A hierarchical evaluation index system for FMS reliability considering coupling relations between system elements

Yanhu Pei 1,2 • Congbin Yang 2,3 • Jingjing Xu 1,2 • Yida Wang 4 • Xiangmin Dong 5

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Abstract
FMS reliability cannot be accurately evaluated without considering coupling relations between system elements. This paper presented a hierarchical and quantitative evaluation index system for FMS based on Petri net models and judgment matrix construction. In the proposed system, influencing factors and their coupling relations related to system elements including human, control systems, and mechanical equipment are analyzed. Based on the above analysis, FMS is described as a hierarchical system composed of the whole-level system, processing system, and transfer system. Petri net for the running process of each system is modelled for reliability simulation analysis. And judgment matrices of indexes are constructed and combined with simulation of Petri net models to determine weighted values for influencing factors. Finally, an application example is completed to verify the effectiveness of the proposed system. Results indicate that the system can help to quantitatively evaluate the reliability of FMS based on availability indexes of elements and clearly show weaknesses of the system from element level, which is a significant basis for the FMS reliability improvement during the design stage.

Keywords FMS reliability • Evaluation index system • Coupling relations • Petri net model

1 Introduction
Flexible manufacturing system (FMS) is a complex and state-time-varying system [1], which is a set of equipment connected by a transfer system, which can place blanks to the processing system and finished work-pieces to the storage system, and also a upper control system is applied to make the whole processing continuous and automatic, as shown in Fig. 1, so that the production can be accurate and efficient [2]. For FMS, reliability is an important performance index, which has been one of the research focuses and difficulties currently [3]. In real manufacturing, companies always only emphasize the reliability of the single equipment, but less focus on the system-level reliability. For example, Cheng et al. [4, 5] presented advanced methods for the reliability analysis of machine tools in previous works. However, they increasingly concern on the implementation of the system function and its related influencing factors. Reliability indexes can make us clearly understand the manufacturing process of FMS from a new and upper-level viewpoint, which is helpful to improve and balance the whole performance of the system even during the design stage [6]. In recent studies, scholars mostly take equipment as the research objective and failures of the single equipment as the main failure mode that affects the system reliability, which did not consider the running features of FMS. Some representative works are summarized and discussed in the following content.

In earlier works, reliability of the production line has been widely studied to find weaknesses of the system, which aims to effectively increase the performance through purposive improvements [7]. Modelling methods of the production line mainly include queuing theory (QT) [8], equivalent
workstation method (EW) [9], and Petri net models (PN) [10]. Among them, QT can only accurately describe simple systems; EW is more applicable to the modelling problem of the serial system, and PN has been well developed due to its accurate descriptions for cases like synchronization, parallel, and conflict and widely used in recent studies [3, 11].

In terms of reliability analysis, some researches were presented considering some system-level features. For example, Vineyard described the failure and maintenance data of FMS using probability distribution, for which the system is divided into mechanism, electron, software, and other components, and each data set is fitted according to given distribution type [12]. Savsar proposed a mathematical model that includes the flexible machine, manipulator, and handling system, to study completely reliable and unreliable flexible manufacturing systems, and compared running conditions of the reliable system and unreliable system based on constant failure rate [13]. Das et al. proposed a multi-objective integrated model of minimum system cost and maximum equipment reliability and carried out the sensitivity analysis of reliability parameters [14]. Wang et al. focused on the problem of insufficient capacity of production line in a car company and presented the technique of system technology improvement under constraints of limited cost and spaces and finally predicted indexies including capacity, idleness ratio, and blocking rate after technology improvement through simulation [15]. Hou optimized the maintenance policies of production line through combining the failure data, maintenance data, expert opinions, and reliability theory [16]. Liu calculated weighted values for influencing factors of system-level reliability and determined reliability indexies of each equipment, using fuzzy synthetic evaluation method, based on ex-factory reliability level of equipment and maintenance technical level, which can help the production line planning during the design stage [17]. Badiea et al. introduced the proper preventive maintenance solutions to the company to increase the reliability of machines of the production line and reduce cases of shutdown, for which mean time between failures, mean down time, and availability were taken as the best indexes for the system maintenance [18]. Xu et al. proposed preventive maintenance models for equipment and divided them into different levels according to mixed failure rate and formulated targeted and differential maintenance strategies [19]. Li established the optimum allocation model for the crankshaft FMS based on functional relations between equipment reliability, repair rate, productivity, and cost, taking lowest improvement cost as the optimization objective, as well as functions and build cost of the buffer capacity unit as constraints [20]. Fan et al. presented proper reliability allocation methods to assign the system reliability allocation index to equipment layer by layer, considering influencing factors of system reliability and cost [21].

