)$ can be regarded as the sample space, where each basic event $a_i(t_i,1)$ (where $i = 1, l, \ldots, n$). Because the basic events are independent of each other, it can be considered that the basic events are incompatible with each other.

Suppose that $A(t_i,1,2)$ contains l events, $A(t_i,1,3)$ contains m-l events, ..., $A(t_i,1,k)$ contains n-m events, namely:

$$A(t_i, 1, 2) = \{a_1(t_i, 1), \ldots, a_l(t_i, 1)\} \quad (5)$$
$$A(t_i, 1, 3) = \{a_{l+1}(t_i, 1), \ldots, a_m(t_i, 1)\} \quad (6)$$
$$\vdots$$
$$A(t_i, 1, k) = \{a_{m+1}(t_i, 1), \ldots, a_n(t_i, 1)\} \quad (7)$$

Set $a_i(t_i, 1) \in \{0, 1\}$, but take $a_i(t_i, 1) \equiv 1$ to indicate that the sending messages is the criterion.

Let $D(t_i, 1, 2), D(t_i, 1, 3), \ldots, D(t_i, 1, k)$ represent that in a certain period t_i, the number of times U_1 send messages to $U_2, U_3, \ldots, U_k$, respectively, namely:

$$D(t_i, 1, 2) = \sum_{i=1}^{l} A(t_i, 1) \quad (8)$$
$$D(t_i, 1, 3) = \sum_{i=l+1}^{m} A(t_i, 1) \quad (9)$$
$$\vdots$$
$$D(t_i, 1, k) = \sum_{i=m+1}^{n} A(t_i, 1) \quad (10)$$

According to the classical probability type of classical probability theory, we can get:

$$P[A(t_i, 1, i)] = D(t_i, 1, i) / \sum_{i=2}^{k} D(t_i, 1, i) \quad (11)$$

Also suppose that in the period of t_j, the set of feedback information by other nodes in the system received by U_j is B, namely:

$$B(t_j, 1) = \left\{b_1(t_j, 1), \ldots, b_l(t_j, 1), b_{l+1}(t_j, 1), \ldots b_m(t_j, 1), \ldots, b_n(t_j, 1)\right\} = \left\{b_j(t_j, 1) \lfloor j = 1, \ldots, l, \ldots, m, \ldots, n\right\} \quad (12)$$

In the same way, let $B(t_j, 2, 1), B(t_j, 3, 1), \ldots, B(t_j, k, 1)$ respectively denote the set of information consultations fed back from U_1 to $U_2, U_3, \ldots, U_k$, and:

$$B(t_j, 1) = B(t_j, 2, 1) \cup B(t_j, 3, 1) \cup \cdots \cup B(t_j, k, 1) \quad (13)$$

Suppose that $B(t_j, 2, 1)$ contains l events, $B(t_j, 3, 1)$ contains m-l events, ..., $B(t_j, k, 1)$ contains n-m events, namely:

$$B(t_j, 2, 1) = \left\{b_1(t_j, 1), \ldots, b_l(t_j, 1)\right\} \quad (14)$$
$$B(t_j, 3, 1) = \left\{b_{l+1}(t_j, 1), \ldots, b_m(t_j, 1)\right\} \quad (15)$$
$$\vdots$$
$$B(t_j, k, 1) = \left\{b_{m+1}(t_j, 1), \ldots, b_n(t_j, 1)\right\} \quad (16)$$

And set $b_j(t_j, 1) \in \{0, 1\}$, when it is 0, it means that it fails to feedback information during t_j; when it is 1, it means that information is fed back in time during t_j.

