Modeling and Performance Analysis of Manufacturing Execution System Based on Petri Net

Mo Taiping[1,*] and Zhao Peisi[2]

[1]School of Mechano-electronic Engineering, Xidian University, Xi'an 710071, China; [2]School of Electronic Engineering & Automation, Guilin University of Electronic Technology, Guilin 541004, China

Abstract: The current Manufacturing Execution System (MES) has many weaknesses, such as poor generality, weak reconfigurability and difficult performance analysis. In order to solve these problems, a functional decomposition diagram was designed based on the functional requirements of MES, and a general petri net model was also established. The complexity and junction features of the model were analyzed based on Petri nets, and the network core layer and system reliability were gotten after the model was transformed to the undirected network diagram. Finally, the best system scheme for different selections was given based on the analysis of reliability.

Keywords: Complexity, manufacturing execution system, modeling, Petri nets, reliability.

1. INTRODUCTION

With the application fields expansion of information system, the scope and complexity of the system is increased greatly. The system includes a large amount of problems upon engineering, technology and efficient allocation of resources. It is different to deal with the top design and make sufficient research, analysis and discussion by virtue of experience. The MES manages the whole manufacturing system according to the production plan, material management strategy, quality standard, quality inspection method and the cost accounting method established by the management department. In addition, it supervises and controls the various links in real-time, so as to achieve the integrative, informationalized and transparent effect on manufacturing process management. However, the current MES has poor generality in the industry, but also there is no convenient way to analyze the complexity and feasibility during the early stage of MES development. In order to solve these problems, a general MES model should be established.

As a formalized description tool, Petri net [1-8] provides formal modeling methods base on graphics and mathematics, and it plays a key role in the process of modeling and performance analysis of complex network system, so the Petri model is estimated in this paper to solve the MES problems.

2. KEY FUNCTION OF MES

MES is a process oriented software management systems, and it plays key role in the three-layer enterprise integration model and it connects the Enterprise Resource Planning Systems (ERP) in the upper layer and the Process Control Systems (PCS) in the lower layer. Manufacturing Execution System Association (MESA) defines functions of the MES function models as: a detail process scheduling, resource allocation and state management, production element allocation, process management, human resource management, maintenance management, quality management, document control, product tracking and product inventory management, performance analysis and data acquisition functions [5]. The MES core functions include production scheduling management, product tracking, material management, process quality management, product storage and shipping and basic production data collection and analysis.

3. THE PETRI NET MODEL OF MES

According to the above-mentioned functions and structure of MES, MES's overall business processes are as follows:

1) Make the corresponding plans according to the sales plan, production process, manufacturing resources and the production mode;

2) Manage the workshop materials according to the storage management strategy, material management mode of production, productive task, input and output information;

3) Develop appropriate online quality management strategy based on quality standards and test methods;

4) Manage production costs based on hours of work, production methods, basic statistics and cost accounting methods;

5) Summarize the system data, including the production statements, material statements, quality statements and production cost statements;

6) Submit statistics and aggregated data, analyze production status.

3.1. System Interface Specification

MES external environment includes ERP, Supply Chain Management (SCM), Product Data Management (PDM) and PCS. According to the business process above, the interface elements should include:

I_1: Marking plan; I_2: Data for each unit; I_4: Production process; I_5: Manufacturing resource; I_6: Mode of production; I_7: Finished goods inventory report; I_8: Quality standards; I_9: Detection method; I_{10}: Cost accounting methods; I_{11}: Production report; I_{12}: Material inventory report; I_{13}: Quality report; I_{14}: Production cost report; I_{15}: Plan reports; I_{16}: Plan change notice; I_{17}: Device report

MES interface is described in Fig. (**1**).

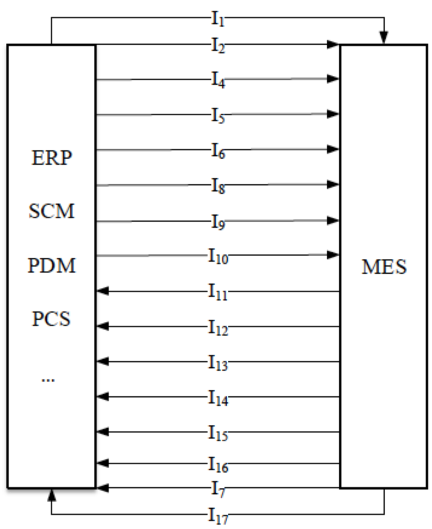

Fig. (1). MES interface description.

3.2. Definition of MES Function Module

Function is one of the basic elements of an information system model. During the design process of information system, the system implementation objectives must be clear. The objectives can be described with the function definition. According to MES business flow diagram, the MES function model can be defined as shown in Fig. (**2**).