In summary, although previous studies of the system reliability of the production line can provide some theoretical and methodological basis, it cannot totally used to solve the reliability problem of FMS, which has its special feature, for example, an upper control system with perception and planning modules is always applied to control the overall production cycle [22]. How to establish a complete reliability index system for FMS considering its self-features is the main purpose of this work. The remainder of this paper is organized as follows: Section 2 presents influencing factors and their coupling analysis of FMS reliability, which makes the composition and running mode FMS clear and provides the basis for the construction of Petri net models of FMS; Section 3 describes the construction and quantization methods of FMS hierarchical reliability evaluation index system based on Petri net models of FMS; Section 4 gives an application example and its results and discussions to verify the effectiveness of the proposed method; Section 5 listed the main conclusions and future works related to this study.
2 Influence factors and their coupling analysis of FMS reliability

The production manufacturing system is often composed of processing equipment for machining, cleaning, and testing. To obtain a flexible and efficient manufacturing process, FMS can set up more than two equipment for certain jobs and integrate workpiece loading and unloading robots, buffer devices, unmanned ground vehicles (UGVs), and stereoscopic warehouse into the system. Also, the state data acquisition and its real-time monitoring, as well as the equipment scheduling management, can be completed through the hierarchical control system.

Therefore, FMS can be divided into three parts: processing equipment, transfer and storage equipment, and hierarchical control system; its basic framework is shown in Fig. 2. The traditional operating process can be described as follows. Upper control system firstly sends working instructions to bottom-level control system of each equipment based on the combination of the product order information and instructions of human. The equipment then works according to instructions sent by the corresponding bottom-level control system and sends back the running state information of each equipment through its sensing system. The detailed instructions for processing and scheduling are analyzed and generated based on state monitoring and decision modules through data collection and analysis and are distributed to bottom-level control systems for real and continuous actions of equipment.

In sum, the reliability evaluation of FMS is a systematic work. From FMS production self, influencing factors of the system reliability include factors of mechanical equipment, control systems, and user. But, failure cases caused by three kinds of factors are shown on the execution effects of equipment, for example, the abnormal indexes of the production rate and execution accuracy. Besides, the failure of upper control system and user action may result in abnormal indexes of more than one equipment. Traditional methods always analyze the production line availability only based on reliability indexes of equipment, but not considering the coupling relations between the failure phenomena of equipment, which reduces the evaluation accuracy of the FMS reliability and goes against the analysis of influencing factors and the proposal of promotion strategies. This work builds the reliability evaluation index system of FMS, considering coupling relations from four aspects including user, upper control system, bottom-level control system, and mechanical equipment.

Figure 3 gives the possible influencing factors of the failure of FMS. From this figure, the following coupling effects between influencing factors can be obtained: (1) wrong commands of upper control system may occur due to wrong operations of users, wrong measurement data from sensors existed in mechanical equipment, as well as its own design in software or hardware; (2) failure of the current element may be caused by its own failure or the failure of one previous element. Therefore, to better show the reliability of the whole system, the influencing weights of the failure of each element to elements of the next level can be used to accurately evaluate the reliability of FMS, for example, the probability that upper control system causes the failure of the one bottom-level control system.

3 Construction and quantization methods of FMS hierarchical reliability evaluation index system

3.1 Construction method of FMS reliability evaluation index system

According to the working feature, the FMS reliability is divided into three levels: The first level is the reliability of the whole system. The second level includes reliability indexes of users, upper control, processing system, and transfer system. The third level is sub-divided into working elements. Detailed explanations of reliability indexes of each level are as follows. The first level index is the availability of FMS, which is used to evaluate the reliability of the whole system.
The second level indexes include reliability indexes of human, upper control system, processing system, and transfer system. The third level for both the processing system and transfer system includes elements like bottom-level control systems and mechanical equipment. Reliability of human is evaluated by human error rate (HER) and availability (A) of each control system and mechanical equipment, which is used to describe the probability of maintaining the specified function of control system or equipment under given time or using conditions. A is related to the mean time between failures (MTBF) and mean time to repair (MTTR), which is uniformly described as element availability (EA), and can be expressed as follows:

\[
EA = \frac{MTBF}{MTBF + MTTR}
\] (1)

Note that the error of human instruction or upper control system may result in abnormal running of more than one equipment; the error of bottom-level control system mainly causes the failure of the controlled equipment; the failure of sensing system mainly can lead to the wrong instructions of the upper control system. When considering the above coupling relations, the incidence rate of association errors between coupling elements should be evaluated firstly, based on values for each element availability can be determined. Finally, the FMS availability index can be modelled based on values of reliability indexes of all elements.