Again, let $D(t_j, 2, 1), D(t_j, 3, 1), \ldots, D(t_j, k, 1)$ represent that in a certain period t_j, the number of times U_1 send messages to $U_2, U_3, \ldots, U_k$, respectively, namely:

$$D(t_i, 2, 1) = \sum_{j=1}^{l} B(t_j, 1) \quad (17)$$
$$D(t_i, 3, 1) = \sum_{j=l+1}^{m} B(t_j, 1) \quad (18)$$
$$\vdots$$
$$D(t_i, k, 1) = \sum_{j=m+1}^{n} B(t_j, 1) \quad (19)$$

According to the above steps, let $A(t_i, 1, i) \cap B(t_j, j, 1) = \emptyset$, the result can be given as follows:

$$P\left\{B(t_j, j, 1) \cap A(t_i, 1, i)\right\} = P\left\{B(t_j, j, 1) \cap A(t_i, 1, i)\right\} / P[A(t_i, 1, i)] = \begin{cases} 0 & i \neq j \\ D(t_j, j, 1)/D(t_i, 1, i) & i = j \end{cases} \quad (20)$$

Therefore, we have the timeliness-quality entropy model by:

$$\begin{aligned} H &= H\left\{B(t_j, 1)|A(t_i, 1)\right\} \\ &= -\sum_{i=2}^{k} P[A(t_i, 1, i)] \sum_{j=2}^{k} P\left\{B(t_j, j, 1)|A(t_i, 1, i)\right\} \\ &\quad \times \log_2 P\left\{B(t_j, j, 1)|A(t_i, 1, i)\right\} \\ &= -\sum_{i=2}^{k}\sum_{j=2}^{k} P[A(t_i, 1, i)] P\left\{B(t_j, j, 1)|A(t_i, 1, i)\right\} \\ &\quad \times \log_2 P\left\{B(t_j, j, 1)|A(t_i, 1, i)\right\} \\ &= -\sum_{i=2}^{k}\sum_{j=2}^{k} D(t_j, j, 1) \times \log_2 D(t_j, j, 1)/D(t_i, 1, i)/ \\ &\quad \times \sum_{i=2}^{k} D(t_i, 1, i) \end{aligned} \quad (21)$$

B. STRUCTURE ORDER

According to the previous analysis, the order of structure information is manifested in two aspects: timeliness entropy and quality entropy. Therefore, we use timeliness index W_1 to indicate the order degree of structure information in circulation timeliness, and quality index W_2 to represent the order degree of the system structure information in circulation accuracy. We assume that these two parts are independent and additive. Thus, the system synthesis structure order $W^{\#}$ can be calculated as follows:

$$W^{\#} = \eta_1 W_1 + \eta_2 W_2 \quad (22)$$

where η_1 and η_2 are the weight coefficients of W_1 and W_2, respectively.

Therefore, by Eq. (21) and Eq. (22), we can quantitatively assess and measure the order of structure information for different system configuration environments. According to Smith [40] proposed the definition of the structure information disorder (the proportion of the occurring Shannon entropy to the maximum Shannon entropy), the structure order W can be expressed by:

$$W = 1 - H/H_m \tag{23}$$

where H and H_m denote the occurring entropy and the maximum entropy for production systems, respectively.

C. TIMELINESS-QUALITY ENTROPY OF PRODUCTION STRUCTURE

Before constructing the timeliness-quality entropy of production structure, we have some descriptions as follows:

To facilitate the construction of the timeliness-quality entropy model, we first assume that the manufacturing information is only transferred between the upper and lower nodes of the production system structure (For instance, for a given part, there is generally only one fixed processing route in the actual manufacturing process). There is no transfer between the same level nodes, and it is carried out layer by layer without layer crossing phenomenon as shown in Fig. 1.

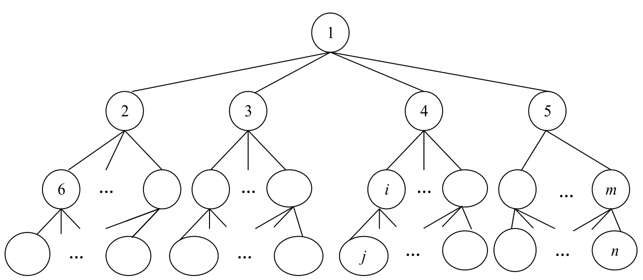

FIGURE 1. The schematic diagram of a systems' hierarchy.

