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A Hybrid Multilevel FTA-FMEA Method for a Flexible Manufacturing Cell Based on Meta-Action and TOPSIS

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ABSTRACT Fault analysis activity is very important for a flexible manufacturing cell (FMC) in the development phase. Fault tree analysis (FTA) and fault mode and effects analysis (FMEA) are widely used for fault analysis. However, they are time-consuming and expensive when fully implemented. In this paper, we propose an improving hybrid multilevel FTA-FMEA method that is the combination of the above two methods. The proposed method has a clear three-layer analysis structure. In the first layer, a system FTA of the FMC is performed to determine the functional fault modes. Then, FMEA is conducted to examine them and the key functional fault modes are selected by criticality analysis. In the second layer, we perform the FTA of the determined key functional fault modes to find out the meta-action/component fault modes. The bottom events of fault trees in this layer show differences due to the subsystems with different features. Same as the first layer, FMEA is conducted subsequently and criticality analysis is also used to determine the key meta-action/component fault modes. In the last layer, we perform the FTA of the determined key meta-action/component fault modes to find out fault causes. Then, the key fault causes are determined by criticality analysis. Risk priority number (RPN) is usually used to determine the priority ranking in criticality analysis, while its calculation way is slightly naïve. In this paper, we use the technique for order preference by similarity to ideal solution (TOPSIS) method to examine the priority ranking of fault modes/causes. Moreover, we consider the correction cost as the fourth indicator to assess the priority. The improving fault analysis method can not only help designers better understand the new FMC but also help decision makers make better decisions. At last, a real FMC as a case is presented to illustrate the proposed method.

INDEX TERMS Flexible manufacturing cell, fault analysis, FTA-FMEA, TOPSIS, meta-action.

I. INTRODUCTION

Although the traditional automated manufacturing technology has high production efficiency, it cannot meet the demand of short-cycle, multi-variety and small-volume production. On-demand production mode puts higher demands on the manufacturing capabilities of enterprises. As some companies bring flexibility into manufacturing system to meet the competitive markets, the flexible manufacturing system (FMS) emerges. Maccarthy and Liu [1] classified flexible manufacturing systems (FMSs) into four categories: a single flexible machine (SFM), a flexible manufacturing cell (FMC), a multi-machine flexible manufacturing system (MMFMS), and a multi-cell flexible manufacturing system (MCFMS). The four categories are differentiated by their structural forms. Compared with FMSs, flexible manufacturing cells (FMCs) need lower investment and cost. They are preferred by middle-small enterprises with limited capital. In addition, FMCs can be easily integrated into a larger FMS at a lower cost when the scale of a company expands. A typical FMC is usually composed of several processing machines, robots and material handling subsystem.

In recent years, FMC being capable of offering desired flexibility attracts lots of attention [2]–[7]. Most of researches focus on the layout and scheduling problem. Although reasonable cell layout and optimized scheduling algorithms can

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improve the performance of an FMC, reliability also plays an important role. For instance, Savsar and Aldaihani [8] developed a stochastic model to analyze the reliability of an FMC with two machines served by a robot. Hamasha *et al.* [9] presented a stochastic model to analyze the reliability of an FMC with a single conveyor, a single robot and one or more machines. Nevertheless, the key point of the research is about the operational reliability of FMC. For manufacturing companies of FMCs, it is necessary to ensure the inherent reliability of products.

In this paper, we propose a hybrid multilevel fault analysis method combining fault tree analysis (FTA) method with fault mode and effects analysis (FMEA) method to improve the inherent reliability of FMCs. The proposed method can help users to perform fault analysis more efficiently. It mainly has three key ideas. The first key idea is that different subsystem of the FMC has different analysis level. In general, when we perform the fault analysis of a complex system, we need decompose it into some subsystems and then decompose subsystems to smaller levels. Until the smallest analysis layer is obtained, the decomposition work is completed. In this paper, we think the decomposition of the mechanical subsystem should be different from the traditional decomposition method. We use the meta-action layer proposed by Prof. Zhang as the smallest decomposition layer of the mechanical subsystem instead of the traditional component layer. The concept of meta-action is illustrated in the Section II-C. The second key idea is to use the FTA and FMEA method alternately. The last key idea is to optimize the criticality ranking way in FMEA. The criticality in the traditional FMEA is ranked by risk priority numbers (RPN). In this paper, we use the technique for order preference by similarity to ideal solution (TOPSIS) method to conduct the criticality ranking.

II. LITERATURE REVIEW

In this section, we give the literature review of the main technologies in the proposed method. The review of FTA and FMEA is introduced in Section II-A and Section II-B respectively. Section II-C reviews the concept of meta-action and Section II-D reviews the TOPSIS method.

A. FAULT TREE ANALYSIS

FTA is a top-down fault behavior investigation method proposed by Watson at Bell Laboratories in 1962. A typical fault tree (FT) is a logical graph composed by events and logic gates and the analysis objects usually are undesired faults or disaster events (top event). As an important tool for safety and reliability analysis, FTA method is also widely used in various fields. Liu *et al.* [10] used the FTA method to analyze the reliability of the brake system. Jin *et al.* [11] used the FTA method to assess the electric field exposure in the whole substation. Jetter *et al.* [12] established the FT of refrigerant exposures used for automotive air-conditioning to estimate the number of service technicians and vehicle occupants in the United States. To analyze the dynamic system such as soft system, Kabir *et al.* [13] extended a fault tree to a temporal fault tree (TFT). Ammar *et al.* [14] also focused on the TFT and proposed a new FTA method that is based on statistical model checking to circumvent the state explosion problem. Joshi *et al.* [15] proposed a prior robustness approach for the Bayesian implementation of the FTA and used in two real-life fields: a spacecraft re-entry and a control system. Ruijters and Stoelinga [16] investigated over 150 papers on the FTA method and presented an in-depth review of the state-of -the-art in FTA. In this paper, we use the FTA method repeatedly to perform the fault analysis of the FMC. The FTA is conducted in system level, subsystem level and meta-action/component level. Similarly, Hu *et al.* [17] also used the FTA to diagnose the faults of manufacturing systems.