Herein, the coupling error-occurred probability from element \(a\) to element \(b\) is represented by

\[
CEP_a = \frac{FT_b^a}{FT_b^b}
\] (2)

where \(FT_b^a\) means the total number of failures that element \(b\) occurred and \(FT_b^b\) means the number of failures of element \(b\) caused by failure of element \(a\), which both can be determined by the field data from practical running of FMS.

Therefore, considering the decoupling relation, the number of failures caused by element \(b\) itself can be calculated by

\[
FT_b = FT_b^b \cdot (1 - CEP_b^a)
\] (3)

\[
MTBF_b = \frac{T}{FT_b}
\] (4)

where \(T\) is the total running time of FMS. Based on Eq. (1), the availability index \(EA_b\) of element \(b\) can be calculated finally. In practical applications, Eqs. (1~4) can help to determine availability values for elements from collected data during the real production process.

In this work, the influencing level of \(EA\) of each element on \(A\) of FMS can be analyzed based on Petri net of the system, which can be used to quantify the influencing weights \(IW\) of each element on the whole system. Therefore, combining with the above analysis of \(EA_b\), the system availability \((SA)\) can be calculated as follows:

\[
SA = IW_{HER} \cdot HER + IW_{uc} \cdot EA_{uc} + IW_{ps} \cdot \sum_{i=1}^{J} IW_{ps,i} + IW_{ts} \cdot \sum_{j=1}^{J} IW_{ts,j} \cdot EA_{ts,j}
\] (5)

where \(IW_{HER}, IW_{uc}, IW_{ps},\) and \(IW_{ts}\) represent influencing weights of human, upper control system, processing system, and transfer system to FMS, respectively. \(EA_{uc}\) denotes the availability value of the upper control system. \(l\) and \(J\) means the number of elements of processing system and transfer system, respectively. \(I\) and \(j\) denote the influencing weight and availability value of the \(ith\) element of processing system, respectively. \(I\) and \(j\) denote the influencing weight and availability value of the \(jth\) element of transfer system, respectively. Reliability evaluation index system of FMS is shown in Table 1, wherein \(EA_{ps}\) and \(EA_{ts}\) mean availability values of the processing system and the transfer system.

| Table 1 Reliability evaluation index system of FMS |
|-----------------------------------------------|
| 1-level | 2-level | 3-level |
| ______ | ______ | ______ |
| \(SA\) | \(HER\) | — |
| \(EA_{uc}\) | — | |
| \(EA_{ps}\) | \(EA_{ps,i}, 0 < i < J+1\) | |
| \(EA_{ts}\) | \(EA_{ts,j}, 0 < j < J+1\) | |

Fig. 3 Possible influencing factors for the failure of FMS
3.2 Quantization method of weighted values based on Petri net

3.2.1 Introduction of FMS Petri net

Petri network model is used to describe the discrete event system using visual graphics, including libraries, transitions, and arcs. Petri net uses ○ and □ to represent libraries and transitions, respectively, and uses transition stimulation to describe the occurrence of an event. A library describes the current state of the element, for example, working state of machine tool or other equipment, number of products in buffer region, and execution state of control systems. A transition is used to describe an event that causes a change in the current state of FMS, like machining, loading, and unloading, which is divided into immediate transition and deterministic transition. An arc is used to determine the relation between the place and transition. Petri network model is expressed by five parts, \( PN = \{P, T, I, O, m_0\} \), wherein \( P = \{p_1, \ldots, p_n\} \) represents a finite set of library; \( T = \{t_1, \ldots, t_n\} \) means a finite set of transition; the input function \( I(p, t) = w \) and the output function \( O \) represent the number of repeats or the set of weights on the directed arc from \( P \) to \( T \) and that from \( T \) to \( P \), respectively, is a non-negative integer that marks beside the arc. Both \( I \) and \( O \) can be denoted by non-negative integer matrix \( n \times m. m_0 \) is the representation of the initial state of FMS.

3.2.2 Petri net hierarchical models of FMS running process

The whole layer shown in Fig. 4 aims to model the working procedure of FMS in macroscopic view, which helps readers to understand the running, layout, and equipment from the whole layer. Different from existing studies, user and control systems are all represented as elements of Petri net, which can accurately describe the system with considering both factors of equipment, algorithms, and user. Explanations for libraries and transitions are listed in Tables 2 and 3.

