Fault Evolution Model of Manufacturing System Based on Small-world Networks

Jian Liu[*]

College of Engineering and Technology, Southwest University, Chongqing, China

*Corresponding Author.

Abstract

Manufacturing system is a multi-level complex dynamic system composed of different types of machines, and machine fault is a major factor of manufacturing system's reliability. Hence, identification of fault evolution path and intensity is the prerequisite of fault prevention for complex manufacturing system. In this paper, a new multi-level model of fault evolution in manufacturing system is proposed. Based on the multi levels of manufacturing system, fault evolution path of manufacturing system has two types.One is physical evolutionpath within a single machine, and the other is flow evolutionpath during manufacturing process. Physical evolution has small-world characteristics, its intensity is the product of fault evolution probability and fault-load between fault nodes. Flow evolutionis judged by production relationships between machines, its intensity is production loss of manufacturing system due to unexpected shutdown of machines. Therefore, the integrated intensity of fault evolution within manufacturing system isthe comprehensive result of physical evolution and flow evolution.Then, ant colony algorithm isapplied to search fault evolution path with maximum intensity, sorting steps of fault evolution intensity is given to support decision making of fault prevention in manufacturing system. In the end, a case study of headstock manufacturing system is provided to verify the efficiency of the proposed method.

Keywords: Manufacturing system,small-world networks, fault evolution, ant colony algorithm

I. Introduction

Manufacturing system is the combination of human, machine, material flow and information flow, which is a complex system composed of manufacturing process and related hardware, software and personnel.In the hardware of the manufacturing system, machine is the main carrier to complete the manufacturing process. Finding and eliminating machine faults is an essential way to improve the reliability of the manufacturing system. Determining the evolution path and evolution intensity of machine faults is the prerequisite for the fault prevention of the manufacturing system [1-2].

In order to determine the transmission path of machine fault, it is necessary to clearly express the hierarchical relationship among manufacturing system, machine and its subsystems, parts and components [3].Experts and scholars use failure mode and effect analysis (FMEA), fault tree analysis (FTA), decision tree (DT), Petri net, fault evolution directed graph (DG), multi-agent system (MAS), cellular automata (CA) and other methods to describe the relationship between different levels of machine, analyze the influence of subsystem and component faults on machine performance, and calculate the probability of fault occurrence [4-5].The disadvantage is that the above method is only limited to the modeling and description of a single machine, and less involved in fault evolution within the scope of manufacturing system.

The existing fault evolution researches mainly focus on a single machine, judge and analyze the cause and evolution path of the faultaccording to the physical connection relationship.If the machine fails, it will spread to other subsystems and parts of the machine through physical connection, resulting in the performance degradation or complete failure of the machine [6-7].If the research object is extended to the whole manufacturing system, a single machine is regarded as a subsystem of manufacturing system. If a machine fails, it will not only degrade its own performance or completely fail, but also spread backward and forward through the production process, resulting in the accumulation of front-end work in process (WIP) and the shortage of follow-up WIP. As a result,

the production capacity of the manufacturing system is reduced or even completely unable to operate.

In this paper, a fault evolution model of manufacturing system based on small-world network is proposed. The fault evolution path of manufacturing system consists of two parts. One is the fault evolution inside the equipment, that is, the physical evolution. The other part is the evolution of fault in manufacturing process, that is, flowevolution.At the same time, ant colony algorithm is applied to search the most intensive fault evolution path, and the evolution intensity of machine fault is sorted to provide suggestions for machine fault prevention in manufacturing system.

This paper is organized as follows. In section 2, small-world network is introduced. A new multi-level model of fault evolutionin manufacturing system is established in section 3 according to the small-world network of single machine and production relationship between different machines in manufacturing process.The algorithm of fault evolution modelof manufacturing system and ant colony optimization algorithm for faultevolution paths searching are given in section 4. A real-life case of headstock manufacturing system is organized to illustrate how the model works in section 5. Finally, section 6 summarizes the findings and addresses possible future research directions.

II. Small-world Network

In 1998, based on human social relations,Watts and Strogatz proposed a small-world network modelwhich reflects the transition from regular network to random network [8].The construction process of small-world network are as follows [9-10].Step 1: Given regular network: in the network, there are N nodes in a ring, and each node is only connected with its nearest $2K$ nodes (Knodes at left and right), $N{\geq}K{\geq}$ 1, which is usually required. Step 2: Randomization of regular network: rewire every old connection in regular network based on probability$p$. The method is to randomly place one endpoint of the connection on a new node (excluding self-loop and double edge) to generate NKplong-range connection.It is not difficult to see that $p{=}$ 0 and $p = 1$ correspond to regular network and random network respectively. With the increase ofprobability$p$, the change from regular network to random network can be graduallyrealized, which as shown in Figure 1.

(P=0)   (0<P<1)   (P=1)

The randomness gradually increases.

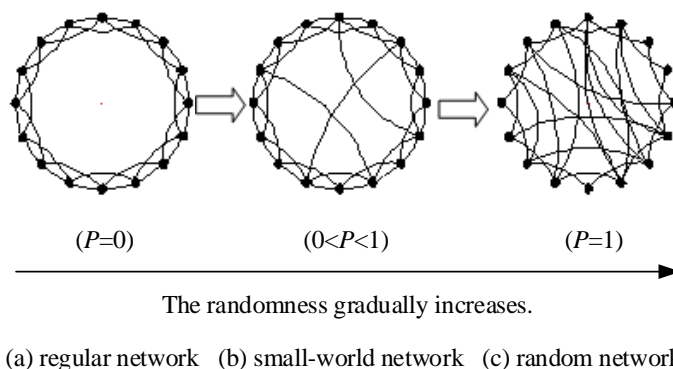(a) regular network   (b) small-world network   (c) random network

Fig 1: Constructing process of small-world networks

There are two important parameters characterizing small-world network.The first one is characteristic path length L.The characteristic path length refers to the average value of the shortest distance between any two nodes in the network, which is representedby $D(i,j)$.It is a characteristic parameter that describes the distance between any two nodes from a global point of view.

$$L = \frac{1}{n(n-1)/2} \sum_{1\leq i,j\leq n} D(i, j) \quad (1)$$

where,L is the characteristic path length,$n$is the number of network nodes, and $D(i,j)$ is the shortest distance between any two nodes,respectively.

