Modelling and Computation of Equipment Reliability for Manufacturing System Based on Petri Net

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Abstract. For the structural complexity of the manufacturing system, it is difficult to decompose and express the equipment reliability; a three-dimensional method based on Petri nets was proposed to model and calculate equipment reliability of manufacturing systems. This method includes three steps: The first step is to model the equipment chain network according to manufacturing process by Petri nets, and the reduction method of series and parallel Petri nets is used to simplify the complexity of Petri nets; The second step is to model each single equipment reliability by tree Petri nets, fault tree analysis (FTA) is adopted to express single equipment reliability, and then FTA is converted to tree Petri nets according to the conversion rule between them; The third step is to integrate chain and tree Petri nets into three-dimensional Petri nets to express the whole equipment reliability of manufacturing system. Finally, the reliability calculation of engine cylinder manufacturing system is taken as an example to verify the proposed method.

1. Introduction

Equipment reliability of manufacturing system plays an important role in improving product quality, reducing product cost and shortening delivery time, it is an important guarantee for enterprise's core competence. In order to expose equipment reliability problems clearly, we need to straighten out the logical relationship of equipment in the manufacturing process, to grasp the hierarchical structure of node equipment in manufacturing process, and to lay the foundation for the follow-up processing of equipment reliability guarantee in manufacturing system. Experts and scholars have used a variety of methods to analyse and model the equipment reliability of manufacturing system. The modular method is used to describe cell layer, system layer and system layer of hybrid process in industrial process [1]. The multi-agent is used to represent the hierarchical model of parts, components and equipment [2]. The Meta model is used to model all kinds of resources in manufacturing systems [3]. The relationships between elements in manufacturing system were used to build system model [4]. The modified randomly state diagram is used to describe the sun-system structure and system hierarchy [5]. Reliability block diagram (RBD) is used to describe all levels of the elements such as components, equipment and workshops of manufacturing system [6]. The component-based method is used to represent various types of the soft and hardware equipment in manufacturing system [7]. The activity-based method is used to control and schedule manufacturing resources [8]. The model-based method is used to allocate manufacturing resource [9]. The ontology-based method is used to describe all sorts of resource in the manufacturing system [10].
In this paper, equipment reliability modelling is divided into three stages: The first is macro level, chain modelling of the whole equipment in manufacturing system according to the production process; The second is micro level, tree modelling of a single equipment in production line according to fault topology; The third is three-dimensional modelling which integrates chain and tree modelling, and equipment reliability of manufacturing system can be established. Therefore, Petri net was introduced to analyse and express the chain, tree and three-dimensional model of equipment reliability in manufacturing system, and the calculation process of the overall equipment reliability in manufacturing system was given. Finally, the proposed method is verified by case.

2. Logic relation of Petri nets and its simplification

Petri nets theory originated in Germany in 1962, C.A.Petri put forward a network theory based on formal modelling and analysing. Petri nets defined formally as \( N = \{P, T, F\} \), among them, \( P = \{p_1, p_2, p_3, \ldots, p_m\} \) express the library collection, it was used to describe the possible system local conditions or state; \( T = \{t_1, t_2, t_3, \ldots, t_n\} \) express change collection, is was used to describe events or change of modified system; Flow relationships \( F \subseteq \{P \times T\} \cup (T \times P) \) defined directed arc between the library and change, it is a pair of ordered pairs formed by \( P \) and \( T \) elements in Petri nets, indicating the connection between them.

The manufacturing system is a complex system composed of much equipment, which is an organic combination of the logical relationship between equipment, including series and parallel relations. The other logical relations such as circulation and selection relations, they are organic combination of series and parallel relations. In view of the above two logical relations, we use the Petri nets to analyse and express it.

2.1. Logical relationship of Petri nets

2.1.1 Series relationship. In Petri nets, if an element before and after a library satisfied serial relationship, that is \( \forall p_a \in P_a \), if \( t_j \in p_a \bullet \) and \( t_j \in p_a \bullet \), \( t_j \) and \( t_j \) are serial relationships, as shown in figure 1.