B. FAULT MODE AND EFFECTS ANALYSIS

Fault mode and effects analysis (FMEA) is an inductive, non-structured and bottom-up method. It has been proven to be a valuable early fault preventative method which can prevent faults from reaching the customers. Traditionally, it is performed by a diverse team comprised by people from different departments. The analysis action of FMEA starts at the component level to get the potential fault modes and examine consequences of these fault modes on the higher level. It can be extended to fault mode, effects and criticality analysis (FMECA).

Nowadays, many scholars have devoted themselves to the study of FMEA. Liu *et al.* [18] investigated 75 FMEA academic journal articles published from 1992 to 2012. They divided the methods in those literature into five main categories: multi-criteria decision making (MCDM), mathematical programming (MP), artificial intelligence (AI) hybrid approaches and others. Khorshidi *et al.* [19] proposed a new data-driven approach to assess the failure behavior and reliability of a large system by FMECA. Sinha and Steel [20] presented a progressive FMECA method used in the offshore wind farm. They analyzed the peculiarity of the offshore wind farm in United Kingdom and then made a slight modification of the existing FMECA method to improve the efficiency and accuracy of analysis. Carpitella *et al.* [21] combined the reliability analysis and MCDM method to optimize maintenance activities of the complex system. They performed the FMECA at first, and then applied the fuzzy TOPSIS (FTOPSIS) method to rank the identified failure modes. Certa *et al.* [22] proposed a comprehensive fault analysis method that is the combination of Dempster-Shafer (DS) theory and FMECA method to deal with the epistemic uncertainty. Deng *et al.* [23] studied the vulnerability of subway system by network theory and FMECA. Liu *et al.* [24] used GO methodology to enhance FMECA in a qualitative and quantitative way. By analyzing the existing research of FMEA/FMECA, we find that the main purpose of those research is to improve the traditional FMECA by alleviating those shortcomings. Most of researches focus on improving the calculation way of RPN. In this paper, we focus on not only the improvement of RPN, but also the analysis form of FMEA. We propose a hybrid fault analysis method that is the combination of FTA and FMECA method. There are also some similar studies about the combination of the two approaches. For instance, Peeters *et al.* [25] proposed a more efficient approach by recursively combining FTA and FMEA. They used the system-function-component decomposition method and conducted the fault analysis by FMEA and FTA at every level. Azadeh *et al.* [26] considered feedbacks of the market in the FTA to determine product faults and defective components. Then, they integrated the FTA and design fault modes and effects analysis (DFMEA) to improve product configuration and meet the costumer's demands. However, they did not consider improving the RPN which is the critical index in FMEA. Moreover, the uniqueness of each subsystem is also not considered.

C. META-ACTION

The meta-action concept proposed by Zhang *et al*. [27] is used to model the assembly reliability initially. Then, Li *et al.* [28] and Ran *et al.* [29] presented the definition of the meta-action: *the action that has the relatively independent controllable and analyzable structure, has the ability to achieve a certain motion target or to achieve a certain goal, and cannot be decomposed into other actions*. Zhang *et al.* [30] revised the definition of meta-action as the elementary mode of motion that can transmit the movement and momentum in a mechanical system. They limited the application of meta-action in mechanical system and defined meta-action unit (MU). Due to the applicability to mechanical system, the meta-action is widely used in reliability analysis of mechanical product. Li *et al*. [31] studied the error propagation mechanism of the meta-action assembly unit. Yu *et al.* [32] proposed a novel definition of failure mode for mechanical systems based on meta-action. Li *et al*. [33] studied the reliability and modal of the key meta-action in computerized numerical control (CNC) machine tool. Literature [34] presented a progressive reliability allocation method for CNC machine tool based on meta-action.

D. FAULT TREE ANALYSIS

TOPSIS as an effective multicriteria decision making method was proposed by Hwang in 1981 [35]. The key point of the method is the construction of the positive ideal solution (PIS) and the negative ideal solution (NIS) for the target to be evaluated. The ranking of these projects is determined by the distance of each project from the PIS and NIS. The calculation process of TOPSIS is easily understandable because it can be presented in a simple mathematical form [36].

Many studies of TOPSIS have been developed in recent years. Chen and Hwang [37] first used the fuzzy number to construct the fuzzy TOPSIS (FTOPSIS). Chu and Lin [38] extended the FTOPSIS method by interval arithmetic of fuzzy numbers. Kumar and Garg [39] developed an extended TOPSIS method based on the connection number of set pair analysis (SPA). The new TOPSIS can calculate the relative closeness of sets of alternatives that are applied to get the ranking order of the alternatives. Rostamzadeh *et al.* [40] developed an integrated fuzzy MCDM method based on the TOPSIS method to evaluate the sustainable supply chain risk management. Garg and Arora [41] developed a nonlinear programming model to solve multi-attribute decision-making problems. In the proposed method, the fractional programming models based on TOPSIS are constructed to get a relative coefficient interval. Pei *et al.* [42] presented a fuzzy linguistic multiset TOPSIS for linguistic decision making.