Transfer system can contain the loading robots, UGVs, buffer devices, guide rail, and unloading robots according to the different degrees of automation. Figure 5 shows the Petri net for set of transfer equipment and their bottom-level control systems, and explanations for its libraries and transitions are listed in Tables 4 and 5, respectively.

The processing system often contains the equipment for rough/fine machining, cleaning, and detecting, which are determined by the manufacturing process of products. Figure 6 shows the Petri net for set of processing equipment, and explanations for its libraries and transitions are listed in Tables 6 and 7, respectively.

3.2.3 Petri net hierarchical models of FMS availability

According to the Petri net models of running processes, FMS is not simply obtained through connecting equipment in series.

### Table 2: Library explanations of the whole-layer Petri net

| Libraries | Explanations                                                                 |
|-----------|-----------------------------------------------------------------------------|
| \( p_1, p_2, p_3, p_4, p_5, p_7 \) | User, upper control system, storage of blanks to be processed, transfer system for loading blanks, processing system, transfer system for unloading work-pieces, storage of finished products |

### Table 3: Transition explanations of the whole-layer Petri net

| Transitions | Explanations                                                                 |
|-------------|-----------------------------------------------------------------------------|
| \( t_1 \)   | User sends an instruction to upper control system                            |
| \( t_2 \)   | Transfer equipment takes the blank, and upper control system sends an instruction to transfer system |
| \( t_3 \)   | The blank is transferred to processing system, and upper control system sends an instruction to processing system |
| \( t_4 \)   | Transfer system takes the finished product, and upper control system sends an instruction to transfer system |
| \( t_5 \)   | The finished product is placed in the storage system                          |
or parallel due to the existence of human, intelligent control systems, and buffer devices. That is, FMS can run even with equipment failure if the equipment can be repaired within the allowable range of the buffer device. Therefore, the FMS availability needs to be analyzed considering failure rate ($\lambda = 1/\text{MTBF}$), maintenance rate ($\mu = 1/\text{MTTR}$), allowable capacity of the buffer device, and production rate of the processing equipment. In practical applications, reliability values for each equipment or control system, including failure rate and maintenance rate, can be obtained through real tests in a certain running time. The FMS availability largely relies on the availability of each element of FMS and also the complexity of the FMS layout. Availability models for the whole-level system, transfer system, and processing system can be established through combining two classical models, which include the parallel and synchronous models and model for the element with buffer device and are presented as follows in detail. And availability models for three systems will be slightly different due to the layout of buffer devices.

**Parallel and synchronous availability model** In Fig. 7, transitions $t_1$ and $t_2$ can be stimulated simultaneously and run independently. Set of two or more processes that run independently is called as parallel model. When they are stimulated by one transition and combined together, the running process like this is called synchronous model.

**Availability model of the element with buffer device** The availability model of one equipment with the buffer device can be established as Fig. 8 based on unit models presented in the reference report [23]. In Fig. 8, $p_{E1}$ and $p_{E2}$ denote the upstream and downstream equipment, and $p_{E3}$ can be a buffer device. $p_{b}$ denotes the state of the buffer device with the allowable number as $k_e$. $p_{e1}$ denotes that the equipment is working, $p_{e2}$ denotes that the working is completed but workpiece is not transferred to the downstream buffer device, $p_{e3}$ denotes that the equipment is idle and can immediately start working once it is stimulated, and $p_{e4}$ denotes that the equipment is in fault state. Models are two closed loops, including the upper triangle loop and the lower rhombic loop.

The running process of the buffer device can be described as follows: Under the condition that $p_{E1}$ completes the operation and $p_{b}$ has vacancy, $t_b$ is stimulated, and then the workpiece is transferred to $p_{b}$. The forbidden arc means that when the stocks of $p_{b}$ are equal to the allowable number $k_e$, $t_b$ is restrained and cannot be stimulated and $p_{E1}$ is blocked.

For the equipment, the running process of the triangle loop can be described as follows: (1) Under the condition that the equipment is idle and the buffer device $p_{b}$ has blanks, $t_{e1}$ is stimulated, and the processing starts. (2) Under this case, if the equipment is in normal state, the processing time will continue $1/\lambda_{e2}$, and then $t_{e2}$ is stimulated. The workpiece will be transferred into $p_{e2}$ once the processing is complete. (3) Under this case, when the downstream buffer device has empty locations, $t_{e3}$ is stimulated, and the equipment returns to idle state.