The second one is clustering coefficient C. The clustering coefficient reflects the closeness of the relationship between the neighboring nodes. Assuming that node i has k_i neighbor nodes, the clustering coefficient of the node i is the ratio of the actual number of edges t_i and the maximum number of possible edges $k_i(k_i-1)/2$. The clustering coefficient of the whole network is defined as the mean value of the clustering coefficient of all nodes in the network.

$$C = \frac{1}{n}\sum_{i=1}^{n}\frac{2t_i}{k_i(k_i-1)} \quad (2)$$

where, C is the clustering coefficient, k_i is the number of nodes connected to the node i, and t_i is the actual number of edges between k_i nodes, respectively.

The randomness of small-world network is between regular network and random network. It has small average distance and large clustering coefficient. The statistic characteristic of small-world network can be expressed as follows.

$$\left.\begin{array}{l} L \geq L_{random} \\ C \geq C_{random} \end{array}\right\} \quad (3)$$

where, L_{random} is the average distance of the random network, $L_{random} \approx \ln n / \ln k$, C_{random} is the clustering coefficient of the random network, $C_{random} \approx K/n$, and K is the average degree of the network nodes, respectively.

III. Fault Network of Manufacturing System

3.1 Small-world network of single machine

A single machine can be regarded as one link in the network node of manufacturing system. Generally speaking, it includes four levels: equipment level, subsystem level, component level and part level. These four levels have the inclusion relationship from large to small, and they are connected according to the assembly rules. In the small-world network of a single machine, the nodes from same component or same subsystem are closely related, which have a large clustering coefficient. The nodes from different components or different subsystems are connected by long-distance connections, which have a sparse relationship and a small clustering coefficient. Therefore, they constitute a small-world network of fault evolution of a single machine [11]. The small-world network of a single machine is shown in Figure 2.
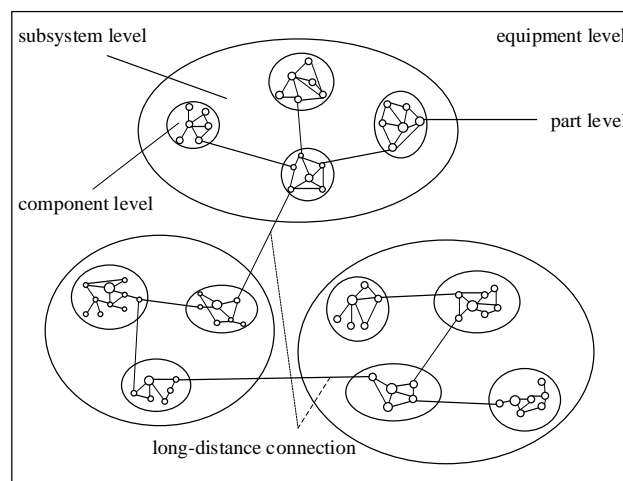

Fig 2: Small-world network of a single machine

3.2 Machine network of manufacturing system

The manufacturing system is composed of many machines. According to the manufacturing process, many machines constitute machine network. The machine network is related to the quantity and type of different

products, processing path, workshop space location and so on. Different types of manufacturing systems choose different machine networks. The common machine networks include mesh, multi-line and snake networks, which are more complex. There are also simple networks, such as straight line,simple linear, ring, U-shaped and semicircle networks. The complex machine network can be further simplified to a relatively simple network, as shown in Figure 3.For simplify, this paper selects the simplest linear machine network to study.
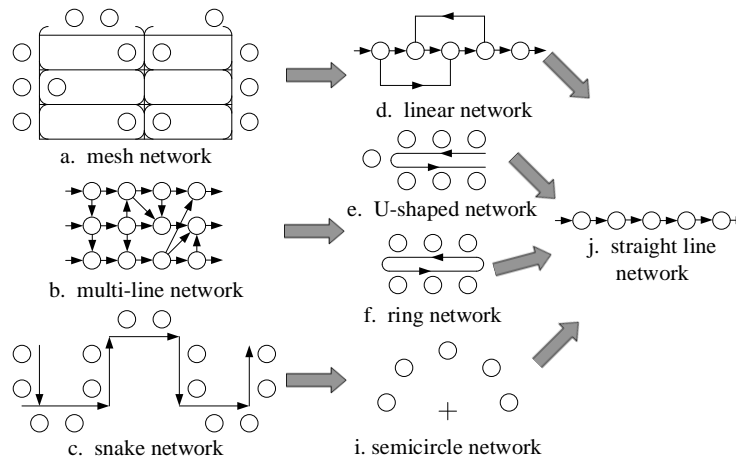