Assumes that the leaf node of the system basic function represents a set T_S, According to the MES function models from Fig. (**2**), T_S, can be described as follows:

$$T_S = \{t_{S11}, t_{S12}, t_{S13}, t_{S21}, t_{S22}, t_{S23}, t_{S24}, t_{S31}, t_{S32}, t_{S33}, t_{S41}, t_{S42}, t_{S43}, t_{S441}, t_{S442}, t_{S443}, t_{S444}, t_{S45}, t_{S51}, t_{S52}, t_{S53}, t_{S54}, t_{S6}, t_{S71}, t_{S72}, t_{S73}, t_{S74}, t_{S81}, t_{S82}\}$$

3.3. Internal Resource Constraints of MES

Information resources is mainly the data, information carrier and related equipment for system operation. In order to improve the utilization of information resources and to facilitate the management and maintenance of information resources, it is necessary to configure all kinds of information resources in the system reasonably.

3.3.1. The Definition of Information Resource set P_S

Based on MES process, the main information resources are as follows:

P_{11}: Operational plan; P_{21}: Production data statistics; P_{22}: Product login information;

P_{23}: Product offline information; P_{25}: Production data of workshop;

P_{31}: Flaw classification information; P_{32}: Flaw classification list; P_{33}: Quality statistics;

P_{41}: Equipment information; P_{43}: Equipment information card;

P_{44}: Equipment check application form; P_{45}: Equipment check statements;

P_{46}: Equipment operating state information; P_{48}: Equipment status report;

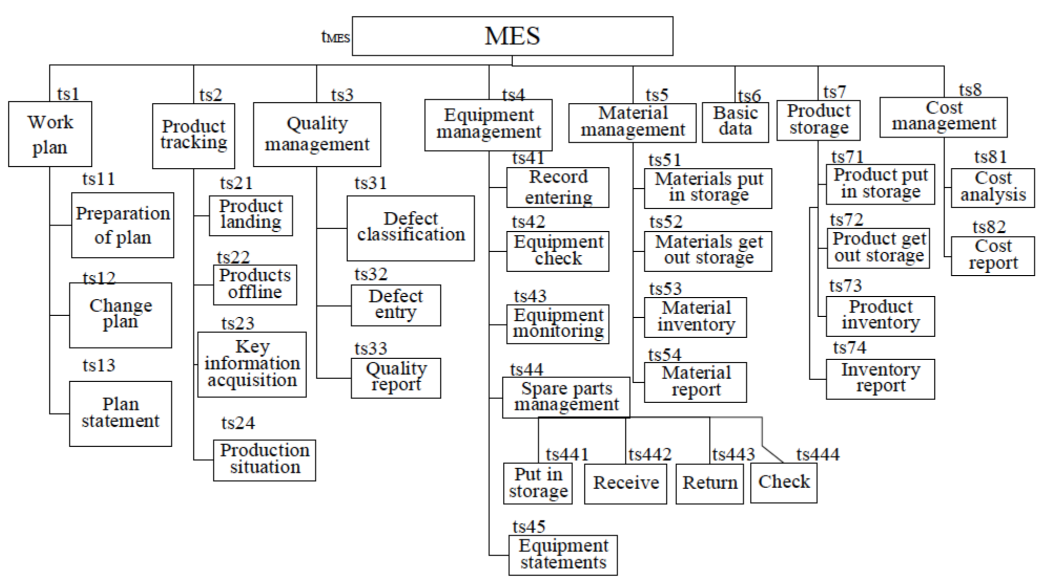

Fig. (2). Functional decomposition diagram of MES.

P_{51}: Material management strategy; P_{52}: Material inventory information;

P_{53}: The output material documents; P_{54}: The warehouse warrant and delivery order of material;

P_{57}: Goods Receiving Note; P_{61}: Spare parts acceptance application form;

P_{62}: Information of spare parts being used; P_{63}: Spare parts inventory;

P_{64}: The warrant and delivery order of spare parts store;

P_{71}: Warehouse warrant of finished products; P_{72}: Inventory information of finished goods;

P_{73}: Delivery order of finished goods; P_{74}: Product inventory list;

P_{81}: Cost analysis and statistics.

Thereby we obtain the set of information resources P_S:

$$P_S = \{P_{11}, P_{21}, P_{22}, P_{23}, P_{25}, P_{31}, P_{32}, P_{33}, P_{41}, P_{43}, P_{44}, P_{45}, P_{46}, P_{48}, P_{51}, P_{52}, P_{53}, P_{54}, P_{57}, P_{61}, P_{62}, P_{63}, P_{64}, P_{71}, P_{72}, P_{73}, P_{74}, P_{81}\} + \{I_1, I_2, I_4, I_5, I_6, I_7, I_8, I_9, I_{10}, I_{11}, I_{12}, I_{13}, I_{14}, I_{15}, I_{16}, I_{17}\}$$