The running process of the rhombic loop can be described as follows: (1) When the equipment is in fault state and transferred to the place $p_{e4}$, $t_{e4}$ is stimulated. (2) Under this case, when the equipment is repaired to normal state by crews, $t_{e5}$ is stimulated, and then the equipment can re-start working. The stimulation rates of $t_{e4}$ and $t_{e5}$ are the failure rate and maintenance rate of the equipment, respectively.

### 3.2.4 Petri net-based availability analysis of FMS

Based on Petri net hierarchical models, the stationary availability $SA$ of FMS can be obtained through taking the same values for reliability indexes $EA$ of all elements, which is used.

| Libraries | Explanations |
|-----------|--------------|
| $p_{c1}$, $p_{c2}$, $p_{c3}$, $p_{c4}$ | Control system of loading system, control system of two UGVs, control system of unloading robot |
| $p_{a1}$, $p_{a2}$, $p_{a3}$, $p_{a4}$ | Loading robot, UGV for pre-processing, UGV for post-processing, unloading robot |
to determine the influence degree ID of the reliability of each element on the whole system. The analysis can be completed using one of Petri net analysis tools, which have been developed very well. Information of FMS, including allowable quantities in buffer device and numbers of equipment, which are determined by the performance or mechanical system of each equipment, should be first inputted for this analysis.

According to the Petri net models of FMS, the analysis is divided into three analyses for the whole-level Petri net (WLPN), the transfer system Petri net (TSPN) and the processing system Petri net (PSPN), respectively. For each system, the influencing level of each element on the system availability is determined according to stable availabilities of the system at different values of $\lambda$ and $\mu$. For elements of one system, the maximum change $SA_{\text{max}}$ and minimum change $SA_{\text{min}}$ of the stable availability of the system are calculated, and then influence levels of elements can be divided into three degrees: major influence, general influence, and minor influence.

### Table 5 Transition explanations of the transfer system Petri net

| Transitions | Explanations |
|-------------|--------------|
| $t_e$       | Upper control system sends instructions to bottom-level control systems of transfer system |
| $t_{41}$    | Loading robot takes the blank from storage, and robotic control system sends instructions to the loading robot |
| $t_{42}$    | Loading robot transfers the workpiece to UGV, and UGV’s control system sends instructions to UGV |
| $t_{43}$    | UGV transfer the workpiece to processing system. |
| $t_{61}$    | UGV takes the workpiece from processing system, and UGV’s control system sends instructions to UGV |
| $t_{62}$    | UGV transfers the workpiece to unloading robot, and robotic control system sends instructions to the unloading robot |
| $t_{63}$    | Unloading robot transfers the workpiece to the storage system |

### Table 6 Library explanations of the processing system Petri net

| Libraries | Explanations |
|-----------|--------------|
| $p_{c5}$, $p_{c6}$, $p_{c7}$ | NC system of machine tool, control system of cleaning equipment, control system of detecting equipment |
| $p_{51}$, $p_{52}$, $p_{53}$ | Machine tool, cleaning equipment, detecting equipment |

### Table 7 Transition explanations of the processing system Petri net

| Transitions | Explanations |
|-------------|--------------|
| $t_{51}$    | Machine tool takes the blank, and NC system sends instructions to machine tool |
| $t_{52}$    | Machine tool transfers the workpiece to cleaning equipment, and bottom-level control system sends instructions to cleaning equipment |
| $t_{53}$    | Cleaning equipment transfers the workpiece to detecting equipment, and bottom-level control system sends instructions to detecting equipment |
| $t_{54}$    | Transfer equipment takes the workpiece |
influence can be marked as level 3, level 2, and level 1 according to the following definition.

\[ \text{SA}_R \in \begin{cases} \frac{2(\text{SA}_{\text{max}} - \text{SA}_{\text{min}})}{3}, \text{SA}_{\text{max}} \leq 3, \text{Level} - 3 \\ \frac{\text{SA}_{\text{max}} - \text{SA}_{\text{min}}}{3}, \frac{2(\text{SA}_{\text{max}} - \text{SA}_{\text{min}})}{3}, \text{Level} - 2 \\ \frac{\text{SA}_{\text{min}}}{3}, \frac{\text{SA}_{\text{max}} - \text{SA}_{\text{min}}}{3}, \text{Level} - 1 \end{cases} \]  

Taking one system as an example, the judgment matrix \( \text{MAT} \) of reliability indexes of the element level relative to index of system level can be constructed based on marked values generated from the above analysis. Scales and their meanings of the matrix are listed in Table 8. And the judgment matrix \( \text{MAT} \) can be designed as Table 9.