Fig 3:Machine network and its evolution process

3.3 Multi-level model of fault evolutionin manufacturing system

As noted above, fault evolution of manufacturing system can be divided into physical evolution of single machine and flowevolution in manufacturing process. Fault evolutionatmachine level is described by small-world network, and flowevolutionat system level is determined by production relationship between machines in manufacturing process.Therefore, the fault evolution of manufacturing system consists of multi levels of network. The four levels (equipment level, subsystem level, component level and part level) at bottom is the small-world network of each machine, which describes the physical evolution in each machine. The upper level is the machine network of manufacturing system, which is determined by the machine layout of manufacturing system, and describes the flowevolution in the manufacturing process.The multi-level model of fault evolution in manufacturing system is shown in Figure 4.
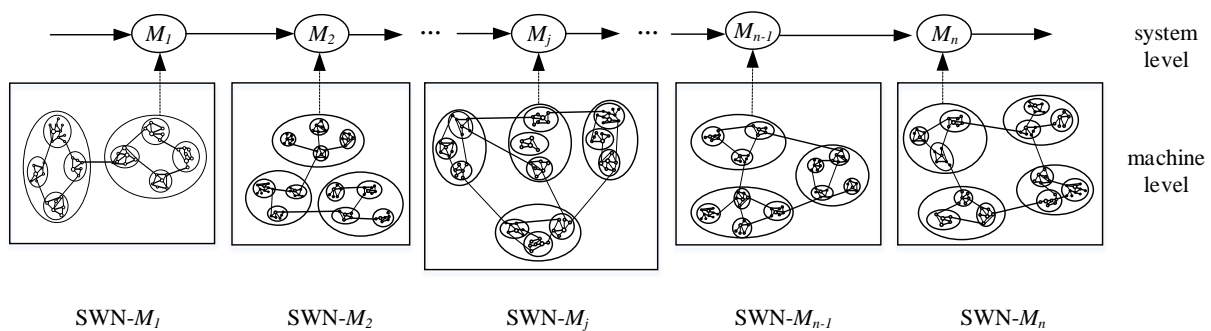

Fig4:Multi-level model of fault evolution in manufacturing system

IV.Fault EvolutionAnalysis of Manufacturing System

4.1 Fault evolutionatmachine level

A single machine consists of its subsystems,which can be further divided into smaller units at part and component level. For example, machining center is composed of spindle, feed system, turntable, exchange frame, tool magazine, chip conveyor and other subsystems. The turntable can be further divided into servo motor, coupling, worm gear pair, gear shaft, lifting cylinder, upper and lower gear plates, gear pair, worktable swivel, bearing group, sealing element, clamping cylinder, claw and other parts,which are combined by physical connection. The fault evolution relationship between each unit can be obtained by fault statistics or reliability test data.Therefore,

according to the idea of graph theory, the basic units of a single machine can be regarded as node V in the physical connection of network, and the fault evolution relationship between them can be regarded as the connection side E, then it can be transformed into the form of network, which is recorded as

$$D = \{V, E, R\} \quad (4)$$

where, R is the relationship set of fault evolution between nodes. If the network has higher clustering coefficient and smaller characteristic path lengththan the random network with the same node size, and satisfies equation (3), it can be considered that the network has small-world characteristics, that is, the node network composed of each basic unit of a single machine is a small-world network.

When a basic unit in the machine fails, it will gradually spread to other related nodes.In the diffusion process, the edge with higher evolution probability is preferred for fault diffusion.When the evolution probability is less than the evolution probability threshold, which depends on the machine, the node is considered to be in a safe state.For the fault network with small-world characteristics, in addition to considering the fault evolution probability between nodes, the degree of nodes and whether there is longrange connection should also be considered. In fact, the total risk of high-frequency small-scale faults is equal to the risk of those large-scale faults. Therefore, when analyzing the fault evolution process, the physical evolution intensity is introduced to integrate these two factors, and the intensity is taken as the weight of the connecting edge. The larger the evolution intensity is, the easier the fault is to spread through this edge, and the larger the scope of the spread is.
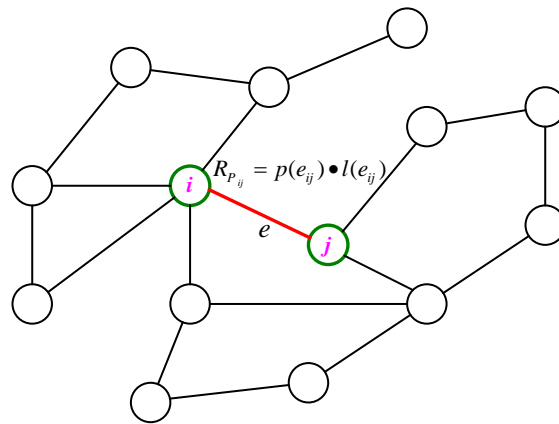

Fig5:Fault evolution intensity of single machine

Considering both faultrate and consequence, the physical evolutionintensity between node v_i and v_j is defined as $R_{P_{ij}}$,the probability of fault propagating directly from node v_i to node v_j is $p(e_{ij})$.If there is no connecting edge between two nodes, the probability is 0. $l(e_{ij})$ represents the load between node v_i and v_j, which as shown in Figure 5.

$$R_{P_{ij}} = p(e_{ij}) \cdot l(e_{ij}) \quad (5)$$

where, $R_{P_{ij}}$ is the physical evolutionintensity between node v_i and v_j, $p(e_{ij})$ is the failure probability from node v_i to v_j, and $l(e_{ij})$ is the load of connecting edge between node v_i and v_j,respectively. The normalized physical evolution intensity R'_P can be described as

$$R'_P = \left. R_{P_{ij}} \middle/ \sum_{i \neq j} R_{P_{ij}} \right. \quad (6)$$

4.2 Fault evolutionatsystem level

In the machine network of manufacturing system, when a machine fails, the productivity of the machine will inevitably drop or zero, which will affect the production state of the previous and subsequent processes, resulting in the production reduction or shutdown of the whole manufacturing process.The total downtime $T(l)$ and capacity loss $Y(l)$ of the whole manufacturing system due to faulty machine are

$$T(l) = \sum_{k=1}^{n} t_{D_k} \quad (7)$$

where, n is the number of machine, l is the number of faulty machine, t_{D_k} is the downtime.

$$Y(l) = \sum_{k=1}^{n} y_{k} = \sum_{k=1}^{n} f_{k} t_{D_{k}} \quad (8)$$

where, k is the number of good machine, y_k is the downtime, f_k is the productivity.