III. HYBRID MULTILEVEL FAULT ANALYSIS METHOD

In this paper, we proposed a hybrid multilevel fault analysis method by using FTA and FMEA repeatedly. The analysis starts at the system level and ends up with the fault mechanism level. The flowchart of the proposed method is shown in Figure 1. The key idea of the proposed method is to use the advantages of FTA and FMEA to perform the fault analysis more efficiently and reasonably.

A. THE ANALYSIS LEVEL OF THE PROPOSED METHOD

As shown in Figure 1, the proposed method has a three-level analysis structure: the system level, meta-action/component level and fault mechanism level. The analysis level indicates the depth of fault analysis. The analysis activities from the system level to the fault mechanism level are gradually deepening, which can help us understand the relationship between each fault mode and system fault. Through layer-by-layer analysis, potential fault modes and causes can be found to the greatest extent.

In the first analysis level, we can get the functional fault mode set of FMC by FTA method. The system fault is caused by the functional faults of these subsystems which are caused by the functional faults of the equipment. Then the FMEA of the determined functional fault modes is performed to help the enterprise improve design. The determined key functional fault modes are considered as the starting point of the second analysis level. FTA is also performed at first in this layer and FMEA on its heels. The results of the second analysis level are some meta-actions/components fault modes which are the origins of the last layer. FTA and FMEA are performed in the same way as the above two levels. The difference is that the FMEA in the last layer may be no longer a traditional FMEA (more explanation in Section III-B). At last, we can get the possible fault mechanism which is the deepest analysis level.

Compared with the traditional fault analysis method, the three-layer structure fault analysis method has understanding hierarchy, systematization and easy operability. It is the greatest possible to find out all the failure modes by the FTA-FMEA method in the upper two layers and the fault causes in the last layer. In addition, the criticality analysis by TOPSIS (See Section III-D) can help analysts obtain critical failure modes and causes, which will save analysis time and cost.

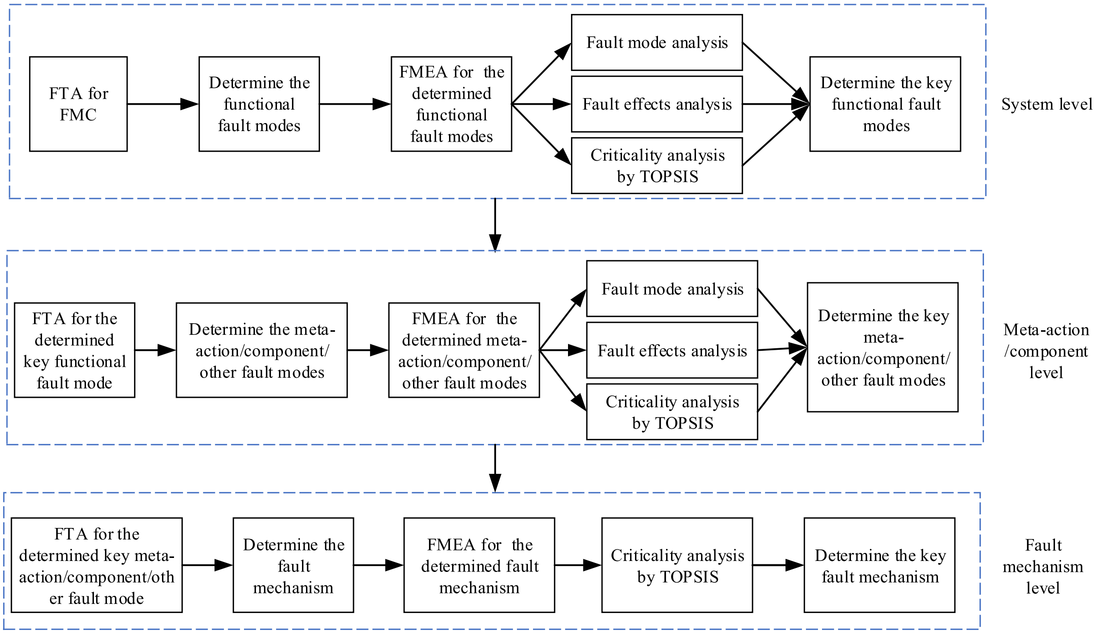

FIGURE 1. Flowchart of the hybrid multilevel fault analysis method of FMC.

B. FTA-FMEA METHOD

The first fault analysis technology in the proposed method is FTA method. It is a structural and deductive method to investigate fault behavior. The analysis target in FTA is the undesired fault state also called top event. The main purpose is to find all the possible fault causes of the top event namely basic events. Some transitional events in the fault tree (FT) are defined as the intermediate events. There are also two events: diamond or undeveloped event and conditional event in the FT. More details of definitions of these events see [43]. The FTA method has many advantages. For instance, strict inference rules can help the analyst understand the system in great depth; the clear and understandable structure can help the person unfamiliar with the system to master the system quickly. However, the FTA method also has some shortcomings when used to analyze a new complex system: the construction of FT is difficult; the top events are not easy to determine; the analysis activity is time-consuming and expensive; quantitative analysis cannot be performed due to the lack of data in the system development phase.

The second fault analysis technology is FMEA method. As a non-structural inductive method, it can identify the potential fault modes and examine their effects on the higher level. In design phase, it can help the designers understand the product, choose the reasonable components and improve the design. Although the principle of FMEA is easy to grasp, the implementation is cumbersome and time-consuming. Shortcomings of the traditional FMEA method see [18].