Since the information sending and feedback mechanism is adopted in the construction of the system structure entropy model in section IV-A, the derived model formula is dynamic. At the same time, considering a particular production structure itself, it has relative stability. Therefore, in order to compute the timeliness-quality entropy of a manufacturing structure, the constructed model can be treated as a special case. Consequently, we let the number of messages producing and reply in Eq. (21) to 1, the contact path length between the two nodes to be directly connected to 1, add 1 for each transit, and only need to calculate the sending events.

According to the above descriptions, we can conclude that the occurring probability of messages transmission between any two nodes in a hierarchy manufacture structure is the percentage of the contact path length of the two nodes to the total contact path length of all nodes in this structure. By Eq. (21), we have an algorithm for the timeliness entropy as follows:

$$\begin{aligned} H_1 &= -\sum_{i=1}^{N}\sum_{j=1}^{N} P(ij)\log_2 P_1(ij) \\ &= -\sum_{i=1}^{N}\sum_{j=1}^{N} \left(L_{ij}|L_t\right)\log_2(L_{ij}|L_t) \end{aligned} \tag{24}$$

where L_{ij} represents the length of the contact path between two nodes, and L_t represents the total length of the contact path for all nodes. The maximum timeliness entropy of the systems H_{1m} is:

$$H_{1m} = \log_2 L_t \tag{25}$$

As far as the calculation of the quality entropy concerned, since it represents the uncertainty of the errors in the process of information transmission between different nodes, the occurring probability of the quality information transmission denotes that the contact span of each node accounts for the total contact span of all nodes in this manufacturing structure. By Eq. (21), we have an algorithm for the quality entropy by:

$$H_2 = -\sum_{i=1}^{N} P_2(i)\log_2 P_2(i) = -\sum_{i=1}^{N} (W_i|L_s)\log_2(W_i|L_s) \tag{26}$$

where W_i represents the contact span of a node, and L_s represents the total contact spans for all nodes. The maximum quality entropy of the systems H_2m is:

$$H_{2m} = \log_2 L_s \tag{27}$$

D. ALGORITHM FOR TIMELINESS-QUALITY INDEX

(1) Determining contact path length of two nodes, L_{ij}.
(2) Calculating the number of contact path length of all nodes, L_t.
(3) Calculating the parameter H_{1m} from Eq. (25).
(4) Calculating the occurring probability $P_1(ij)$.
(5) Calculating the parameter H_1 from Eq. (24).
(6) Calculating the timeliness index W_1 by Eq. (23).

Similarly, six steps can be considered to obtain the quality index W_2 by Eq. (23), Eq. (26) and Eq. (27) proposed in section IV-C as follows:

(1) Determining the contact spans of each node, W_i.
(2) Calculating the total contact spans of all nodes L_s.
(3) Calculating the parameter H_{2m} by Eq. (27).
(4) Calculating the occurring probability $P_2(i)$.
(5) Calculating the parameter H_2 from Eq. (26).
(6) Calculating the quality index W_2 by Eq. (23).

V. EMPIRICAL STUDY

The proposed approach will be employed to a technical transformation project of a workshop to provide a basis for the empirical research in this section.

TABLE 1. The calculation of the timeliness index.

Before the technological transformation				After the technological transformation		
Length and mark of contact path		Sum	$P(ij)$	Length and mark of contact path	Sum	$P(ij)$
1	0-S_1, 0-S_3, 0-S_{10}, 0-$S_{14}\cdots$.	16×1	1/448	0-S_1, 0-S_3, 0-S_{10}, 0-S_{14}, S_1–S_2, S_2–S_3, S_5–$S_6\cdots$	18×1	1/172
2	S_1–S_2, S_5–S_6, 2×S_7–$S_8\cdots$.	18×2	1/448	S_3–S_4, S_6–S_7, 2×S_7–$S_8\cdots$.	15×2	1/172
3	S_3–S_{17}, S_{15}–S_{16}, S_{20}–S$_8\cdots$.	20×3	1/448	S_3–S_{17}, S_{16}–S_8, S_{15}–$S_{16}\cdots$.	12×3	1/172
4	0-S_{10}, S_{10}–S_{11}, S_9–$S_6\cdots$.	14×4	1/448	S_6–$S_8\cdots$.	10×4	1/172
5	S_3–S_6, S_{11}–S_{12}, S_{12}–$S_{13}\cdots$.	18×5	1/448	S_{12}–$S_{13}\cdots$.	6×5	1/172
6	S_6–S_7, S_{13}–S$_8\cdots$.	12×6	1/448	S_3–$S_8\cdots$.	3×6	1/172
8	S_8–$S_9\cdots$.	6×8	1/448			
10	S$_{14}$–S$_7\cdots$.	7×10	1/448			
Total		448			172	