For manufacturing system, the response of machine layout to fault evolution is obviously different. The following two cases are discussed.

(1) In special cases, if the manufacturing system is an assembly line, there is no buffer between processes, the cycle timeof each process is equal, the productivity of each machine is the same, which is equal to the productivity of the whole assembly line, and the downtime of each machine is equal to the maintenance time of the faulty machine.

$$\begin{cases} f_{k} = f \\ t_{D_{k}} = t_{R_{l}} \\ T(l) = \sum_{k=1}^{n} t_{D_{k}} = n t_{R_{l}} \\ Y(l) = \sum_{k=1}^{n} y_{k} = \sum_{k=1}^{n} f_{k} t_{D_{k}} = n t_{R_{l}} f \end{cases} \quad (9)$$

where, f is the productivity of the whole production line, $t_{R_{l}}$ is the maintenance time.

(2) In normal cases, if the manufacturing system has buffers between processes, the cycle time of each process is not equal, the downtime of each machine is different. Because of the buffer, the closer to the faultymachine, the greater the impact, and the farther away from the faultymachine, the smaller the impact.The number of WIP that can be processed by front-end and follow-up machine is discussed as follows.For the front-end machine of the faultymachine M_l, due to the faultymachine thatcannotwork,the number of products that can continue processing is the remaining capacity of the buffers.The closer to the faultymachine, the less the number of products that can continue processing.On the contrary, the farther away from the faultymachine, the more products can continue to be processed,which as shown in Figure 6.For the machine k, the number $Z_k$of products that can continue to be processed is equal to the sum of the remaining capacity from buffer $k+1$ to buffer l.

$$Z_{k} = (b_{k+1_{max}} - b_{k+1}) + \cdots + (b_{l_{max}} - b_{l}) = \sum_{k+1 \to l} (b_{k_{max}} - b_{k}) \quad (10)$$

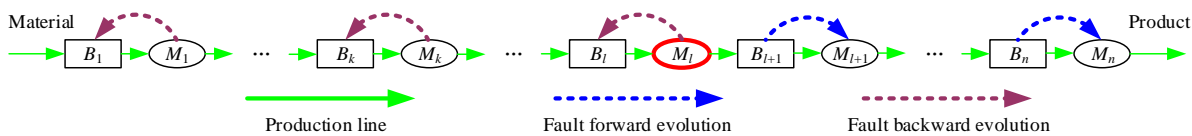where, $b_k$is the number of productsin buffer, $b_{k_{max}}$ is the maximum buffer capacity.

Fig6:Fault evolutionmodel at system level ($1 \leq k < l$)

For the follow-up machine of the faultymachine M_l, the number of WIP in the buffer is the number of products available for processing because the faulty machine cannot continue to be processed.The closer to the faultymachine, the less the number of products that can continue processing.On the contrary, the farther away from the faultymachine, the more products can continue to be processed,which as shown in Figure 7. For the machine k, the number $Z_k$of products that can continueprocessingis equal to the sum of the existing WIPfrom buffer $l+1$ to buffer k.

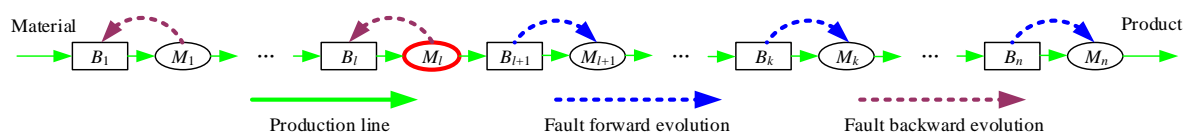$$Z_{k} = b_{l+1} + \cdots + b_{k-1} + b_{k} = \sum_{l+1 \to k} b_{k} \quad (11)$$

Fig 7:Fault evolution model at system level ($n \geq k > l$)

Taking the above two cases into consideration, the number Z_k of WIPat machine k is

$$Z_k = \begin{cases} \sum\limits_{k+1 \to l} (b_{k_{max}} - b_k); & 1 \le k < l \\ \sum\limits_{l+1 \to k} b_k & ; \quad n \ge k > l \end{cases} \tag{12}$$

The time t_k for continuous processing at machine k is

$$t_k = Z_k / f_k = \begin{cases} \sum\limits_{k+1 \to l} (b_{k_{max}} - b_k)/f_k; & 1 \le k < l \\ \sum\limits_{l+1 \to k} b_k/f_k & ; \quad n \ge k > l \end{cases} \tag{13}$$

When the machine M_l fails, the downtime t_{D_k} of machine k equal to the difference between maintenance time t_{R_l} and continuous processing time t_k of machine k.

$$t_{D_k} = t_{R_l} - t_k \tag{14}$$

The total downtime $T(l)$ and capacity loss $Y(l)$ of the whole manufacturing system are

$$T(l) = \sum_{k=1}^{n} (t_{R_l} - t_k) \tag{15}$$

$$Y(l) = \sum_{k=1}^{n} y_k = \sum_{k=1}^{n} f_k (t_{R_l} - t_k) \tag{16}$$

The fault of a certain machine in the manufacturing system will result in a series of serious consequences, such ascapacity loss, delayed delivery, maintenance costs, waste of manpower, etc. In terms of the comprehensive impact on the manufacturing system, capacity loss is the most fundamental and important factor. Therefore, this paper takes the capacity loss caused by fault as the flowevolutionintensity of manufacturing system.