3.3.2. The Definition of Resource Constraints set P_T for T_S

The set of the constrained subset of the used resource by each function model is called the system information resource constraint set [8], which is expressed by T_S. Based on the system model, we get the system information resource constraint set P_T:

$$P_T = \{P_{ts11}, P_{ts12}, P_{ts13}, P_{ts21}, P_{ts22}, P_{ts23}, P_{ts24}, P_{ts31}, P_{ts32}, P_{ts33}, P_{ts41}, P_{ts42}, P_{ts43}, P_{ts441}, P_{ts442}, P_{ts443}, P_{ts444}, P_{ts45}, P_{ts51}, P_{ts52}, P_{ts53}, P_{ts54}, P_{ts6}, P_{ts71}, P_{ts72}, P_{ts73}, P_{ts74}, P_{ts81}, P_{ts82}\}$$

In the formula,

$P_{ts11} = \{I_1; P_{11}\}$, $P_{ts12} = \{P_{11}; P_{11}, I_{15}, I_{16}\}$, $P_{ts13} = \{P_{11}; I_{15}\}$,
$P_{ts21} = \{I_4, I_5, I_6, P_{11}, P_{25}; P_{22}\}$, $P_{ts22} = \{I_5, P_{25}; P_{23}\}$,
$P_{ts23} = \{P_{22}, P_{23}; P_{21}\}$, $P_{ts24} = \{P_{21}; I_{11}\}$, $P_{ts31} = \{P_{31}; P_{32}\}$,
$P_{ts32} = \{I_8, I_9, P_{23}, P_{31}; P_{33}\}$, $P_{ts33} = \{P_{33}; I_{13}\}$, $P_{ts41} = \{P_{41}; P_{43}\}$,
$P_{ts42} = \{P_{43}, P_{44}; P_{45}\}$, $P_{ts43} = \{P_{46}; P_{48}\}$, $P_{ts441} = \{P_{61}; P_{63}\}$,
$P_{ts442} = \{P_{63}; P_{62}\}$, $P_{ts443} = \{P_{62}; P_{63}\}$, $P_{ts444} = \{P_{62}; P_{64}\}$,
$P_{ts45} = \{P_{45}, P_{48}, P_{64}; I_{17}\}$, $P_{ts51} = \{P_{51}, P_{57}; P_{52}\}$,
$P_{ts52} = \{P_{51}, P_{52}; P_{52}, P_{53}\}$, $P_{ts53} = \{P_{52}, P_{53}, P_{57}; P_{54}\}$,
$P_{ts54} = \{P_{54}; I_{12}\}$, $P_{ts6} = \{I_2; I_{25}, I_{31}, P_{41}, P_{51}\}$,
$P_{ts71} = \{P_{11}, P_{71}; P_{72}\}$, $P_{ts72} = \{P_{72}; P_{72}, P_{73}\}$,
$P_{ts73} = \{P_{71}, P_{73}; P_{72}, P_{74}\}$, $P_{ts74} = \{P_{72}, P_{74}; I_7\}$,
$P_{ts81} = \{I_6, I_{10}, P_{21}, P_{53}; P_{81}\}$, $P_{ts82} = \{P_{81}; I_{14}\}$.

3.4. Integration of Petri Net Model

Based on Petri net theory, in view of the MES system, a basic concept model between the actual problem and the system model is established. The model can be used to describe and analyze the MES system efficiently and quickly.

With the relevant theories of Petri net modeling, the Petri nets model of MES can be established as showed in Fig. (**3**). All the nodes elements in the graph are defined previously.

4. PERFORMANCE ANALYSIS OF MES SYSTEM MODEL

4.1. Analysis of Model Complexity

The MES system complexity is the complex characteristics in the elements, structure, status and process, etc. The relationship between the elements and structure reflects the static structure characteristics of the system, and the status and process characteristics depict the dynamic behavior of the system [7].

Setting the system complexity of the elements as C_n, the correlation complexity of the system as C_r, structural complexity as C_S. Since the influence of C_n and C_r on the structural complexity is different and the correlation coefficient between C_n and the system structural complexity is λ, then [4]

$$C_S = \lambda C_n + (1-\lambda) C_r \quad (1)$$

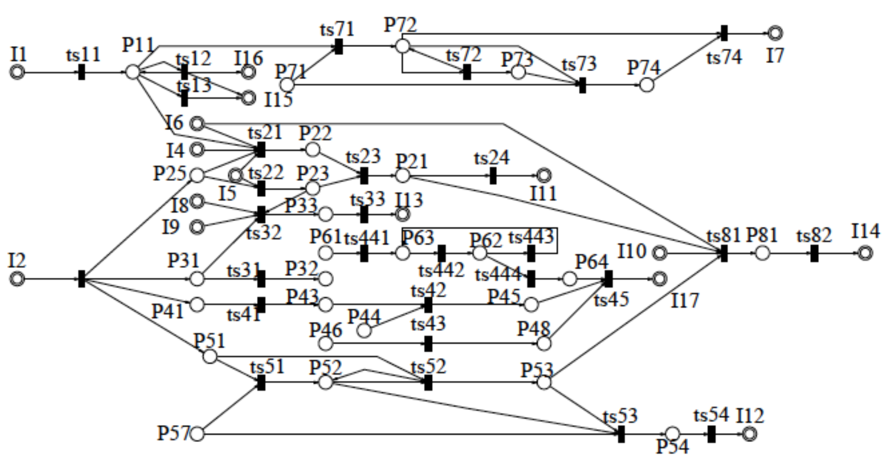

Fig. (3). Petri nets model H_1 of MES.