A job shop of Baotou Dacheng manufacturing group in Baotou was chosen as a research objective. The chief machining tasks of the job shop are to manufacture the inside accessories of the retarder set. The job shop has a total of more than one hundred stations. Also, there are dozens of parts processed every week, and the batches are almost unchanged. Ten components of the retarder are taken and only the four typical parts A, B, C, and D from the components are illustrated due to limited space in Fig. 2. 'S' in Fig. 2 represents "station".

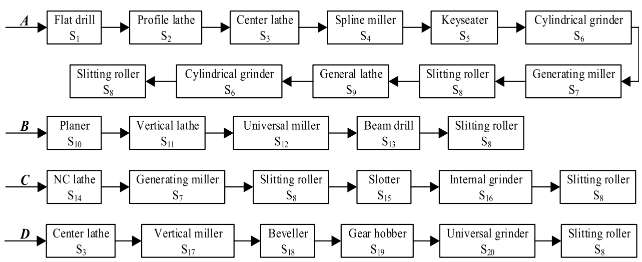

FIGURE 2. The machining routes and notations for the four typical parts.

A. MANUFACTURING LAYOUT DESCRIPTION

Before the implementation of technical innovation, the job shop was arranged into four departments, and its stations were conducted a functional layout, as exhibited in Fig. 3. It's observed that this arrangement form led to discontinuous workflow, and most of the processed jobs were transferred forward and backward among multiple departments on account of non-optimized manufacturing structure, like seriously convoluted machining paths, redundantly cross logistics, complicated station groups, and so on.

To facilitate calculation, we first explain the transmission of processing information in different workstations. According to Fig. 3, each time the information flow passes through a station along with the vertical and horizontal directions, the length of contact path (i.e. the figure marked by the line in Figure 3) is increased by 1. When the information flow crosses each department, the length of contact path will increase by 2. Also, several considerations should be stressed below: (1) The solid and dashed lines in Fig. 3 and Fig. 4 reflect the stations routes of the components manufactured, and the direction along the arrow represents the sequence of the parts machined; (2) The figures on different straight lines denote the number of the stations that the information flow passes through along the vertical and horizontal directions; (3) Although the workstations that did not manufacture these four work pieces do not appear in Figures 3 and 4, they have been used to calculate contact path.

B. ORDER INDEX SOLUTION

To solve the problems analyzed in section V-A, the company has carried out the technological transformation project. Group machining is enlarged according to the similarity in the machining accessories. Simultaneously, the cellular arrangement of the stations is implemented after considering the working routes and the stations' location, as shown in Fig. 4. We can observe that the unreasonable transport is shorten with effect compared to the previous equipment layouts form, with a remarkable reduction of circuitous and convoluted machining paths.

Consequently, we can acquire the calculation results of the timeliness-quality using Eq. (22), Eq. (25), which are listed in Table 1 and Table 2. Since it is impossible to jump between the front and back procedures during the processing of the parts, the contact path of the manufacturing structure only appears at the stations where the working path is continuous.

According to the steps of calculating the timeliness-quality index stated in section IV-D, the workflow of obtaining the timeliness-quality algorithm exhibited in Fig. 5 is made to illustrate the computational procedure of the structure order better.

Through the workflow of the timeliness-quality index in Fig. 5, we can first obtain the parameter H_{1m} before the technological transformation by Eq. (25) (For convenience, "log" here is expressed as a logarithm with base 10):

$$H_{1m} = \lg L_t = \lg 448 = 2.6$$

TABLE 2. The calculation of the quality index.