In this paper, we use the two fault analysis methods repeatedly to present a clearer and more efficient fault analysis method. The fault of an FMC is treated as the top event of the FT in the first analysis stage. The basic events in the first FT are mainly the functional fault modes which are also the fault causes of the top event. The first FTA is used to determine the functional fault modes and present the system structure of the FMC. The FMEA is performed to examine these functional fault modes and identify the key ones. The process of building the first FT gives a good interpretation of the FMC for the designers. In Figure 1, the top events of the fault trees (FTs) in the second analysis level are the key functional fault modes determined by criticality analysis in the first analysis level. While, the basic events of these FTs show different types because of the different functional fault modes. For the functional fault modes of the mechanical subsystem, the results are the meta-action fault modes. For the electronic subsystem, the results are the component fault modes. In this paper, we just consider the two subsystems and the other subsystem such as software subsystem is not involved. In the last stage, the FTA is conducted to find out the fault mechanism of these key fault modes. Compared to the traditional use of the FTA method, the construction of the FT in the proposed method is more targeted and efficient due to the use of FMEA in every stage.

The FMEA is performed after using the FTA method in each analysis level. It includes three parts: fault mode analysis (FMA), fault effects analysis (FEA) and criticality analysis (CA). The FMA and the FEA are performed as same as the traditional way, while the CA is different. In the traditional CA, risk priority number (RPN) is used to assess the criticality of the fault modes. It is determined by three indicators: effect severity ranking (S), occurrence probability ranking (O) and detection difficulty ranking (D). Severity (S) refers to an assessment of the severity of the effect of a potential failure mode on the next higher-level component, subsystem or system. Its level is in general ranked from 1 to 10, where 1 represents the slightest effect and

10 represents the worst effect. Occurrence (O) refers to the probability of fault mode occurring. Its level is also ranked from 1 to 10, where 1 represents the minimum probability and 10 represents the maximal probability. Detection (D) refers to the possibility that the estimated fault mode is detected. Although its level is also ranked from 1 to 10, the meaning is contrary to S and O, where 1 indicates the highest degree of certainty and 10 indicates the lowest degree of certainty. The RPN is calculated by multiplying the three indicators ($\mathrm{RPN} = \mathrm{S} \times \mathrm{O} \times \mathrm{D}$). In general, the larger value of RPN means the higher priority of the fault mode. However, the calculation way of RPN by multiplying the three indicators with the same importance is slightly naive. For instance, considering two fault modes with the same RPN value 80 ($\mathrm{S}\times\mathrm{O}\times\mathrm{D}$), one is calculated by $8\times5\times2$ and another is calculated by $2\times5\times8$. When the occurrence levels of the two fault modes are the same, the severity ranking of the first fault mode is 8, which means that this fault mode is critical and should be more concerned despite the lower detection ranking. In this paper, we treat the calculation of RPN as a multiple attribute decision problem. In addition, we add the correction cost as a new indicator when determining the fault mode ranking. The TOPSIS method is used to solve the multiple attribute decision problem.

When the criticality analysis is completed, we can determine the key fault modes which should be treated as the top events of FTs in the next analysis level. The number of key fault modes is determined by a certain threshold set by the analyst. If the threshold is too large, the analysis activity in the next level will greatly increase. If the threshold is too small, some key fault modes may be neglected. Thus, a reasonable threshold is very important for the whole analysis activity.

C. META-ACTION

FMC is a complex system composed by some subsystems such as mechanical subsystem, electrical subsystem and hydraulic subsystem. The mechanical subsystem plays the role of basic carrier. Compared to other subsystems, the mechanical subsystem has the following characteristics. 1) Dependency between the parts. The function of the mechanical subsystem is realized by the interaction of parts. The faults of the parts are not independent; 2) Insufficient fault data. There are many non-standard parts in the mechanical subsystem. It is impossible to obtain enough data through experiments like electronic components. Especially for some large-scale expensive CNC machine tools, it is expensive to carry out reliability tests to obtain fault data; 3) Numerous parts. The number of parts in the mechanical subsystem is usually numerous. Due to these characteristics of the mechanical subsystem, subjective expert data is more used to perform the quantitative fault analysis of mechanical subsystem. In this paper, we apply the concept of meta-action to study the mechanical subsystem of FMC. There are some reasons for the decision. Due to the dependency between the parts, it is inaccurate to analyze the mechanical subsystem by analyzing individual parts. In addition, if the fault analysis is performed in the component level, the uncertainty of subjective data will expand as it transmits from the part level to the subsystem level.

The core idea of the meta-action theory is to study the mechanical system from the perspective of motion. The function of the mechanical subsystem is performed by a series of actions. The entirety of all parts in a stable structure to complete a meta-action is defined as meta-action unit (MU). Thus, the mechanical system can be decomposed into a series of meta-action units (MUs) in structure. According to [30], a meta-action unit in general consists of five elements: input part, middle part, strut member, fastener and output part. The input part and output part are the key elements for MU. In addition, there are two basic types of MUs: rotation MU and translation MU. The explanatory diagram of the two type MUs is shown in Figure 2.

In Figure 2, a rotation MU and a translation MU are presented. The input part of the rotation MU is the motor