In the MES Petri net model, the node is the element of the system, the influence of the node on system complexity can be described as the ratio between the number of in-arcs and out-arcs of the node and the total number of network connections arcs, that is

$$\lambda = \frac{1}{|T|+|P|}\sum_{i=1}^{|T|+|P|}\left(\frac{|{}^{\bullet}x_i|+|x_i^{\bullet}|}{|X|}\right) \quad x_i \in X \tag{2}$$

$|X|$ represents the number of elements in set X.

When we use Petri nets model to describe the MES, the elements complexity C_n is the function of location (Place) and transition nodes number in Petri model, set C_n as

$$C_n = \frac{1}{2}\left(\frac{|P|-1}{|P|}+\frac{|T|-1}{|T|}\right) \tag{3}$$

If $|P| = m$, $|T| = n$, then

$$C_n = \frac{1}{2}\left(\frac{m-1}{m}+\frac{n-1}{n}\right) = \frac{2mn-m-n}{2mn} \tag{4}$$

In Petri net, when any position node p_i is the enter location of two or more transition nodes $t_j\left(j=1,\ 2,\ \cdots,n\right)$, as $p_i \in \left({}^{\bullet}t_1 \cap {}^{\bullet}t_2 \cap \cdots\right)$, $|p_i^{\bullet} > 1|$, there is a conflict structure, denoted as $K_i = \langle p_i\{t_1,t_2,\cdots\}\rangle$. Conflict will cause the system behavior uncertainties, that is, the resources competition of the conflict structure makes it complicated to manage and control the system resources. So it is necessary to analyze the correlation complexity of the allocation, generation and use of the resource.

Definition 1 [2] Set the correlation complexity of any node p_i in Petri net as c_{pi} , then

$$c_{pi} = \frac{|p_i^{\bullet}|}{|{}^{\bullet}p_i|+|p_i^{\bullet}|} \tag{5}$$

From Definition 1, the correlation complexity C_P of location set P can be derived as:

$$C_P = \frac{1}{|P|}\sum_{i=1}^{|P|}\frac{|p_i^{\bullet}|}{|{}^{\bullet}p_i|+|p_i^{\bullet}|} = \frac{1}{m}\sum_{i=1}^{m}\frac{|p_i^{\bullet}|}{|{}^{\bullet}p_i|+|p_i^{\bullet}|} \tag{6}$$

Similarly, the correlation complexity C_T of transition set in Petri net can be defined as

$$C_T = \frac{1}{|T|}\sum_{j=1}^{|T|}\frac{|{}^{\bullet}t_j|}{|{}^{\bullet}t_j|+|t_j^{\bullet}|} = \frac{1}{n}\sum_{j=1}^{n}\frac{|{}^{\bullet}t_j|}{|{}^{\bullet}t_j|+|t_j^{\bullet}|} \tag{7}$$

Then the entire MES Petri net structure complexity C_r can be expressed as the average value of location set correlation complexity and transition set correlation complexity, as

$$C_r = \frac{C_P + C_T}{2} \tag{8}$$

From the Petri net model of MES system in Fig. (**3**) and the above definitions, the Petri net structural complexity of MES can be analyzed.

The number of elements in Place node set is $|P| = m = 28$

The number of elements in Transition node set is $|T| = n = 29$

The set of directed arc in net is $|F| = 88$

The number of the node set whose pre-set and post-set are not empty is $|X| = 48$

According to the above parameters and related definitions, the value of C_n , λ , C_P , C_T , C_r , C_S can be obtained respectively as Table **1**.

Table 1. Result of experiments and theory.

Parameter Name	C_n	λ	C_P	C_T	C_r	C_S
Value	0.96	0.03	0.62	0.48	0.55	0.56

The structure correlation complexity of the Petri net is mainly determined by C_r , and the relationship between correlation structural condition and C_r is shown in Table **2**. By the value of C_r in Table **1** and the criteria in Table **2**, it is easy to see that MES system is a correlation system with certain complex structures.

Table 2. The relationship between Petri net correlation structural and C_r .

The Range of C_r	Correlation Complexity
1	Maximum
0	Minimum
$0 < C_r < 1/2$	Correlation structure simple
1/2	Correlation structure ideal
$1/2 < C_r < 1$	Correlation structure complex

4.2. Characteristics of the Model Node

The main influence factor of an information system is the change of technology and demand environment. Therefore, scalable functionality is the basic requirements of modern enterprise information system. However, the function can't exist separately from the structure. So, we need to discuss the relationship among the elements of the various components of MES systems.