Contact span	1	2	3	4	5	6	7
Contact mark	$S_1, S_{11}, S_{15}\cdots$	$S_{12}, S_{13}, S_{14}, S_{17}\cdots$	$S_2\cdots$	$S_6\cdots$	$S_{19}\cdots$	$\cdots$	$S_8\cdots$
P_i	1/92	2/92	3/92	4/92	5/92	6/92	7/92
Sum	4×1	10×2	6×3	4×4	3×5	2×6	1×7

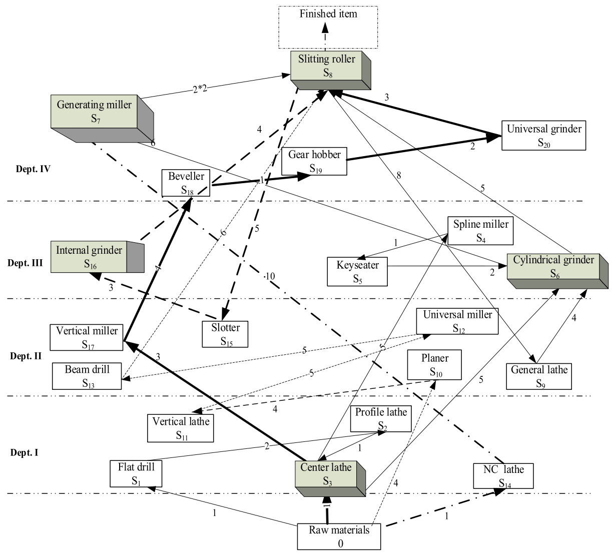

FIGURE 3. The facilities layout before the technological transformation.

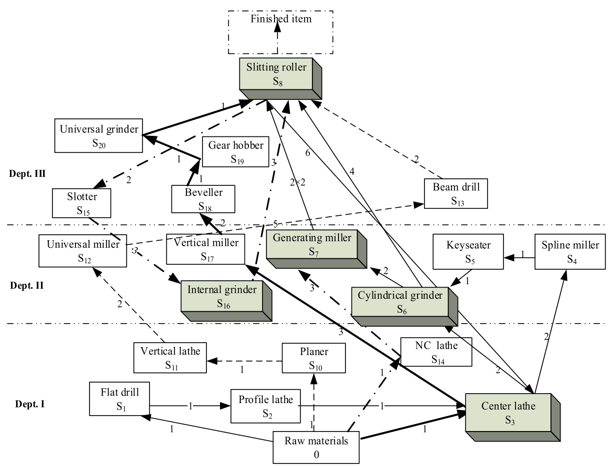

FIGURE 4. The facilities layout after the technological transformation.

Second, we can acquire the timeliness entropy before optimization H_1 according to Eq. (24):

$$H_1 = -\sum_{i=1}^{N}\sum_{j=1}^{N} P_1(ij)\lg P_1(ij) = -\sum_{i=1}^{N}\sum_{j=1}^{N}(L_{ij}|L_t)\lg(L_{ij}|L_t)$$
$$= -(\frac{1\times 16}{448}\lg\frac{1}{448} + \frac{2\times 18}{448}\lg\frac{2}{448} + \frac{20\times 3}{448}\lg\frac{3}{448}$$
$$+\cdots+\frac{7\times 10}{448}\times\lg\frac{10}{448})$$
$$= 2.19$$

Third, the timeliness index W_1 can be computed by Eq. (23):

$$W_1 = 1 - H_1/H_{1m} = 0.23$$

In turn, H'_{1m}, H'_1, W'_1, H_{2m}, H_2, and W_2 can all be calculated through the formula constructed. Therefore, we have the results as follows:

$$H_{1m} = \lg 448 = 2.65,\ H_1 = 2.19,\ W_1 = 0.17$$
$$H'_{1m} = \lg 172 = 2.23,\ H'_1 = 1.6,\ W'_1 = 0.28$$
$$H_{2m} = \lg 92 = 1.96,\ H_2 = 1.43,\ W_2 = 0.26$$

Since the processing procedures before and after the technological transformation projects have not altered, the connection spans are constant. Consequently, quality entropy only needs to be calculated once.