The series relation describes the serial arrangement of the equipment in the manufacturing process. The status of the former equipment affects the production state of the following equipment, as shown in figure 1. For example, equipment is in the state of downtime or maintenance due to failure, which will cause the subsequent equipment to be idle in the absence of WIP, which will lead to the standstill of the whole production line. The reliability of the equipment cluster in series is the product of the reliability of all the equipment in the equipment group, namely:

\[
R_s = R_{s1} \times R_{s2} \times \cdots \times R_{sn} = \prod_{i=1}^{n} R_{si}
\]  

Among them, \( n \) is the quantity of equipment, \( R_s \) is the reliability of equipment group which have series relationships; \( R_{si} \) (\( i = 1, 2, \ldots , n \)) is the reliability of \( i \)-th equipment.

2.1.2 Parallel relationship. In Petri nets, if an element before and after a library satisfied parallel relationship, that is \( \forall t \in T \), if \( p_{si} \in \bullet_i(t) \bullet \), \( p_{oj} \in \bullet_j(t) \bullet \) and \( p_{ou} \in \bullet \bullet (t) \), \( p_{oj} \in \bullet \bullet (t) \), \( t_i \) and \( t_j \) are parallel relationships, as shown in figure 2.

The parallel relation describes that each device in the manufacturing cell performs the same production task, if a device is out of order or in a state of shutdown, other equipment can replace the production task of the equipment, and it will not affect the production status of the following process. Namely, the production cell has redundant capacity, or the process is the key and important step of manufacturing systems, except equipment in production state, they have backup equipment, two sorts of
equipment constitute a parallel relationship. The reliability of equipment in a parallel relationship as follows:

\[ R_p = 1 - (1 - R_{p1})(1 - R_{p2}) \cdots (1 - R_{pn}) \]

\[ = 1 - \prod_{i=1}^{n} (1 - R_{pi}) \]  \( (2) \)

2.1.3 Logical relation reduction. In order to simplify the modeling process of the manufacturing system, series and parallel relations can be further simplified, the equipment group is simplified to single equivalent equipment, and reliability of simplified equivalent equipment is equivalent to that of the former group. Simplified equivalent equipment can further be assembled into a new group according to logical relations until the requirements are met. In this way, complex manufacturing system with much equipment can be simplified into simple manufacturing systems. The simplification of the above two logical relations is shown in Table 1.

| Logic relations | Petri net graphics | Simplified graphics | Reliability computation | Equivalent reliability | Manufacturing mode |
|-----------------|-------------------|---------------------|------------------------|------------------------|-------------------|
| Series relationship | ![Series relationship Petri net](image1) | ![Series relationship simplified](image2) | \( R_s = \sum_{i=1}^{n} R_{pi} \) | \( R_s \) | Flow line production |
| Parallel relationship | ![Parallel relationship Petri net](image3) | ![Parallel relationship simplified](image4) | \( R_p = 1 - \prod_{i=2}^{n} (1 - R_{pi}) \) | \( R_p \) | Parallel production |

3. Reliability modelling of equipment in manufacturing system

3.1. Chain modeling of equipment layer in manufacturing system

At the macro level, the manufacturing system is composed of several manufacturing cell, the manufacturing cell also be combined in accordance with the same logical relationship, namely manufacturing system is neither pure series system, parallel system, hybrid system but by many manufacturing cells in series and parallel combinations. For example, a manufacturing system composed of four manufacturing cells(MC), MC1 is composed of two equipment, equipment 1 and 2 have series relationship, MC2 is composed of three equipment, equipment 3, 4, 5 are connected in series, MC3 consists of five devices, both the series and parallel relationships between devices, equipment 7, 8, 9 have a parallel relationship, and then connected with equipment 6, 10 in a series relationship again, MC4 is composed of two equipment, equipment 11, 12 is connected in series, as shown in figure 3.