The influence of each node on the system can be analyzed and defined by the relationship between the node and other nodes in the system. And the coupling strength is used to measure the influence of each node at different locations on the system performance. This feature needs to be obtained by analyzing the relationship between one node and other nodes. Coupling strength is defined as follows:

Definition 2 [2] Suppose $x_i \in P \cup T$ is any node on the net, $\left|{}^{\bullet}x_i\right| \neq 0 \wedge \left|x_i^{\bullet}\right| \neq 0$. $d(x_i)$ is the coupling strength of the node x_i on the net, as

$$d(x_i) = \frac{1}{2}\left(\frac{|Mx_i|}{M_S} + \frac{|R_{\max}(x_i)|}{|X|}\right). \tag{9}$$

Among them, Mx_i is the set of all mesh correlated with the node x_i; $R_{max}(x_i)$ is the maximum one among the sum of x_i's pre-set and post-set and the set of other nodes related to node x_i in the largest mesh; $|X|$ is the number of the node set whose pre-set and post-set are not empty.

Not considering the elements of the interface, according to the Petri net model on Fig. (**3**), the number of mesh M_S in the figure is 13, illustrated in Fig. (**4**). Analyzing the information resource set and feature set without interface nodes in H_1, we get coupling strength of each node $d(x_i)$ and heavy weight node x_i^* (Node's coupling strength is greater than the average of coupling strength) [6], as shown in Fig. (**5**).

Fig. (**5**) shows the average coupling strength for each node $D_\Sigma = 0.08$, so we get the set of these key function nodes T_k and the set of these key resource nodes P_k:

$$T_k = \{t_{s21}, t_{s22}, t_{s23}, t_{s32}, t_{s51}, t_{s52}, t_{s53}, t_{s6}, t_{s72}, t_{s73}, t_{s81}\}$$

$$P_k = \{P_{21}, P_{22}, P_{23}, P_{25}, P_{31}, P_{51}, P_{52}, P_{53}, P_{71}, P_{72}, P_{73}\}$$

Therefore, in the daily maintenance and adjustment process, for the above key functions nodes and key resource nodes we should try to avoid or reduce the appropriate modifications to ensure the stability and reliability of the system operation.

4.3. The Core Layer of Petri Net and Reliability Analysis

For any information system applied to manufacturing, there must be one or more elements playing a decisive role on the system structure and performance. Under normal circumstances, we map the Petri net model of the MES systems as two types of undirected network diagram with weighted nodes and sides at the same time. According to the definition in [2] literature, we can analyze the MES Petri core network and the reliability of the system by solving the kernel and kernel degree of directed network system in the MES Petri network.

The transition node directed network graph D_t and the place node directed network graph D_p of MES information resource configuration model is shown in Fig. (**6**).

As shown in Fig. (**6**), the weighted kernel degree and weighted kernel of the two weighted undirected net graphs G_t and G_p corresponding with D_p and D_t are as follows:

$$h(G_t) = 1, \delta^*(G_t) = (\{t_{s11}, t_{s71}, t_{s74}, t_{s6}, t_{s21}, t_{s23}, t_{s81}, t_{s51}, t_{s52}\}, \{t_{s11}t_{s71}, t_{s71}t_{s74}, t_{s6}t_{s21}, t_{s21}t_{s23}, t_{s23}t_{s81}, t_{s6}t_{s51}, t_{s51}t_{s52}, t_{s52}t_{s81}\})$$

$$h(G_p) = 1, \delta^*(G_p) = (\{P_{11}, P_{72}, P_{25}, P_{22}, P_{21}, P_{51}, P_{52}, P_{53}\}, \{P_{11}P_{72}, P_{11}P_{22}, P_{25}P_{22}, P_{22}P_{21}, P_{51}P_{52}, P_{52}P_{53}\})$$

The weighted kernel and the weighted kernel degree of MES are

$$h(H) = h(G_t) + h(G_p) = 1 + 1 = 2$$

$$\delta^*(H) = \delta^*(G_t) \cup \delta^*(G_p) = (\{t_{s11}, t_{s71}, t_{s74}, t_{s6}, t_{s21}, t_{s23}, t_{s81}, t_{s51}, t_{s52}, t_{s81}, P_{11}, P_{72}, P_{25}, P_{22}, P_{21}, P_{51}, P_{52}, P_{53}\}, \{t_{s11}t_{s71}, t_{s71}t_{s74}, t_{s6}t_{s21}, t_{s21}t_{s23}, t_{s23}t_{s81}, t_{s6}t_{s51}, t_{s6}t_{s52}, t_{s51}t_{s52}, t_{s52}t_{s81}, P_{11}P_{72}, P_{11}P_{72}, P_{25}P_{22}, P_{22}P_{21}, P_{51}P_{52}, P_{52}P_{53}\})$$

The core of the Petri net model described by $\delta^*(H)$ is showed in Fig. (**7**).

Fig. (**7**) is the more central network H_2 relative to Fig. (**3**). In the process of model design and test implementation, we should ensure the reachability and soundness of this level network firstly, then we can design a reliable system more efficient and fast.