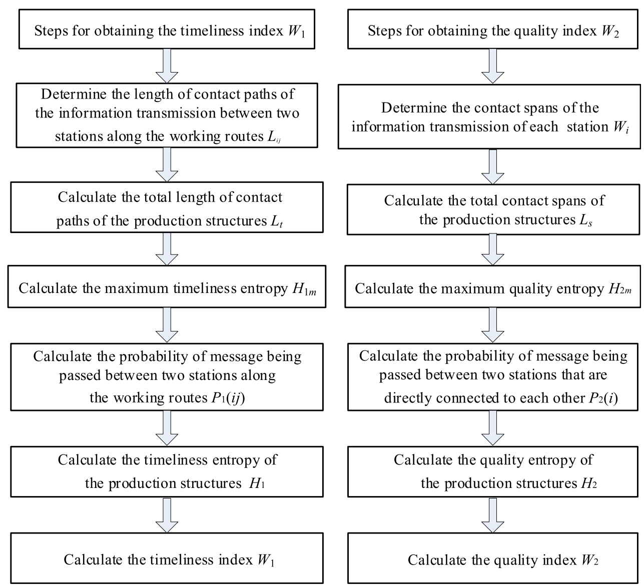

FIGURE 5. The workflow of obtaining the timeliness-quality index.

In Eq. (23), for simplification, we let η_1 and η_2 be both 0.5, then the timeliness-quality index can be calculated by:

Before the technological transformation:

$$W^{\#} = \eta_1 W_1 \times +\eta_2 W_2 = 0.5\times 0.17 + 0.5\times 0.26 = 0.215$$

After the technological transformation:

$$W^{\#\prime} = \eta_1 W'_1 \times +\eta_2 W'_2 = 0.5\times 0.28 + 0.5\times 0.26 = 0.27$$

Finally, we can acquire the improvement in efficiency I for the structure order before and after the technological transformation:

$$I = (0.27 - 0.215)/0.215 = 26\%$$

C. RESULTS AND DISCUSSION

Analyzing the calculation process and results in section V-B with the presented approach led to the following key findings:

(1) First, the length of the contact path, the main parameter in the timeliness index, reflects the machining paths of parts in the process of information transmission. Therefore, the longer the length of contact paths, the more complex the structure of production systems. Besides, it denotes the distance of processing stations in space, which means that it takes more time to transfer between different stations when processing parts with longer the length of contact path.

(2) Second, the span of the contact path, the main parameter in the quality index, represents the degree of utilization of processing stations and potential bottleneck stations. Through Fig. 3 and Fig. 4, we can find that, for example, S_8, S_3, S_6, S_7 and S16, which are highlighted in the form of the cube, they are utilized in the processing of multiple parts and possibly become the bottleneck stations of the job shop. To improve the processing efficiency of all parts, the number of these processing stations must be increased, or the manufacturing procedures of different parts need to be redesigned.

(3) Finally, the structure order algorithm, jointed the timeliness-quality entropy model of production structures modified, is a useful tool to assess the running performance of diverse configuration environments quantitatively. The results obtained demonstrate its applicability and effectiveness.

VI. CONCLUSION

This paper has addressed the problem of the deficiency of algorithms that can be employed to appraise the running performance of production systems under diverse system configuration environments. Based on the conditional entropy theory, for the first time, a timeliness-quality entropy approach, jointed a structure order index developed, is proposed to appraise the order degree of manufacture structures quantitatively and screen manufacturing layouts appropriately. Some of the main contributions are as follows: (1) Presenting a timeliness-quality entropy algorithm with general characteristics to lay a theoretical foundation for screening different structure solutions. (2) Proposing a structural order index, jointed the timeliness-quality entropy approach, as a useful tool, to appraise the running performance of diverse manufacturing arrangements quantitatively. (3) Based on the approach developed, conducting an empirical study to verify its rationality and demonstrate the applicability and effectiveness of this approach.

The further research will focus on developing the timeliness-quality entropy model with the mechanism of horizontal messages transmission, and exploring the specific meaning of the weight coefficient and how to facilitate the calculation on the contact length and the contact span easier. Besides, more useful approaches for appraising the running performance of production systems are worthy of further investigation and discussion.

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