According to the above judgment matrix, the weight coefficient of each index of the element level relative to the system level can be calculated by using the matrix eigenvector and the relevant knowledge of the maximum feature. In order to avoid the discordant phenomenon in the AHP (analytic hierarchy process), the consistency test of the matrix should be further carried out to explain the rationality of the index weight.

Therefore, the weight coefficients of the reliability index system of FMS can be calculated through four steps: (1) the eigenvector of the judgment matrix is calculated, that is, the product of each row of the comparison matrix; (2) the \( N \)th root of \( M \) is calculated; (3) normalization; and (4) consistency check.

Based on this proposed method, the reliability of FMS can be evaluated based on availabilities of all elements, which can help to improve the reliability level during the design or layout stage of FMS. In the practical application, the availability of each element can be determined through single analysis, for example, availability of the control system can be obtained through simulation tests using computers, and availability of each equipment can be evaluated based on the experience data. Therefore, compared with the traditional method, which collects error data of the whole system during a certain trial period of production, the proposed method can largely reduce the cost of reliability evaluation of FMS, including saving time and money.

4 Application example, results, and discussions

In this section, we use a FMS for box-type components machining as an example, which includes loading robot, machine tool, detecting equipment, unloading robot, UGVs, and control systems of each element, as well as the PC-based control system, as shown in Fig. 9. Herein, reliability indexes (MTBF, MTTR) of each element are first set as Table 10 before the analysis, which can be obtained from running data of each of them in practical application of the proposed method. Also,
the reliability index $HER$ of human is set as 0.9999, and allowable number of the buffer device is set as 10. The working quantities per hour of the robot, machine tool, and detecting equipment are set as 720, 12, and 120, respectively.

According to Table 10, the availability value, failure rate, and maintenance rate of each element are listed in Table 11, which are important parameters associated with the reliability for each element and will be used in the system availability analysis of the following simulation.

Based on the proposed method, availability of Petri nets of three systems including the whole-level system (WS), processing system (PS), and transfer system (TS) of FMS can be obtained, respectively. The availability analysis is completed using SPNP6.0 software, which is a relatively mature analysis software for random Petri net model developed by Kishor S. Trivedi and his team of USA Duke university. In this simulation work, availability of Petri nets for three systems (WSPT, PSPT, TSPT) is analyzed. For each system, according to features of elements, values of $\lambda$ are taken from $0.5 \times 10^{-3}$ to $2 \times 10^{-3}$ for mechanical equipment and taken from $1 \times 10^{-5}$ to $9 \times 10^{-5}$ for controllers during the simulation. And values of $\mu$ are taken from 0.1 to 1 for each element. And based on Eq. (6), the influencing levels can be determined, which is shown in Table 12.

Using the calculation method of weighted values presented in Section 3.2.4, weighted values for each level of FMS can be obtained as Table 13. Substituting availabilities of elements of Table 11 into Eqs. (5~8), the availability of FMS can be calculated as 0.8516, which can be used to evaluate the reliability of FMS.

5 Conclusions and future works

This paper presented a hierarchical reliability evaluation index system for FMS considering coupling relations between system elements. In this work, influencing factors of system-level reliability are divided into elements from four aspects, human, upper control system, bottom-level control systems, and mechanical equipment, and their coupling relations are analyzed based on the basic framework of FMS. Hierarchical Petri net models from the whole layer and function layers (processing system and transfer system) are constructed to describe the overall system. Then the quantification method of weighted values for the evaluation index system is presented combining simulation analysis of Petri net models and judgment matrix construction of indexes. An application example is presented to show the effectiveness of the proposed method, and the following conclusions are obtained.

(1) Based on the proposed method, the reliability of FMS can be quantitatively evaluated based on availability indexes of each element. This evaluation can provide data foundation for the layout design of FMS.

(2) From the results, we know that for the element level, the influence size of the machine tool and UGVs on reliability of FMS is the first and second places, which means that availabilities of machine tool and UGVs need to be focused and increased to improve the reliability of the whole FMS.