From formula (1) and (2), it can be known that:

\[ R_{c1} = R_t R_s \]  \( (3) \)
\[
R_{c2} = R_5 R_6 R_7 \tag{4}
\]
\[
R_{c3} = R_8 (1 - (1 - R_i) (1 - R_p) (1 - R_q) R_{10} \tag{5}
\]
\[
R_{c4} = R_{11} R_{12} \tag{6}
\]

Wherein, the manufacture cells 2 and 3 are in parallel relationship, and take formula (4), (5) in type (2), then:
\[
R_{c2c3} = 1 - (1 - R_{c2}) (1 - R_{c3}) = 1 - (1 - R_5 R_6 R_7) (1 - R_8 (1 - (1 - R_i) (1 - R_p) (1 - R_q) R_{10})) \tag{7}
\]

Reliability of the whole manufacturing system is composed of the four manufacturing cells, cell 2, 3 have parallel relationship, and then have series relationship with cell 1, 4. From formula (1), (2), shows that the equipment reliability of the whole manufacturing system:
\[
R = R_{11} R_{c2c3} R_{c4} \tag{8}
\]

And take formula (3), (6), (7) in type (8):
\[
R = R_5 R_6 (1 - R_7) (1 - R_8) (1 - R_9) (1 - R_{10}) R_{11} R_{12} \tag{9}
\]

3.2. Tree modeling of equipment layer in manufacturing system

The reliability of the manufacturing system is integrated that of manufacturing cells, reliability of the manufacturing cell is integrated that of each equipment, the reliability of each equipment is integrated that of each component. FTA (Fault Tree Analysis) is a classic method for fault analysis and reliability calculation, and FTA and the Petri network can be transformed into each other. Therefore, equipment failure can be analysed with FTA, then FTA can be converted into Petri net. So this method can exploit the advantages of FTA and Petri net, and also can express the reliability of the whole manufacturing system with unified Petri net.

3.2.1 Conversion between FTA and Petri net. The automatic conversion between FTA and Petri net can be realized by computer program [11]. In addition, FTA model can also be directly converted manually, and its conversion rules are shown in table 2.

| Or gate | And gate | Inhibit gate | Not gate | M/n voting gate |
|---------|----------|--------------|----------|----------------|
| ![FTA Or gate](image1) | ![FTA And gate](image2) | ![FTA Inhibit gate](image3) | ![FTA Not gate](image4) | ![FTA M/n voting gate](image5) |
| ![Petri net Or gate](image6) | ![Petri net And gate](image7) | ![Petri net Inhibit gate](image8) | ![Petri net Not gate](image9) | ![Petri net M/n voting gate](image10) |

For example, the FTA model of a device as shown in Figure 4 (a), and then can be transformed into Petri net model as shown in figure 4 (b) according to the rules in table 2. Single equipment’s Petri net can be done through this transformation.
3.2.2 Minimum path sets and cut sets solved by Petri nets. In the application of FTA, the downlink method is often used to search the minimum cut set, and its computation is very large, and the NP hard problem is usually happened. Petri net model simplified various FTA logic connections into place and transfer, the directed arc is used as the connection edge of the network, the fault model of manufacturing system is simple and easy to understand, what's more, graph theory can be used to analyse and deal with the problem of fault diagnosis. The main analysing methods of Petri net are reachability analysis and state equation, the state equation to describe the dynamic behaviour of Petri net, reflecting the state of the system changes and events; it is realized through marking change of Petri net. The state equation of Petri net is used to solve the minimal path set and minimal cut set, so as to reduce the computational complexity of the solution process.

Petri net can be represented as \( N = (P, T, F, W, M_0) \), \( P = \{p_1, p_2, \cdots, p_n\} \) is limited library collection; \( T = \{t_1, t_2, \cdots, t_m\} \) is a limited move set; \( F \subseteq (P \times T) \cup (P \times T) \) is the connection and transfer arc set library; \( W : F \{1, 2, 3, \cdots\} \) is weight function of directed arc; \( M_0 \) is the initial identification of libraries.