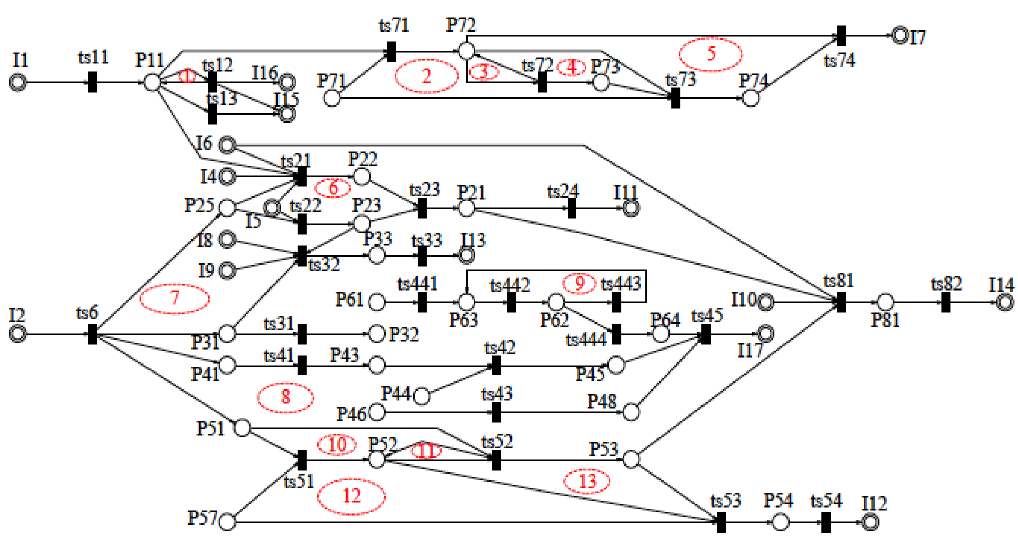

Fig. (4). Meshes in the Petri net model of MES.

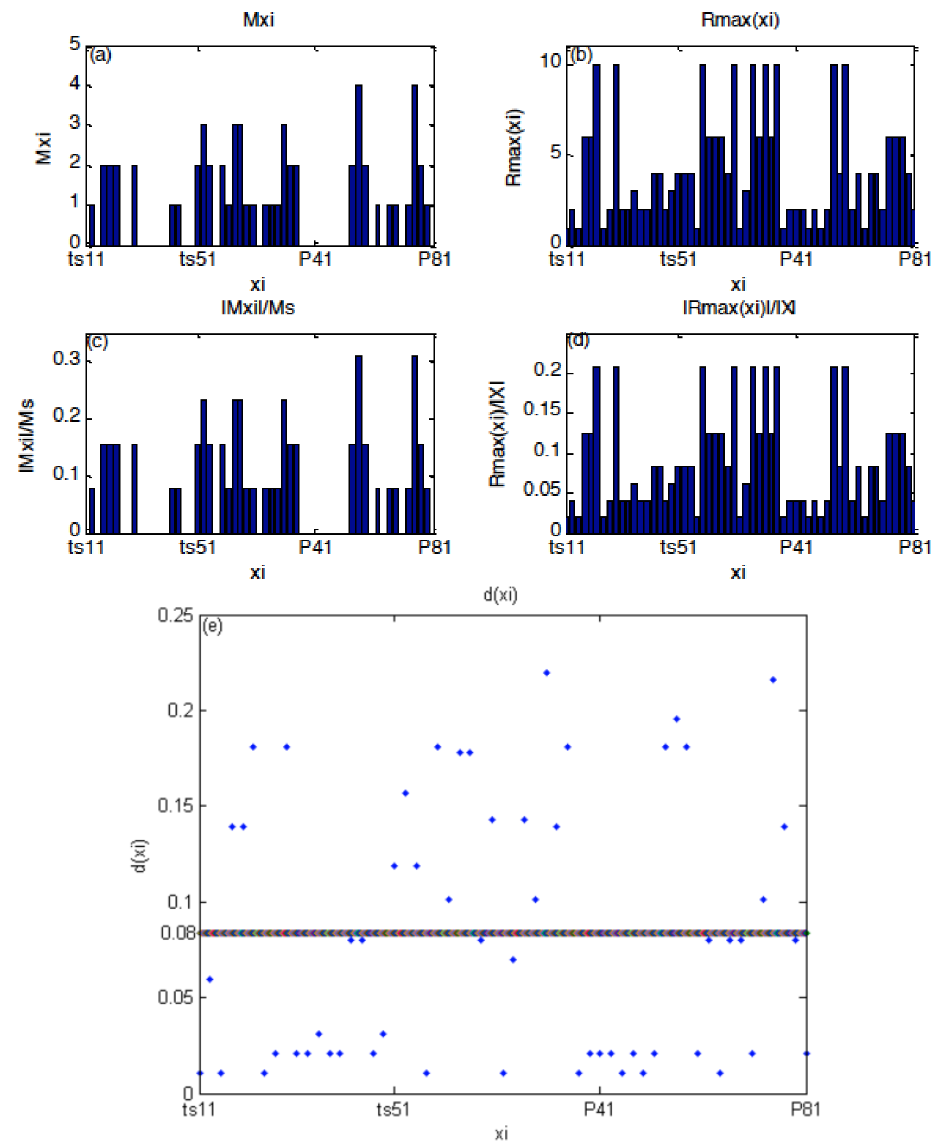

Fig. (5). (**a**) The mesh set of each node; (**b**) The sum of pre-set & post-set; (**c**) The mesh set weight of each node; (**d**) The weight of the sum of pre-set & post-set; (**e**) Coupling strength of each node.