From this work, availability values for single elements can be obtained from the practical running process of FMS based

![Fig. 9 Framework of the box-type components machining FMS](image-url)
### Table 10  Reliability indexes for each element of the FMS

| Index   | Loading robot | Machine tool | Detecting equipment | Unloading robot | UGVs |
|---------|---------------|--------------|---------------------|-----------------|------|
| MTBF    | 850           | 1000         | 2000                | 850             | 800  |
| MTTR    | 3             | 5            | 6                   | 3               | 2    |

Index Robotic controller Numerical control system Controller for detecting Controller for UGVs PC-based control system

| MTBF    | 15,000        | 20,000       | 20,000              | 15,000          | 30,000 |
|---------|---------------|--------------|---------------------|-----------------|--------|
| MTTR    | 2             | 3            | 3                   | 2               | 1      |

### Table 11  Availability value, failure rate, and maintenance rate of each element of FMS

| Index   | Loading robot | Machine tool | Detecting equipment | Unloading robot | UGVs |
|---------|---------------|--------------|---------------------|-----------------|------|
| EA      | 0.9965        | 0.9950       | 0.9970              | 0.9965          | 0.9975 |
| \( \lambda \) | 1.18\( \times 10^{-3} \) | 1\( \times 10^{-3} \) | 0.5\( \times 10^{-3} \) | 1.18\( \times 10^{-3} \) | 1.25\( \times 10^{-3} \) |
| \( \mu \) | 0.33          | 0.2          | 0.17                | 0.33            | 0.5   |

Index Robotic controller Numerical control system Controller for detecting Controller for UGVs PC-based control system

| EA      | 0.9999        | 0.9998       | 0.9998              | 0.9999          | 0.9999 |
| \( \lambda \) | 6.67\( \times 10^{-5} \) | 5\( \times 10^{-5} \) | 5\( \times 10^{-5} \) | 6.67\( \times 10^{-5} \) | 3.33\( \times 10^{-5} \) |
| \( \mu \) | 0.2           | 0.33         | 0.33                | 0.2             | 1     |

### Table 12  Influencing level of elements on three systems WSPT, PSPT, TSPT

| WSPT | Human | PC-based control system | Transfer system 1 | Processing system | Transfer system 2 | —   |
|------|-------|-------------------------|-------------------|-------------------|-------------------|-----|
| Level | 1     | 3                       | 2                  | 2                 | 2                 | —   |
| PSPT | Machine tool | Detecting equipment | Numerical control system | Controller for detecting | — | — |
| Level | 3     | 2                       | 2                  | 2                 | —                 | —   |
| TSPT | Loading Robot | UGVs | Unloading robot | Robotic controller 1 | Controller for UGVs | Robotic controller 2 |
| Level | 2     | 3                       | 2                  | 1                 | 1                 | 1   |

### Table 13  Weighted values for each level of FMS, wherein \( EA_{ls}, EA_{ugv}, EA_{u}, EA_{ncs}, EA_{ugv1}, \) and \( EA_{ugv} \) represent availability values for loading robot, UGV, unloading robot, and their controllers, respectively; \( EA_{mt}, EA_{de}, EA_{ncs}, \) and \( EA_{std} \) denote availability values for machine tool, detecting equipment, and their controllers, respectively

| 1-level | 2-level | Weighted values | 3-level | Weighted values |
|---------|---------|-----------------|---------|-----------------|
| SA      | HER     | 0.2786          | —       | —               |
|         | \( EA_{ls} \) | 0.2786 | —       | —               |
|         | \( EA_{ugv} \) | 0.1476 | \( EA_{ls} \) | 0.1885 |
|         | \( EA_{ugv1} \) | 0.3264 | \( EA_{ugv} \) | 0.1885 |
|         | \( EA_{ncs} \) | 0.0989 | \( EA_{ncs} \) | 0.0989 |
|         | \( EA_{std} \) | 0.0989 | \( EA_{std} \) | 0.0989 |
|         | \( EA_{ugv} \) | 0.1476 | \( EA_{ugv} \) | 0.1476 |
|         | \( EA_{mt} \) | 0.4 | \( EA_{mt} \) | 0.4 |
|         | \( EA_{de} \) | 0.2 | \( EA_{de} \) | 0.2 |
|         | \( EA_{ncs} \) | 0.2 | \( EA_{ncs} \) | 0.2 |
|         | \( EA_{std} \) | 0.2 | \( EA_{std} \) | 0.2 |
on Eq. (4) and also can be obtained through real tests in a certain running time of each element. Obviously, considering other coupling relations like sharing of water and electricity, values based on the latter way can help obtain a more accurate evaluation system for FMS reliability. In this work, the evaluation system was obtained from the given values of these parameters. In future works, authors will apply the proposed evaluation method into a real FMS, to reveal the effect size of other coupling relations through real experiments. If it has a major effect, the modified method will be studied further. If the effect is minor, the accuracy of the evaluation system obtained based on the proposed method can be validated.