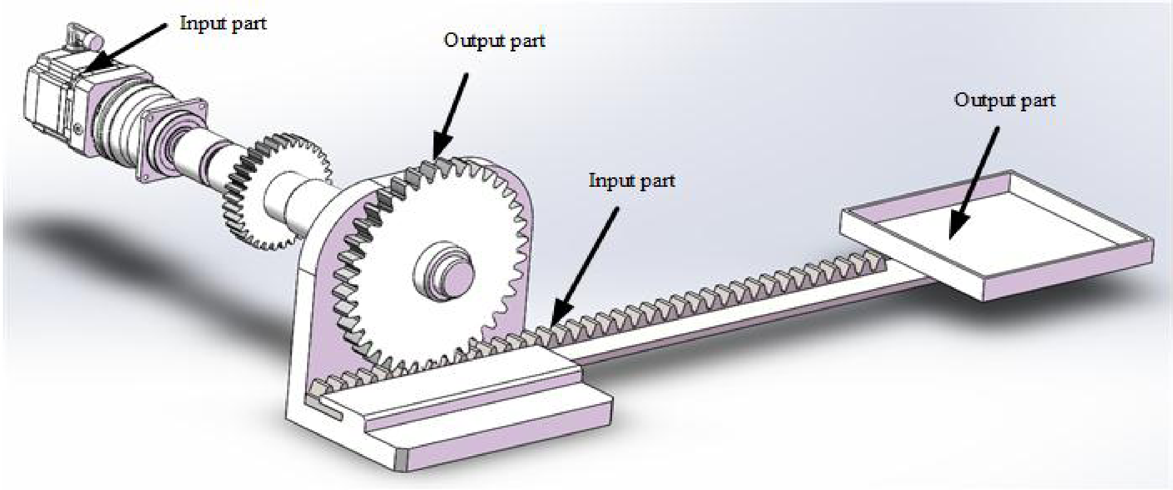

FIGURE 2. The explanatory diagram of two basic MUs.

and the output part is the gear which is also the power source of the next translation MU. The input part of the translation MU is the rack and the output part is the tray. To simply show the two meta-action units, we only give this diagram that ignores some elements. The function of the mechanical system in Figure 2 is performed by the two MUs. Similarly, functions of the mechanical subsystem of an FMC can also be performed by a series of MUs. Therefore, the fault analysis of the mechanical subsystem in the second analysis level in Figure 1 can be performed in meta-action level.

D. CRITICALITY ANALYSIS BY TOPSIS

As shown in Figure 1, the TOPSIS method is used to analyze the criticality of determined fault modes in every analysis level. It is a good effective multi-index evaluation method. Its main idea is to construct the positive ideal solution (PIS) and negative ideal solution (NIS) of the evaluated object, and then calculate the distance to PIS and NIS to complete the ranking problem. The distance in TOPSIS is the Euclidean distance.

Considering each fault mode as a decision scheme, all the determined fault modes make up a decision scheme set. The four indicators: severity, occurrence probability, detection and cost (SODC) are treated as the attribute variable to assess every decision scheme. The PIS is the virtual best scheme where every attribute value is optimal, on the contrary the NIS is the virtual worst scheme where each attribute value is the worst. Then we can compare the distance between each scheme and the positive and negative ideal solutions to determine the priority of these schemes. The best scheme is near the PIS and away from NIS and the worst scheme is inverse. The fault mode represented by the worst scheme has a high priority level, which needs to be prioritized and eliminated in time. The TOPSIS method can be performed as follows.

Step 1. Determine the decision matrix

The first step concerns a multi-attribute decision matrix $A = \left(a_{ij}\right)_{m\times n}$.Then we need perform data preprocessing to obtain a normalized decision matrix $B = \left(b_{ij}\right)_{m\times n}$. The data preprocessing is necessary because of the following reasons. Firstly, the four attributes SODC have different types, which makes it impossible to judge the priority of each scheme directly from the attribute value. Another reason is the different measurement unit of each attribute value. The last reason is that the values of different attributes vary greatly.

The normalized decision matrix can be obtained by the following equation

$$b_{ij} = a_{ij} \Big/ \sum_{i=1}^{m} a_{ij}^{2}, \quad i = 1, 2, \ldots, m;\ j = 1, 2, 3, 4 \tag{1}$$

Step 2. Construct the weighted normalized decision matrix

Considering the weight vector of the four attributes $w = (w_1, w_2, w_3, w_4)^T$, the weighted normalized decision matrix $C = \left(c_{ij}\right)_{m\times 4}$ can be obtained by the following equation

$$c_{ij} = w_j \cdot b_{ij}, \quad i = 1, 2, \ldots, m;\ j = 1, 2, 3, 4 \tag{2}$$

Step 3. Determine the PIS and NIS

We suppose that C^+ refers to the PIS and C^- the NIS. They are presented as follows:

$$C^{+} = \left\{\left(\max_i c_{ij} \left| j \in J\right.\right), \left(\min_i c_{ij} \left| j \in J^{*}\right.\right)\right\} \tag{3}$$

$$C^{-} = \left\{\left(\min_i c_{ij} \left| j \in J\right.\right), \left(\max_i c_{ij} \left| j \in J^{*}\right.\right)\right\} \tag{4}$$

where $J = \{\textit{jassociated with the benefit attribute}\}$ and $J^* = \{\textit{jassociated with the benefit attribute}\}$

Step 4. Calculate the distance from each scheme to the PIS and NIS

The distance to C^+ is

$$d_i^{+} = \sqrt{\sum_{j=1}^{4}\left(c_{ij} - c_j^{+}\right)^{2}}, \quad i = 1, 2, \ldots, m \tag{5}$$

and the distance to C^- is

$$d_i^{-} = \sqrt{\sum_{j=1}^{4}\left(c_{ij} - c_j^{-}\right)^{2}}, \quad i = 1, 2, \ldots, m \tag{6}$$

where c_j^+ is the PIS of the jth attribute, and c_j^- is the NIS of the jth attribute.

Step 5. Calculate the ranking value of each scheme

The comprehensive evaluation index can be calculated by the following equation

$$f_i = d_i^{-} \big/ \left(d_i^{-} + d_i^{+}\right), \quad i = 1, 2, \ldots, m \tag{7}$$

At last, the priority of the scheme can be determined according to the value of f_i, that is, the priority of the fault mode can be determined.