The state equation of the Petri net is:

\[
M_{k+1} = M_k + A^T x_k
\]

(10)

\( M_k, M_{k+1} \) — Marking of the net before and after ignition;

\( A \) — incidence matrix of net, \( A = \begin{bmatrix} a_{ij} \end{bmatrix}_{n \times m} \), \( a_{ij} = a_{ij}^+ - a_{ij}^- \), \( a_{ij}^+ = w(t_i, p_j) \), \( a_{ij}^- = w(p_j, t_i) \);

\( x_k \) — \( k \) ignition transfer sequence, consisting of 0, 1 column matrix;

Minimal cut set and path set were solved by state equation followed by four rules:

Rule 1: For the output library \( p_{out} \), \( \exists t_i (i = 1, 2, \cdots n) \) make \( \sum_t w(t_i, p_{out}) > 1 \), then all the import library \( \{p_m\} \) of \( \{t_i\} \) arranged horizontally;

Rule 2: For the output library \( p_{out} \), \( \exists t_i (i = 1, 2, \cdots n) \) make \( \sum_t w(t_i, p_{out}) = 1 \), then all the import library \( \{p_m\} \) of \( \{t_i\} \) listed vertically.

Rule 3: when all the libraries are replaced by basic library, the common elements in the row direction are expanded in the form of product to form the set of paths. The common elements in the column direction are expanded in the form of product to form the cut set matrix, when the matrix element is empty, it can be replaced by \( \emptyset \).
Rule 4: Eliminate superset of path sets matrix and cut set matrix, then minimum path sets and cut sets can be get.

3.3. Three-dimensional equipment reliability model of manufacturing system

3.3.1 Hierarchical modeling of equipment reliability in manufacturing systems

The equipment reliability of manufacturing system is divided into five levels, that is, system layer, cell layer, Petri net layer, FTA layer and functional structure layer, as shown in figure 5. Among them, the system layer represents the logic relationship of each manufacturing cell, the cell layer can get reliability of the equipment manufacturing unit through logic operation, Petri net layer using Petri net to find the minimum cut sets and the minimal path set, FTA layer will convert FTA into Petri net, functional structure layer can abstract function structure of equipment as FTA. The equipment reliability solving process of manufacturing system is shown in figure 6:

Manufacturing system has a lot of equipment and complex logical relations, it is necessary to follow the certain steps to obtain the whole reliability of the manufacturing system. It includes following five steps:

1) Build an FTA model of single equipment. FTA is a classic method to analyse the equipment failure and calculate equipment reliability, FTA model was built according to the function and structure of equipment. If the equipment structure is complex, FTA model can be built for each layer or block first, then each layer, each block, is logically combined into a complete FTA model of the equipment by logic relationship.

2) Build a Petri net of fault model for single equipment. Relative to FTA, Petri has the advantages of simple, intuitive and easy to calculate. If FTA was converted into Petri net, it is conducive to make a unified expression and calculation of system reliability according to the corresponding conversion symbol in table 1 or conversion algorithm by computer automatically.

3) Find the minimal path set and the minimum cut set. By using the constructed equipment Petri net, the minimal path set and minimum cut set of the fault are obtained according to the state equation of the Petri net, and then the reliability of the single equipment is obtained.

4) Obtaining equipment reliability of the manufacturing cell. The reliability of manufacturing cell is composed of each equipment reliability according to the logical relationship between equipment. According to the formula (1), (2), (3) , to calculate the reliability of manufacturing cell.

5) Calculate the overall equipment reliability of manufacturing system. Manufacturing system is made up of manufacturing cell according to the logical relation. The manufacturing cell can be regarded as the equivalent equipment composed of many equipment, according to the formula (4) and (5) , the overall equipment reliability of manufacturing system can be obtained.
4. Illustrative examples

4.1. Manufacturing system modeling
The flexible production line layout of an engine cylinder is shown in figure 7. In the production line, although only one VMC (vertical machining centre) can satisfy the production demand, for the higher equipment failure rate, two equipment were arranged to ensure the smooth production, namely VMC1 and VMC2, formed a parallel relationship. The crankcase and cylinder need to assembly after completion of processing, only the two equipment processing synchronous (their production quantity according to the assembly relationship is proportional), the production line will not be affected. If a MC fails and affect production, the follow-up process will be affected, so the cylinder processing (including VMC1, VMC2, HMC (Vertical machining centre) 1, HMC2 and HMC3) has series with crank manufacturing (including VMC3, VMC4, HMC4, HMC5). In addition, equipment such as cleaning, air tightness, cylinder closing, inspection, decomposition and packing are seldom broken down, which can be simplified for convenience of modelling. As a result, the entire manufacturing system can be simplified and rearranged, as shown in figure 8.