$$R_A = Y(l) \tag{17}$$

The normalized flowevolution intensity R'_A is

$$R'_A = Y(l) \Big/ \sum_{l=1}^{n} Y(l) \tag{18}$$

4.3 Fault evolutionatmulti levelsof manufacturing system

As noted above, there are two types of fault evolutionwithin manufacturing system, one is physical evolution in a single machine, the other is flowevolution in machine network. At the lower level of fault evolution, the fault evolves inside the machine, from the fault node to the adjacent node, and then to the adjacent components and subsystems through the long-distance connection, resulting in the performance degradation or shutdown of the machine. In the second stage of fault evolution, the performance of the faulty machine decreases or stops, resulting in the productivity of the process decreasing or being zero, which will gradually affect the production state of other machine in the manufacturing process. The WIP produced by the front-end machine gradually accumulates, and the number of WIP that can be processed by the follow-up machine gradually decreases, resulting in the performance of the manufacturing system decreasing or completely unable to operate. The fault evolutionat multi levels of the whole manufacturing system is shown in Figure 8.
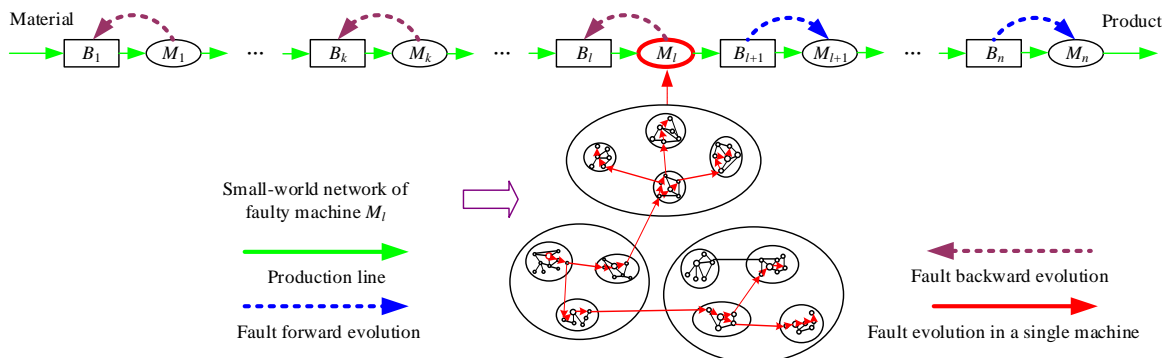

Fig 8: Fault evolutionat multi levels of manufacturing system

According to equation (6) and (18), the integrated intensity R of fault evolution within manufacturing system is the comprehensive result of physical evolution and flow evolution.

$$R = R_P' \cdot R_A' \tag{19}$$

4.4 Fault evolution path searching based on ant colony algorithm

According to the integrated intensity of whole manufacturing system, it can be concluded that the fault path with the largest evolution intensity is the most likelyfault occurs.In the process of fault evolution, the longer the evolution path, the smaller the probability that the fault occurs on the evolution path.Therefore, a probability constraint condition can be set. If the probability is no more than the probability constraint condition, the fault evolution can be considered as a small probability event, which will not occur, and the fault evolution process will end.

$$\left. \begin{array}{l} \max \sum R \\ \text{s.t} \ \prod_k p_{ij} \ge p \end{array} \right\} \tag{20}$$

where, p is threshold value of probability, which depends on machine. When the evolution probability is no more than p, the fault evolution process is considered to be terminated.The fault evolution model belongs to the problem of searching optimal path on graph, which is solved by ant colony algorithm in this paper.

Suppose that there are m ants distributed on $n$nodes, the transition probability of the$k$th ant from node$v_i$to node$v_j$is as follows

$$p_{ij}^k = \begin{cases} \dfrac{[\tau_{ij}]^\alpha [\eta_{ij}]^\beta}{\sum\limits_{l \in J_k(i)} [\tau_{ij}]^\alpha [\eta_{ij}]^\beta}, & path_k \in J_k(i) \\ 0 & , \ \text{otherwise} \end{cases} \tag{21}$$

where, $path_k$ is the path of the kth ant, τ_{ij} isthe number of pheromones between node $v_i$andv_j, which can take a constantas the initial value, η_{ij} is a self-heuristic factor, which describes the expected degree from node $v_i$to nodev_j. Because the edge with higher diffusion intensity is preferred for fault evolution, the self-heuristic value is defined as

$$\eta_{ij} = R \tag{22}$$

$J_k(i)$ isthe set of nodes that the kth ant is allowed to select. A tabu set $tabu_k$is set to record the nodes that the kth ant has passed by. α is the control pheromone, and β is the influence parameter of self-heuristic factor on probability. $\alpha, \beta > 0$ reflects the important relationship among pheromone,self-heuristic factor and the integrated intensity R of fault evolution within manufacturing system.

In order to ensure the global of the result, a pseudo-random ratio rule is applied in ant colony algorithm. That is, $q_0$is set as aparameter, $0 \le q_0 \le 1$. A random number$q$is taken before each ant selects the next node.Comparing$q$ with the parameterq_0, and put forward the state transition rule, that is

$$j = \begin{cases} \arg \max\limits_{j \in J_k(i)} [\tau_{ij}]^\alpha [R]^\beta, & q \le q_0 \\ J & , \ \text{otherwise} \end{cases} \tag{23}$$

where$J$is a selected number according to equation (22).