Notice that if we want to compare the priority order of fault modes from different fault trees, we must ensure the ideal solutions are the same. The fault modes from different fault trees compose a new fault mode set which can be analyzed by the TOPSIS method. If we want to know the order of bottom events in a certain fault tree, the priority can also be obtained by the TOPSIS method.

IV. CASE STUDY

In this section, we present a case study of an FMC by the proposed method. The FMC mainly consists of two CNC machine tools, a three-dimensional stereoscopic warehouse, five line-warehouses, an assembly machine, a measurement machine, a welding machine, a robot, an automated guided vehicle (AGV) and a super-control system. The FMC is supported by Nanjing Gongda CNC Technology Co., Ltd and the analysis work is performed by the authors together with analysts in the company. Due to the confidentiality and simplification of the results, we only present partial results to explain the proposed method.

Firstly, the system FTA of the FMC is performed to find out all the functional fault modes shown in Figure 3. The top event of the FTA in the system level is *the abnormal operation of the FMC*. Different color block diagrams indicate different event and some branches are not exhibited to simplify the

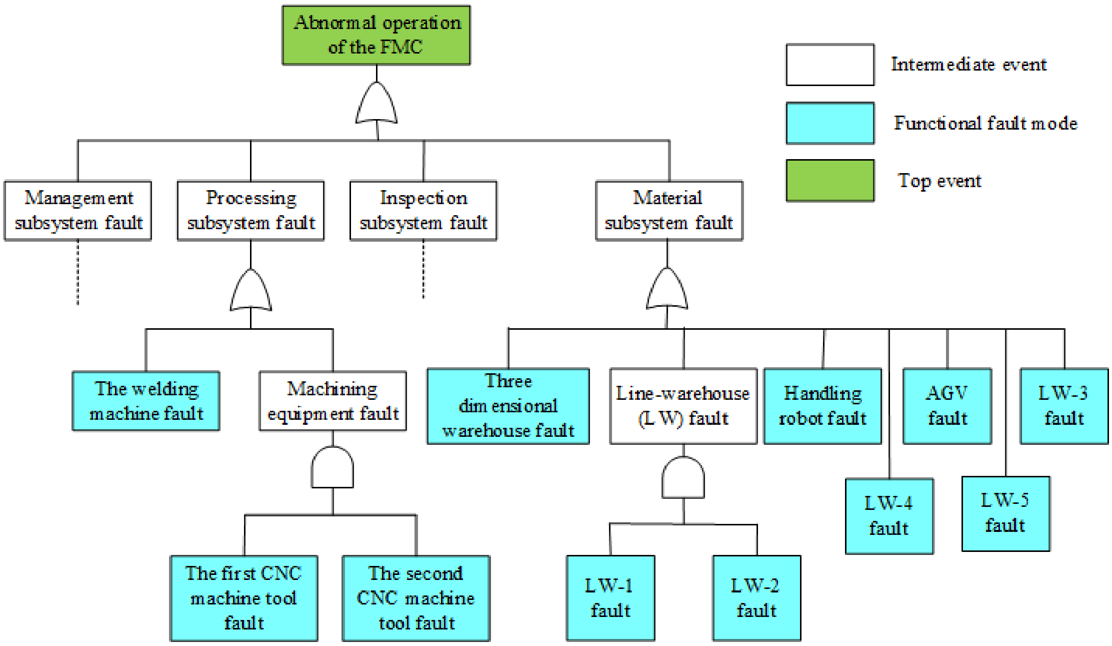

FIGURE 3. The FTA in the first analysis level (partial).

diagram. In Figure 3, we depict 11 functional fault modes to illustrate the results of the system FTA. Then we perform the FMEA on the 11 functional fault modes. The criticality analysis is conducted by TOPSIS method to identify the key function fault modes. Based on the subjective data provided by a cross-functional expert team, the ranking of these functional fault modes is obtained. Table 1 shows the analysis result. The traditional RPN is also calculated to compare with the ranking result by TOPSIS method. Substituting the data in Table 1 to (1)-(7), we can get the PIS (0.0587, 0.03, 0.021, 0.0185) and NIS (0.1174, 0.15, 0.1048, 0.1234). According to the value of f_i in Table 1, the ranking of the scheme is 5, 6, 8, 11, 9, 4, 7, 10, 1, 2, 3 where the 5th and 6th scheme are the best and the 2nd scheme and the 3rd scheme are the worst, which means the 2nd fault mode and the 3rd fault mode have the highest priority and should be corrected in time. The different thresholds of f_i determine the number of key functional fault modes. For example, if we set 0.8 as the threshold of f_i, the functional fault modes with values less than 0.8 are the key functional fault modes, and thus the number of the functional fault modes is 7. If the threshold is 0.7, the number is 6. In addition, the fault modes with the same RPN value will also have different priorities. For example, the fault modes 4, 5 have the same RPN, while the fault mode 4 has a higher priority because of the correction cost.

TABLE 1. The first level FMEA (partial).