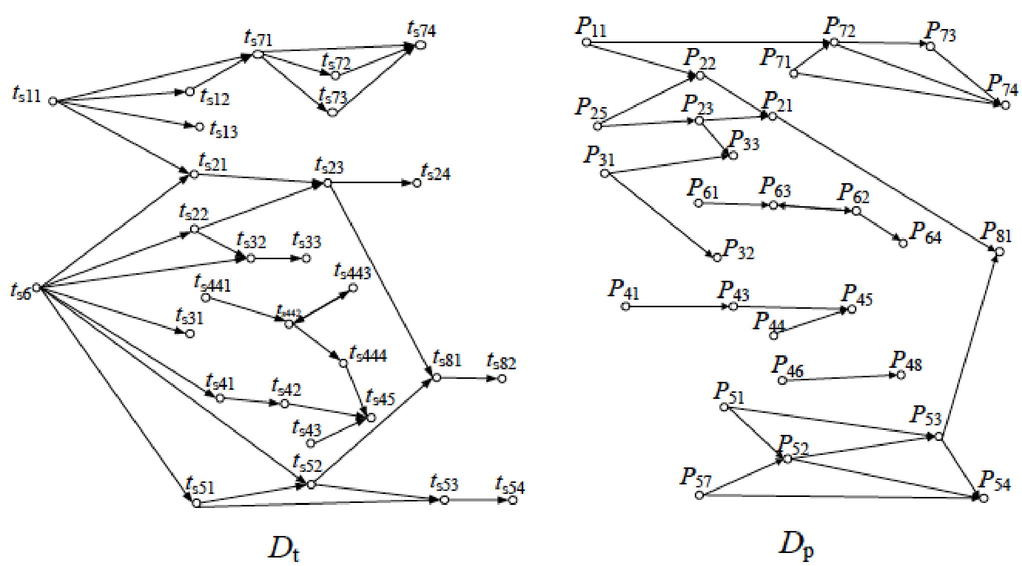

Fig. (6). Two types of directed network graphs of MES resource allocation model.

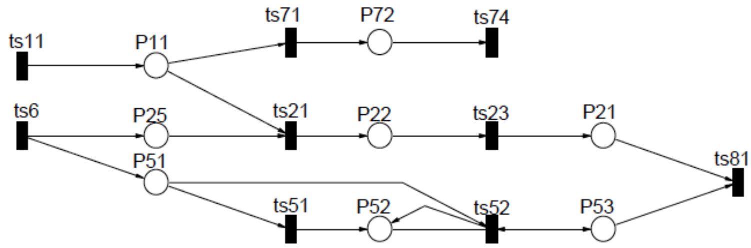

Fig. (7). The core layer network model H2 of MES.

If we do further analysis to network H_2, we can get the "core" of the core layer: $H_3 = \delta^*(H_2)$, as shown in Fig. (**8**). Its practical significance is the analysis reports about the system output production when the system inputs basic data.

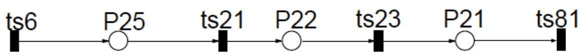

Fig. (8). The highest core network diagram H_3 of MES.

The reliability of the system is one of the important indicators of system. For the system composed with various elements, the reliability of the system can be measured with the reliability of the various elements. Set the reliability of the system as $R_s(t)$, the reliability of the various elements as $R_i(t),(i=1,2,\cdots,n)$, then the relationship between the series system and the parallel system can be shown as follows:

$$R_s(t) = \prod_{i=1}^{n} R_i(t) \tag{10}$$

$$R_s(t) = 1 - \prod_{i=1}^{n} \left(1 - R_i(t)\right) \tag{11}$$

For general redundant system, the two same devices parallel to form a unit, then the equipment reliability with dual redundant can be obtained by (12):

$$R_r(t) = 1 - \left(1 - R(t)\right)\left(1 - R(t)\right) = 2R(t) - R^2(t) \tag{12}$$

Assume that the important degree of each network layer node is I_j, the important degree of the most basic network node I_1 is 1, and the node important degree add 1 when the network increases one layer, so $I_j = j$, and the important degree of all nodes I_S is

$$I_S = \sum_{j=1}^{m} I_j \left| H_j - H_{j+1} \right| \tag{13}$$

The reliability allocation ratio K_j for each network layer is

$$K_j = \frac{I_j \left| H_j - H_{j+1} \right|}{I_S} \times 100\% \tag{14}$$

According to the definition of core degrees, we can see that each layer of network structure maintains its own connectivity. The operation of one layer cannot be affected by the fault of any another layers, so we assume that the reliability of each network layer is $R_i(t)$, and then the overall reliability of the system is expressed approximately as

$$R_s(t) = \sum_{j=1}^{m} R_i(t) K_j \tag{15}$$

The reliability $R_i(t)$ of each network layer can be calculated depending on the situation by (10) and (11).