It is worth noting that the increment of pheromone on the connecting edge e_{ij} is determined by the self-heuristic value η_{ij}. Because the pheromone on the connecting edge can volatilize, the pheromone on the evolution path is updated according to the local update rule of equation (24).

$$\tau_{ij} = (1 - \rho)\tau_{ij} + \rho \Delta \tau_{ij} \tag{24}$$

where, ρ is the volatility of pheromones ($0 < \rho < 1$), τ_{ij} is the number of pheromones, $\Delta \tau_{ij}$ is the increment of pheromones.Suppose that after all ants complete one visit to all nodes, the pheromones of all connecting edges are updated by applying the global update rule.

$$\tau_{ij} = (1 - \rho)\tau_{ij} + \rho \prod_{k=1}^{m} \Delta \tau_{ij_m} \tag{25}$$

$$\Delta \tau_{ij_m} = \begin{cases} R, & e_{ij} \in H_m \\ 0, & \text{otherwise} \end{cases} \quad (26)$$

where, H_m is the optimal path obtained by the kth ant at last time. If the kth ant traverses all nodes, it is said that k satisfies the feasible solution. If the same solution is found at the end of the iteration or without degradation, the iteration ends and the result is output. The flow chart of ant colony algorithm for fault evolution path searching of manufacturing system is shown in Figure 9.

4.5 Fault prevention of manufacturing system

With the help of ant colony algorithm, the maximum fault risk and evolution path of each machine can be determined. However, there are many machines in the manufacturing system, so it is necessary to compare and sort the maximum fault evolution intensity of all machines, and give priority to the fault with greater risk and wider influence. It can provide good suggestions for fault prevention of manufacturing system. The machine fault prevention process of manufacturing system is shown in Figure 10.
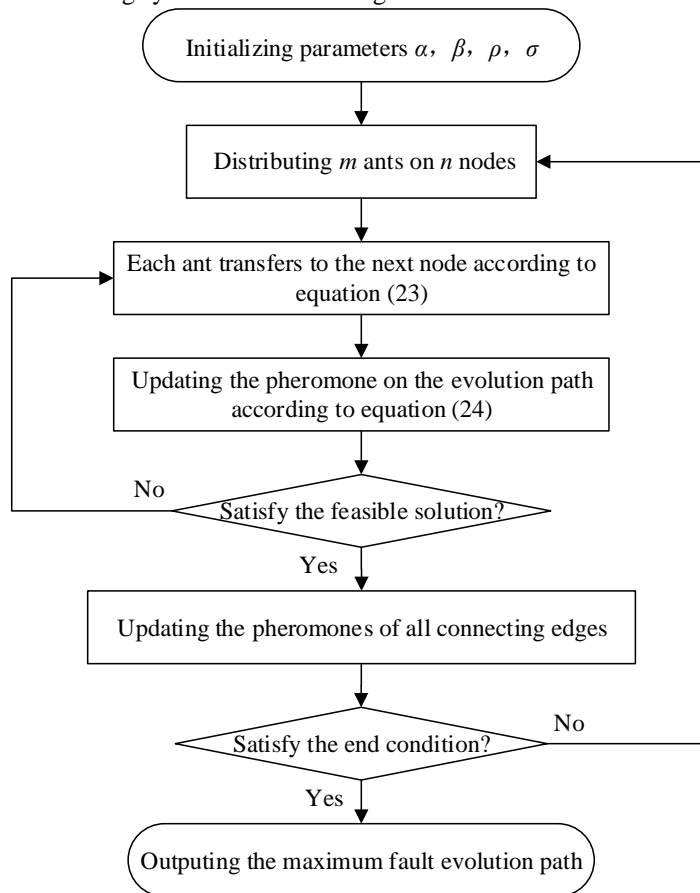

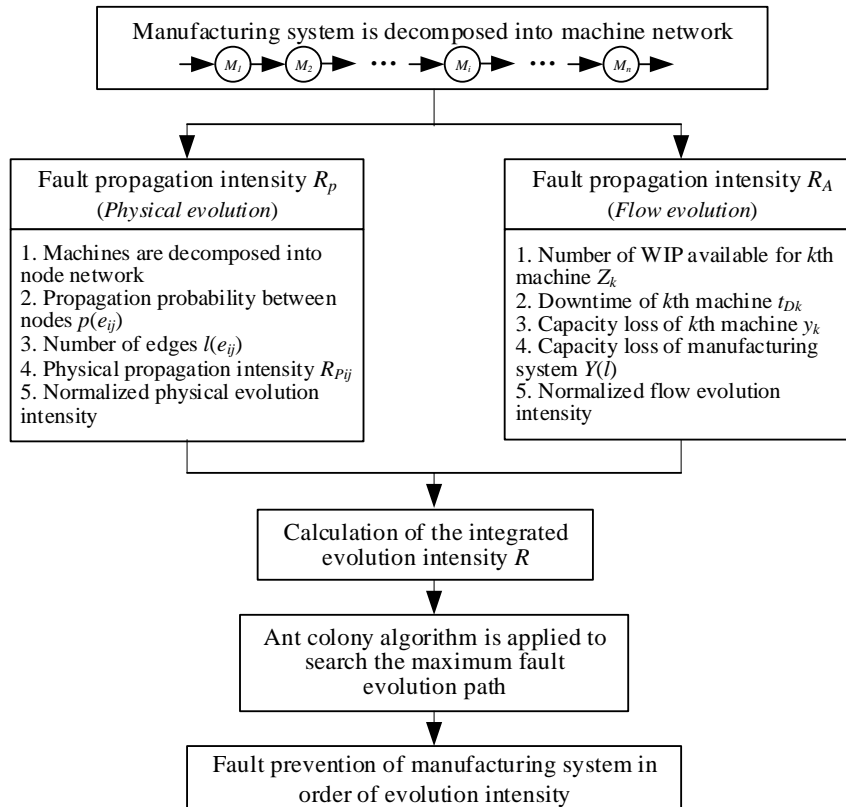*Fig 9: Ant colony algorithm for fault evolution path searching of manufacturing system*