	Fault mode	S	O	D	C/k¥	Traditional RPN	f_i
1	The welding machine fault	8	4	3	100	96	0.3950
2	The first CNC machine tool fault	7	5	4	200	140	0.1264
3	The second CNC machine tool fault	7	5	4	200	140	0.1264
4	Three-dimensional warehouse fault	8	1	2	80	16	0.6895
5	LW-1 fault	4	2	2	30	16	0.8165
6	LW-2 fault	4	2	2	30	16	0.8165
7	Handling robot fault	6	3	2	40	36	0.6573
8	LW-4 fault	5	2	2	30	20	0.8004
9	AGV fault	7	2	1	50	14	0.7338
10	LW-5 fault	5	2	5	30	20	0.6164
11	LW-3 fault	5	2	2	30	20	0.8004

Secondly, the determined key functional fault modes are analyzed in the second level by the FTA method. As an example, the FT of the key functional fault mode *the first CNC machine tools fault* is presented in Figure 4. The bottom events in fault tree vary according to different subsystems. Here, we give the analysis of the mechanical subsystem. The FTA of the mechanical subsystem is performed from the motion to meta-action because the function of mechanical subsystem is realized by a series of meta-actions. In Figure 4, the main motion fault is analyzed and 10 meta-action fault modes are obtained. Then the FMEA is performed to examine these meta-action fault modes. CA is also conducted by TOPSIS just same as the previous analysis level to determine the key meta-action fault modes. The partial analysis result of FMEA is depicted in Table 2. The PIS is (0.0949, 0.0577, 0.0275, 0.0428) and the NIS is (0.0949, 0.1732, 0.0688, 0.1283). The ranking of f_i is 4 5 6 7 8 9 2 3 1 10 where the meta-action fault mode 10 has the highest priority and should

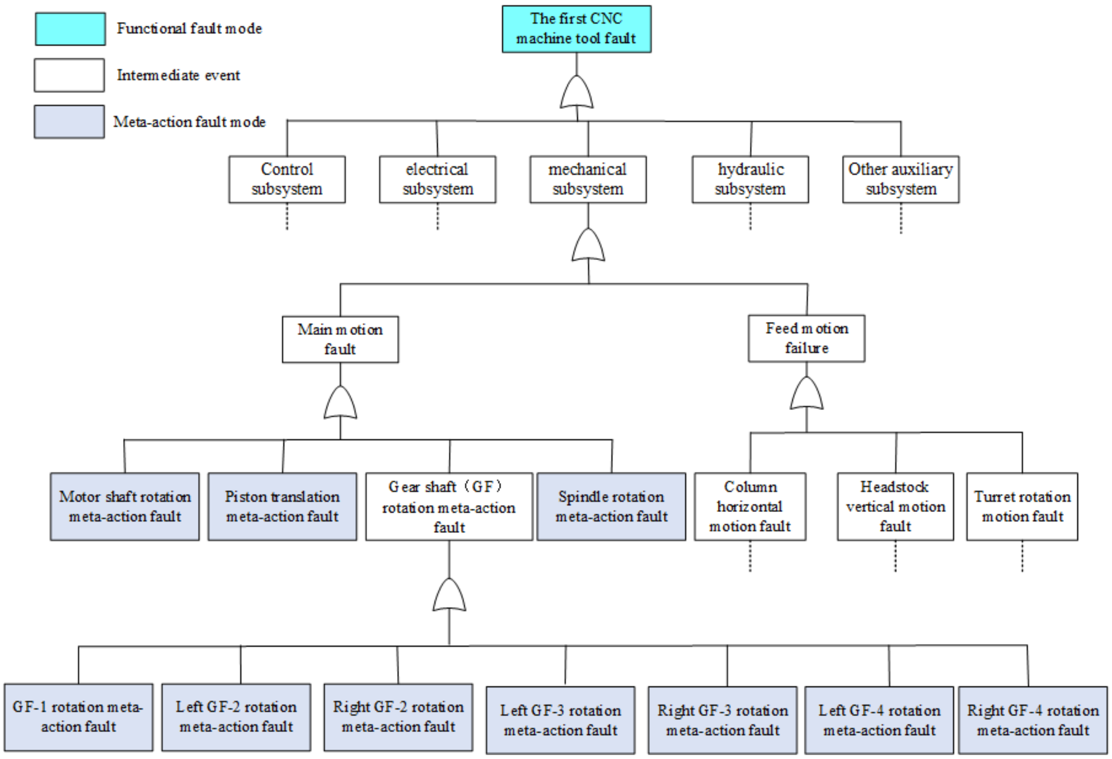

FIGURE 4. The FTA in the second analysis level (partial).

TABLE 2. The second level FMEA (partial).

	Fault mode	S	O	D	C/k¥	Traditional RPN	f_i
1	Motor shaft rotation meta-action fault	8	2	2	10	32	0.5656
2	Piston translation meta-action fault	8	2	4	5	64	0.6194
3	GF-1 rotation meta-action fault	8	2	4	5	64	0.6194
4	Left GF-2 rotation meta-action fault	8	1	5	5	40	0.7767
5	Right GF-2 rotation meta-action fault	8	1	5	5	40	0.7767
6	Left GF-3 rotation meta-action fault	8	1	5	5	40	0.7767
7	Right GF-3 rotation meta-action fault	8	1	5	5	40	0.7767
8	Left GF-4 rotation meta-action fault	8	1	5	6	40	0.7669
9	Right GF-4 rotation meta-action fault	8	1	5	6	40	0.7669
10	Spindle rotation meta-action fault	8	3	5	15	120	0

TABLE 3. The last level FMEA (partial).

	Fault mode	S	O	D	C/k¥	Traditional RPN	f_i
1	Spindle bearing damage	9	1	3	0	27	0.8159
2	fastening nut loosening	8	2	2	0.5	32	0.7377
3	Left Input gear wear	8	5	4	0.5	160	0.5092
4	Right input gear wear	8	5	4	0.5	160	0.5092
5	Gasket wear	6	4	3	0.5	72	0.6040
6	Bad bearing assembly	8	5	5	2	200	0.0623
7	Improper bearing preload	8	3	5	1	120	0.4603
8	Poor bearing precision	8	4	3	0.5	96	0.5838
9	Inappropriate input gear clearance	6	5	4	0.5	120	0.5268

be tackled firstly. According to the threshold set by analyst, the key meta-action fault modes can be determined.