![Figure 7. Engine cylinder manufacturing system](image1)

![Figure 8. Simplified and rearranged cylinder manufacturing system](image2)

According to the logical arrangement of the equipment shown in Fig. 8, a Petri net chain of the cylinder manufacturing process can be constructed, as shown in figure 9.

![Figure 9. Petri nets model of cylinder manufacturing system](image3)

4.2. Equipment reliability calculation of manufacturing system
The reliability of manufacturing system is composed of manufacturing cells (MCs), and the reliability of manufacturing cell is composed of equipment reliability. Therefore, in order to obtain the reliability of equipment in manufacturing system, the reliability of each equipment must be required. Limited to space, VMC1 is selected to demonstrate the reliability of single equipment based on Petri nets.

First, build the device FTA model, as shown in figure 10. A fault Petri net model of VMC1 is constructed in accordance with the comparative relationship in Table 2, as shown in Figure 11, the meaning of the fault code and the state equation are shown in Table 3 and 4.
Figure 10. FTA model of VMC1

Table 3. Fault code of VMC1.

| No. | Failure events                      | No. | Failure events                      |
|-----|-------------------------------------|-----|-------------------------------------|
| TOP | Crystallizer cannot be used         | X8  | Clasp is not installed correctly    |
| E1  | Crystallizer steel leakage          | X9  | Crystallizer copper tube thermal deformation |
| E2  | Crystallizer structure              | X10 | Crystallizer copper tube measurement error |
| E3  | Crystallizer steel spill            | X11 | Crystallizer copper tube steel      |
| E4  | Crystallizer taper is wrong         | X12 | Molten steel temperature is low     |
| E5  | Molten steel temperature is low     | X13 | Bag cover not down                  |
| E6  | Mechanism is not normal             | X14 | Nozzle brick wall steel             |
| E7  | Tundish molten steel 1 temperature is low | X15 | Mechanism not to close             |
| E8  | Mechanism not installed correctly   | X16 | Tundish is not removed in time      |
| E9  | Baking temperature is low           | X17 | Tundish permanent lining high cooling rate |
| X1  | A cold water valve                  | X18 | Tundish ladle cover deformation     |
| X2  | Foot-roller radian is wrong         | X19 | Stopper is not vertical             |
| X3  | Steel hang on the Crystallizer      | X20 | Stopper screw is not vertical       |
| X4  | Vibration don't start               | X21 | Stopper mechanism is not separated  |
| X5  | Emergency knife don't start         | X22 | Tundish nozzle failure              |
| X6  | Casting curve setup is not correct  | X23 | Stopper refractory not fully baked  |
| X7  | Co60 zero drift                    | X24 | Burning medium supply failure      |

Table 4. State equation of fault Petri nets for VMC1.

\[
\begin{bmatrix}
X_4 & X_6 & X_{10} & X_{11} & X_{15} & X_{17} & X_{22} & X_{18} & X_{13} & X_{14} & X_5 & X_6
X_1 & X_3 & X_4 & \emptyset & \emptyset & \emptyset & \emptyset & \emptyset & X_6 & X_7
X_2 & X_5 & X_6 & \emptyset & \emptyset & \emptyset & \emptyset & \emptyset & X_7 & X_8
\emptyset & \emptyset & \emptyset & \emptyset & \emptyset & \emptyset & \emptyset & \emptyset & \emptyset & X_8 & X_9
\emptyset & \emptyset & \emptyset & \emptyset & \emptyset & \emptyset & \emptyset & \emptyset & \emptyset & \emptyset & X_9 & X_{10}
\end{bmatrix}
\]

In the cut set matrix, the minimum cut set is formed when the other cut sets is removed as the set of the elements, and finally the FTA minimum cut set of the stainless square billet caster mould is obtained, there are 13 in all:
\{X_8, X_1, X_2\}, \{X_9, X_1, X_2\}, \{X_10, X_1, X_2\}, \{X_11, X_1, X_2\}, \{X_16, X_3,
Table 5. Minimum cut sets probability tables of VMC1.