Fig 10: The machine fault prevention process of manufacturing system

V. Numerical Example

The layout and process flow of a headstock manufacturing system are shown in Figure 11 and table 1. The manufacturing system has five precision horizontal machining centers (MC) and one cleaning machine (CM). The material conveying device is a rail guide vehicle (RGV), which realizes information communication through wireless infrared technology, and carries work piece formachining centers. A three-dimensional warehouse with 48 storage locations and two loading/unloading stations (LUS) are also set up in the manufacturing system. The central control system (CCS) in the main control station is responsible for the monitoring of the operation state, production scheduling and fault diagnosis of the whole manufacturing system.
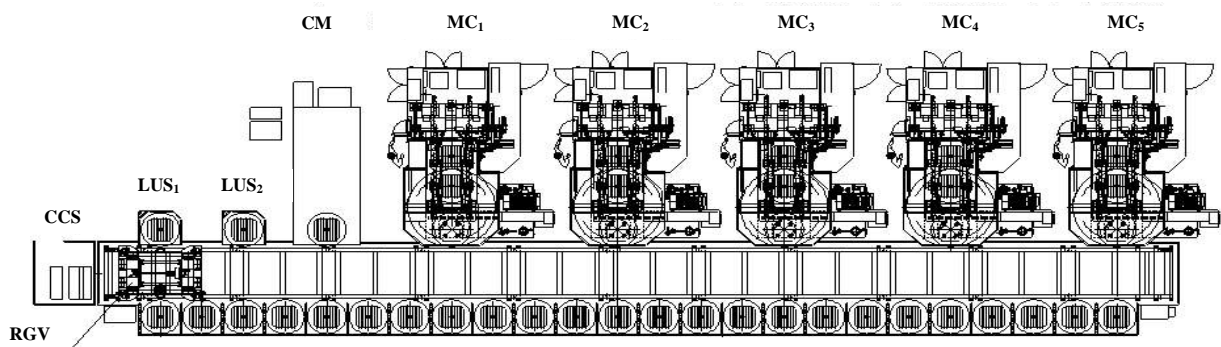

Fig 11: Layout of headstock manufacturing system

Table 1 Processes of headstock manufacturing system

Process machine	Process number	Process content
MC_1	$OP01$	Semi finish milling Ra 3.2 surface at the bottom

	OP02	Boring φ92 hole at the bottom
	OP03	Semi finish boring φ100Js6 hole to φ99
	OP04	Drilling 10×φ17.5 hole
	OP05	Chamfering φ17.5 hole
MC_2	OP06	Semi finish milling Ra 3.2 circular lapping surface at the top
	OP07	Semi finish milling Ra 3.2 lapping surface at the top cavity
	OP08	Semi finish boring φ80Js6 hole to φ79
	OP09	Semi finish boring φ114.3H7 hole to φ112
MC_3	OP10	Finish milling Ra 3.2 surface at the bottom
	OP11	Semi finish boring φ100Js6 hole to φ99.7
	OP12	Finish boring φ100Js6 hole
	OP13	Chamfering φ100Js6 hole
	OP14	Drilling 6×M8 to φ6.75, deep 19
	OP15	Chamfering M8 hole
	OP16	Tapping 6×M8
MC_4	OP17	Finish milling Ra 3.2 circular lapping surface at the top
	OP18	Finish milling Ra 3.2 lapping surface at the top cavity
	OP19	Semi finish boringφ80Js6 hole to φ79.7
	OP20	Finish boringφ80Js6 hole
	OP21	Semi finish boringφ114.3H7 hole to φ114
	OP22	Finish boringφ114.3H7 hole
	OP23	Chamfering φ80Js6 hole and φ114.3H7 hole
MC_5	OP24	Drilling4×M6 to φ5, deep 13
	OP25	Drilling4×M12 to φ10.2, deep 29
	OP26	Chamfering M6 hole and M12 hole
	OP27	Tapping 4×M6
	OP28	Tapping 4×M12
CM	OP29	Cleaning

In order to analyze the fault evolution, it is necessary to decompose each machine in the manufacturing system and establish the fault evolution network of each machine. For simplify, this paper takesthe NC turntable as an example to analyze. According to the physical connection relationship between the basic units of the turntable, it is transformed into a small-world network. The fault evolution probability between nodes can be obtained according to historical or experimental statistical data, and the fault evolutionintensity of each edge can be obtained according to equation (5). The results are shown in Figure 12. The title of components corresponding to each node in Figure 12 are shown in Table 2.
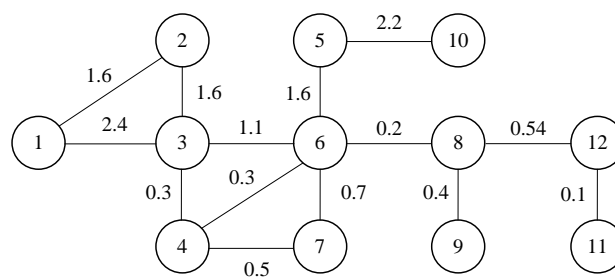

Fig 11: Small-world network of NC turntable

Table 2Part name of each corresponding node in small-world network of NC turntable

Node	Name	Node	Name	Node	Name
1	Servo motor	5	Lifting cylinder	9	Bearing group
2	Coupling	6	Upper and lower gear plates	10	Sealing element
3	Worm gear pair	7	Gear pair	11	Clamping cylinder
4	Gear shaft	8	Worktable swivel	12	Claw

According to equation (1) and (2), the characteristic path length and clustering coefficient of small-world network

can be obtained. According to equation (3), the characteristic path length and clustering coefficient of random network with the same number of nodes can be obtained. The results are shown in Table 3.Compared with the random network with the same number of nodes, the network has larger characteristic path length and smaller clustering coefficient, which indicates that the network has small-world characteristics.