Assume that the reliability of 57 nodes running separately in Fig. (**4**) are $R_i(t) = 98\%$ (i=1,2,…,57), then the Petri net model of MES can be decomposed into three network layer: H_1 in Fig. (**3**), H_2 in Fig. (**7**) and H_3 in Fig. (**8**), the corresponding important degree I_j and reliability allocation proportion K_j as shown in Table **3**.

According to calculation results in Table **3**, we obtained the system required equipment and corresponding reliability comparison table based on four different redundancy schemes, as showed in Table **4**.

Table 3. Important degree and reliability comparison of three network layers.

Level	H_1	H_2	H_3
$\lvert H_j\rvert - \lvert H_{j+1}\rvert$	40	10	7
I_j	1	2	3
K_j	49.3%	24.7%	26.0%

From Table **4**, we know that the system reliability order of the four system redundancy schemes are ②③④① from high to low. Considering the case of less equipment and high reliability, our choice is Scheme ④. In case of allowed charges, we choose Scheme ③.

As can be seen from reliability analysis process of the system, the conclusive influence on the reliability of the system is not only the reliability of each node, but also the importance and reliability of each core level in the system. So, before the system design, we should design a preliminary system model according to the actual demand of function and performance, then we should analyze and improve the system core layer further to meet the requirements of reliability and funds.

CONCLUSION

Based on the functional structure of MES, a Petri net model is established according to the relationship between the function nodes and the resource nodes, then the reliability and complexity of the model was analyzed according to reliability analysis theory and graph theory methods.

Table 4. Important degree and reliability comparison of three network layers.

Redundancy Scheme	Device Number *n*	Reliability Degree R_S (%)	Scheme Comparison	Added Value of Equipment Number (%)	Added Value of Reliability (%)
① No node is redundant	57	0.03			
② All nodes are redundan	114	97.5	②:①	100	50.4
③ Nodes in H_2 are redundant	74	72.2	③:①	29.8	11.4
			③:②	-35.0	-25.9
④ Nodes in H_3 are redundant	64	68.0	④:①	12.3	4.9
			④:②	-43.8	-30.2
			④:③	-13.5	-5.8

From the analysis results, we can see that the MES system model has certain complexity, and the MES Petri net model can make a good description of the relationship between each functional component of MES, and it provides a good model design basis for the early development of MES software. For the reliability analysis, the main characteristics of the model can be clearly presented by the network core layer, but the core layer H_2 still has some limitation, and it cannot reflect the characteristics of the core layer from the best angle. So, in the future study, we need to improve H_2, deeply to maximize the response model characteristics and increase the model reliability further.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

ACKNOWLEDGEMENTS

Declared none.

REFERENCES

[1] X. G. Li, C. B. Li, F. Liu, and L. L. Li, "Modeling and quantification methods for carbon emission in machine tools manufacturing processes based on Petri nets," *Computer Integrated Manufacturing Systems*, vol. 18, no. 12, pp. 2723-2735, 2012.

[2] J. Wang, "Analysis of hierarchy structure in information system based on the Petri Nets," *Computer Engineering and Applications*, no. 4, pp. 89-91, 2002.

[3] G. Zhang, J. Liu, H. Ge, and H. Zhang, "Modeling for assemb-ly reliability based on generalized stochastic Petri Nets," *Computer Integrated Manufacturing Systems*, vol. 18, no. 3, pp. 507-512. 2012.

[4] J. Wang, and R. Gan, "Information system modeling based on Petri Nets," *Chinese Journal of Management Science*, vol. 8, no. 2, pp. 20-27, 2000.

[5] Q. Wang, *Service-Oriented Manufacturing Execution System Theory and Application*, Zhejiang University Press, Hangzhou, 2012.

[6] M. J. Rabbani, F. M. Ahmad, J. Baladi, Y. A. Khan, and R. A. Naqvi, "Modeling and simulation approach for an industrial manufacturing execution system," *IEEE 3rd International Conference on System Engineering and Technology (ICSET 2013)*, no. 8, pp. 26-31, 2013.

[7] O. Djamila, and P. Sanja, "A survey of dynamic scheduling in manufacturing systems," *Intelligent Systems Design and Applications*, vol. 12, no. 8, pp. 417-431, 2009.

[8] C. Cao, N. Wang, and Y. Wang, "On UML and Petri Net based modeling of integratable manufacturing executing system," *Mechanical Science and Technology*, vol. 23, no. 9, pp. 1093-1102, 2004.

Received: June 10, 2015 Revised: July 29, 2015 Accepted: August 15, 2015