| Minimum cut sets | Probability  | Minimum cut sets | Probability  | Minimum cut sets | Probability  |
|------------------|-------------|------------------|-------------|------------------|-------------|
| \{X_9, X_1, X_2\} | 2.00×10^{-5} | \{X_{18}, X_1, X_4\} | 7.00×10^{-6} | \{X_5, X_6, X_{15}, X_7\} | 5.40×10^{-7} |
| \{X_{10}, X_1, X_2\} | 1.50×10^{-5} | \{X_{12}, X_3, X_4\} | 5.00×10^{-6} | \{X_{22}, X_{23}, X_{24}, X_3, X_4\} | 8.00×10^{-9} |
| \{X_8, X_1, X_2\} | 1.00×10^{-5} | \{X_{14}, X_3, X_4\} | 4.00×10^{-6} | \{X_5, X_6, X_{19}, X_{20}, X_{21}, X_7\} | 3.78×10^{-10} |
| \{X_{17}, X_1, X_4\} | 8.00×10^{-6} | \{X_{16}, X_1, X_4\} | 3.00×10^{-6} | \{X_5, X_6, X_{15}, X_7\} | 7.50×10^{-6} |
| \{X_{11}, X_1, X_2\} | 7.50×10^{-6} | \{X_{13}, X_3, X_4\} | 2.00×10^{-6} | \{X_5, X_6, X_{15}, X_7\} | 3.78×10^{-10} |

Probability of top event occurrence is 8.20×10^{-5}, it can be gained by operation results, namely the probability that crystallizer cannot be use is 8.20×10^{-5}, that is, the failure rate is 0.95.

Referring to the solving process of VMC2, the failure rate of each equipment in the manufacturing system can be obtained, as shown in table 6.

Table 6. Failure rate of each equipment.

| Equipment   | VMC1 | VMC2 | VMC3 | VMC4 | HMC1 | HMC2 | HMC3 | HMC4 | HMC5 | HMC6 | QM |
|-------------|------|------|------|------|------|------|------|------|------|------|----|
| Failure rate| 0.95 | 0.93 | 0.92 | 0.96 | 0.91 | 0.89 | 0.92 | 0.96 | 0.91 | 0.98 | 0.93 |

Take each equipment failure rate into formula (1), (2):

MC1 has two parallel equipment, VMC1 and VMC2, its reliability $R_{c1} = 1 \times (1 - 0.95) \times (1 - 0.93) = 0.9965$, MC2 has three series equipment, HMC1, HMC2 and HMC3, its reliability $R_{c2} = 0.91 \times 0.89 \times 0.92 = 0.7451$, and MC3 has four series equipment, VMC3, VMC4, HMC4 and HMC5, its reliability $R_{c3} = 0.92 \times 0.96 \times 0.96 \times 0.91 = 0.7716$. MC4 has two parallel equipment, HMC6 and Quilting Machine, its reliability. $R_{c4} = 0.98 \times 0.93 = 0.9114$. Then MC1 series with and MC2, MC3 and MC4, so the overall reliability of the equipment in manufacturing system is:

$R = R_{c1} \times R_{c2} \times R_{c3} \times R_{c4} = 0.9965 \times 0.7451 \times 0.7716 \times 0.9114 = 0.5221$

5. Conclusions

The modelling method of manufacturing system using powerful modelling function of Petri net, combining macro and micro analysis of manufacturing system, using Petri net logic relation and its reduction method to express chain structure of equipment network in manufacturing process, introducing FTA to express the hierarchical structure of a single equipment on network node and converting it into a Petri net, and integrating these two methods under the Petri net, and expressing the whole equipment reliability of manufacturing system in a three-dimensional way, the modelling process is simple, intuitive and efficient. Of course, this method has be merged with traditional research fields of reliability, such as fault analysing and positioning, fault generation and transmission mechanism, fault knowledge acquisition and use, fault hazard classification and processing, etc. In order to play a comprehensive analysis and protection equipment reliability of manufacturing system, they will be incorporated into the three-dimensional modelling framework of Petri net. In addition, the proposed three-dimensional modelling method has strong versatility and can be widely applied to the analysis and modelling of complex systems.

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