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**Code availability** Not applicable.

**Declarations**

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**References**

1. Kammoun MA, Rezg N (2018) Toward the optimal selective main-
tenance for multi-component systems using observed failure: ap-
plied to the FMS study case [J]. Int J Adv Manuf Technol 96:1093–
1107.
2. Li XZ, Gao Y (2020) Design and simulation of load-unload system
using industrial robot for flexible manufacturing line [J]. Design
Res 08:63–67.
3. Liu B. (2015) Research on reliability assessment method of engine
cylinder block flexible production line [D]. Jilin University of
China.
4. Cheng Q, Wang C, Sun DY et al (2021) A new reliability allocation
method for machine tools using the intuitionistic trapezoidal fuzzy
numbers and TOPSIS. Int J Adv Manuf Technol. https://doi.org/10.1007/s00170-021-07331-9
5. Cheng Q, Sun BW, Zhao YS et al (2016) A method to analyze the
machining accuracy reliability sensitivity of machine tools based on
fast Markov chain simulation [J]. Eksploatacja i Niezawodnos-
Maintenance and Reliability 18(4):552–564.
6. Mahmood K, Karaulova T, Otto T, Shevtshenko E (2017) Performance
analysis of a flexible manufacturing system (FMS) [J]. Proc Cirp 63:424–429.
7. Liberopoulos G, Tsrouhas P (2005) Reliability analysis of an au-
tomated pizza production line [J]. J Food Eng 69(1):79–96.
8. Zhang N, Cui G (2013) Software reliability growth models based
on queuing theory [J]. Intell Comp Appl 3(02):16–19.
9. Shu SG (1992) An analysis of the repairable computer integrated
manufacturing system (CIMS) with buffers and a study of the sys-
tem reliability [J]. Instit Autom Chin Aced Sci 1992(01):15–22.
10. Tüysüz F, Kahraman C (2010) Modeling a flexible manufacturing
 cell using stochastic Petri nets with fuzzy parameters [J]. Expert
Syst Appl 37(5):3910–3920.
11. Wang L, Dai W, Ai J, Duan W, Zhao Y (2020) Reliability evalu-
aton for manufacturing system based on dynamic adaptive fuzzy
reasoning Petri net [J]. IEEE Access 8:167276–167287.
12. Vineyard M, Amoako-Gyampah K (1999) JR Meredith. Failure
rate distributions for flexible manufacturing systems: an empirical
study [J]. Eur J Oper Res 116(1):139–155
13. Savsar M (2000) Reliability analysis of a flexible manufacturing
 cell [J]. Reliab Eng Syst Saf 67(2):147–152.
14. Das K, Lashkari RS, Sengupta S (2007) Reliability consideration
in the design and analysis of cellular manufacturing systems [J]. Int J
Prod Econ 105(1):243–262.
15. Wang G, Song S, Shin YW et al (2014) A simulation based study
on increasing production capacity in a crankshaft line considering
limited budget and space [J]. J Korean Instit Ind Eng 40(5):481–491.
16. Chao H (2017) Maintenance strategy of car crankshaft automatic
production line [D], Jilin University, Jilin.
17. Chang L (2015) Reliability allocation method of car crankshaft
production line based on comprehensive fuzzy evaluation[D].
Jilin University, Jilin.
18. Badiea AM, Adel AA, Aamer HA (2020) Effect of preventive
maintenance on the production line machines and systems reliabil-
ity: case study [J].Curr J Appl Sci Technol:58–65.
19. Xu B., Wang Z., Luo W, et al. A research on the combined main-
tenance strategy for production line equipment based on mixed
failure rate [J]. Mathematical Problems in Engineering, Hindawi,
2021:1-15, February.
20. Li ZS (2020) Research on reliability improvement technology of
crankshaft grinding automation flexible system [D]. Beijing
University of Technology, Beijng.
21. Fan JW, Wang MM, Li WH, et al. (2020) Research on reliability
distribution of crankshaft grinding automation flexible production
system [J]. National Science and Technology Major Project Item
IV. (10):35-40.
22. Liu ZF, Yan J, Cheng Q et al (2019) The mixed production mode
considering continuous and intermittent processing for an energy-
efficient hybrid flow shop scheduling [J]. J Clean Prod 246:119071
23. Zhibin J. (2004) Petri nets and their applications in modeling and
control of manufacturing systems [M]. Machinery Industry Press.