In the end, we use FTA method to analyze the determined meta-action fault modes. Here, the meta-action fault mode *spindle rotation meta-action fault* is analyzed, of which the FT is shown in Figure 5. A meta-action may have diverse type fault modes. Figure 5 shows that the *spindle rotation meta-action fault* has five fault modes. Here, we present two fault modes *unstable rotation* and *poor rotation precision* and get 9 fault causes. In this analysis level, the failure mechanism of the fault mode is studied to get the fault causes. Thus, the FMEA at this level cannot be performed like the traditional FMEA because the basic events in the FT are not fault modes. While, CA can still be performed to find out the key fault causes.

Therefore, the result of the abnormal FMEA is shown in Table 3. The PIS is (0.0777, 0.0248, 0.0352, 0) and the NIS is (0.1165, 0.1241, 0.0880, 0.1569). The ranking of f_i is 1 2 5

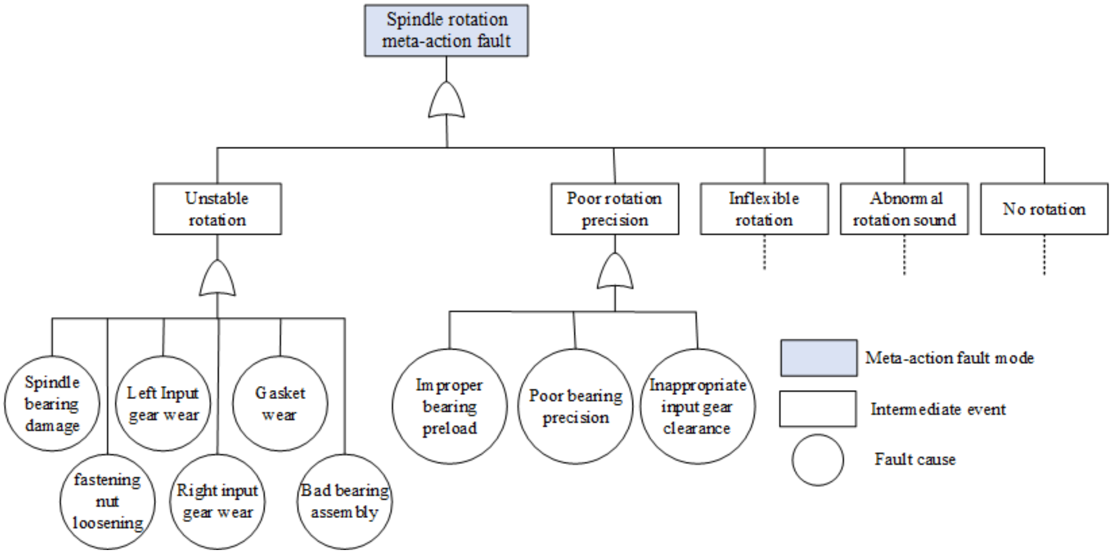

FIGURE 5. The FTA in the last analysis level (partial).

8 9 3 4 7 6 where the fault cause 6 has the highest priority and should be tackled firstly. The difference from the upper two analysis layers is that the fault causes instead of fault modes are paid more attention. In addition, different types of meta-action fault modes are considered in the analysis. We can distinguish between fault mode and fault cause in this layer because the basic events in the FTA are all fault causes. While in the above two layers, the basic events in FTA are both the fault causes and fault modes. Therefore, the fault analysis in the last layer is the deepest.

V. CONCLUSION

In this paper, we propose a hybrid multilevel fault analysis method for an FMC. FTA and FMEA are both widely used in fault analysis. However, they are time-consuming and expensive if thoroughly performed for a complex system. To improve analysis efficiency and reduce cost, the proposed method applies them in a progressive manner.

The proposed method has a three-layer structure. FTA and FMEA are performed orderly in every analysis level. FTA is used to find all the potential fault modes/causes firstly. FMEA is applied subsequently to identify the key fault modes/causes. The clear layer-by-layer analysis process on one hand can be easily performed, on the other hand can help analysts better understand a new FMC in the design phase.

Considering the uniqueness of subsystems, basic events in the FTA at the second analysis level are different. For the electrical subsystem, the FTA-FMEA is performed in the traditional way. We study the particularity of the mechanical subsystem and apply meta-action theory in the fault analysis. Meta-action theory has proven to be an effective applicable tool for studying the reliability of mechanical systems [29]–[34]. FTA is performed to get the potential meta-action fault modes and FMEA is performed to identify the key meta-action fault modes. The application of meta-action theory can help analysts better understand the function implementation way of the mechanical subsystem. Moreover, it can also reduce the complexity of the mechanical subsystem FTA because a meta-action unit is treated as a basic fault analysis element.

RPN is often used in criticality analysis, while its calculation seems naïve. In this paper, we use the TOPSIS method to determine the priority of fault modes/causes. In addition, the correction cost is treated as the fourth attribute in TOPSIS. The priority of the fault modes/causes can be determined by the distance to the PIS and NIS. The ranking result is more reasonable for the decision makers in a company. They can make more reasonable corrections to improve the reliability of the FMC based on the company's financial condition.

The application of the proposed method in our cooperating company verifies its efficiency and cost-saving. We believe the proposed method can not only be applied in the fault analysis of the FMC but also other systems. While, for the more complex system such as a large flexible manufacturing system (FMS), the applicability of the proposed method is not verified yet. Therefore, our future work is to find the appropriate fault analysis method for the large complex FMS. In the end, the problem that a fault cause appears in the fault trees of different fault modes is also one of our future work.

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