Table 3Statistical characteristics of fault network

Parameter	n	K	L	L_{random}	C	C_{random}
Value	14	3	2.4725	2.4022	0.3265	0.2143

In order to obtain the fault evolution path with the greatest risk, the relevant parameters of ant colony algorithm are set as shown in Table 4.Through calculation, the evolution path of the greatest risk is 10-5-6, and the risk value is 3.52.

Table 4Parameters of ant colony algorithm

Parameter	α	β	ρ	σ	q_0	m	N_c
Value	1	1	0.2	0.5	0.6	10	100

According to equation (6) and (18), the physical and flowevolution intensity of manufacturing system can be obtained. According to equation (19) and ant colony algorithm, the maximum evolution intensity and its path of each machine can be obtained. The order of maximum evolution intensity of each machineare shown in Table 5.

Table 5Ranking of fault intensity of manufacturing system

Process machine	R'_P	R'_A	R	Rank
MC_1	0.148	0.089	0.013	3
MC_2	0.063	0.134	0.008	5
MC_3	0.123	0.162	0.020	2
MC_4	0.179	0.129	0.023	1
MC_5	0.108	0.094	0.010	4
CM	0.028	0.031	0.001	6

VI. Conclusion

In this paper, the fault evolution of manufacturing system is divided into two categories: physical evolution and flowevolution. To solve the problem that the current fault evolution research is limited to a single machine, by determining the intensity and path of the fault evolution of manufacturing system, and sorting the maximum fault evolutionintensity of each machine, it can provide good suggestions for the machine fault prevention of manufacturing system.The main conclusions are as follows.

(1) From the point of view of physical connection relationship, fault can only propagate in a single machine relying on the connection relationship between each other, and there is no physical fault evolution relationship between the two basic units without connection relationship.

(2) From the perspective of manufacturing system as a whole, although there is no physical connection between machines, they can be closely linked through the demand relationship between processes. If one machine fails, it will not spread the fault itself to other machine, but it will affect the production state of other machine, and then affect the production capacity of manufacturing system.Therefore, the influence evolution of equipment failure in the manufacturing process cannot be ignored.

(3) Small-world network has the characteristics of both regular network and random network. It depends on the physical connection relationship between the basic units of machine to determine the evolutionintensity and evolution path, which is simpler than the calculation process of traditional fault evolution analysis method. However, its basic idea is based on the statistical principle, less consideration is given to the details of the fault, and its calculation results may be different from the real situation. This analysis method should also be combined with advanced methods to further improve the accuracy of fault analysis.

Acknowledgements

References

[1] C. Su, S.Y. Wang, "Dynamic reliability simulation for manufacturing system based on stochastic failure sequence analysis," Journal of Mechanical Engineering, vol. 47, no. 24, pp. 165-169, 2011.

[2] A. Bleakie, D. Djurdjanovic, "Feature extraction, condition monitoring, and fault modeling in semiconductor manufacturing systems," Computers in Industry, vol. 64, no. 3, pp. 203-213, 2013.

[3] A.P. Ulmeanu, "Analytical method to determine uncertainty propagation in fault trees by means of binary decision diagrams," IEEE Transactions on Reliability, vol. 61, no. 1, pp. 84-94, 2012.

[4] G.P. Wang, Y.Z. Jia, G.X. Shen, et al., "Fuzzy evaluation analysis on cooling system failure mode criticality of machining center," Transactions of the Chinese Society of Agricultural Machinery, vol. 39, no. 3, pp. 171-175, 2008.

[5] S. Markus, H. Robert, S. Ulrich, "Source identification of plant-wide faults based on k nearest neighbor time delay estimation," Journal of Process Control, vol. 22, no. 3, pp. 583-598, 2012.

[6] W.R. Hou, Z.H. Jiang, Y.L. Jin, "Reliability-based opportunistic preventive maintenance model of multi units serial parallel system," Journal of Shanghai Jiaotong University, vol. 43, no. 4, pp. 658-662, 2009.

[7] B.F. Huang, L. Shen, X.J. Zhou, et al., "Fault feature extraction of Rolling element bearing based on morphological undecimated wavelet decomposition," Transactions of the Chinese Society of Agricultural Machinery, vol. 41, no. 2, pp. 203-207, 2010.

[8] D.J. Watts, S.H. Strogatz, "Collective dynamics of "small-world" networks," Nature, vol. 393, no. 4, pp. 440-442, 1998.

[9] J.M. Gao, L. Guo, Z.Y. Gao, "Failure propagation analysis for complex system based on small-world network model," Reliability and Maintainability Symposium. 2009.

[10] H.Q. Jiang, J.M. Gao, F.M. Chen, et al., "Vulnerability analysis to distributed and complex electromechanical system based on network property," Computer Integrated Manufacturing Systems, vol. 15, no. 4, pp. 791-796, 2009.

[11] H.D. Zanette, "Dynamics of rumor propagation on small-world networks," Physical Review, vol. 65, no. 5, 19-27, 2002.