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عملية الميكنة بنهج النمذجة للموثوقية الأمثل في نظم التصنيع المعرضة للفشل

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الخلاصة

تحليل الموثوقية يلعب دورا هاما في توفير التكاليف وتحسين إنتاجية نظم التصنيع. ويولى اهتمام يذكر لأساليب التحليل الموثوقية للحد من آثار فشل في المرحلة الأولى من الأنشطة تصميم النظام مثل عملية التخطيط. وتقترح هذه المقالة نهج النمذجة عملية موجهة نحو تشكيل لتحسين موثوقية نظم التصنيع. في هذا النهج، يتم فصل الدول عملية آلات على التمييز بين التقليدي نهج النمذجة موثوقية للمكونات الالكترونية. يتم استخدام الرسم البياني الحدث لحساب موثوقية النظام من حيث الدول التي تمر بمرحلة انتقالية. للتدليل على صحة النهج المقترح، تصنيع نظام متجر المهمة التي أنتجت وقدمت عالية الجهد الأجهزة الكهربائية كمثال على ذلك. ويستنتج من ذلك أن خطط عملية المختلفة لها تأثير هام على موثوقية النظام. يمكن أن النهج المقترح سيساعد صنع القرار لخطط جدولة يمكن الاعتماد عليها في الإنتاج الحقيقي.

A machining process oriented modeling approach for reliability optimization of failure-prone manufacturing systems

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ABSTRACT

Reliability analysis plays an important role in cost saving and productivity improvement of manufacturing systems. Little attention is paid to reliability analysis methods to reduce failure effects in the initial stage of system design activities such as process planning. This article proposes a machining process oriented modeling approach for reliability optimization of manufacturing systems. In the approach, machines' operation states are separated to distinguish traditional reliability modeling approach for electronic components. An event graph is used for computing system reliability in terms of states transition. To demonstrate the validity of the proposed approach, a job shop manufacturing system that produces high-voltage electrical apparatus is provided as an example. It is concluded that different process schemes have important influence on system reliability. The proposed approach can assist the decision-making for reliable scheduling plans in real production.

Keywords: Event graph; manufacturing system; process planning; reliability modeling; reliability optimization.

INTRODUCTION

The current economically globalized and highly competitive landscape requires that manufacturing plants are reliable enough to resist uncertain risks, both inside and outside. Reliability analysis, which deals with failures and its effects, plays a significant role in cost reduction and productivity gains. Maintenance costs take up a large percentage of the total cost, especially for a failure-prone manufacturing system with deteriorated equipment. Mobley has referred that maintenance cost can represent between 15 and 60 percent of the cost of goods produced (Mobley, 2002). In addition to high cost of maintenance activities, other inconveniences caused by failures include downtime production losses, high overall inventory, quality deterioration, delay of delivery time, etc. Thus reliability improvement of manufacturing system is crucial for enhancing the competitiveness of enterprises.

Reliability analysis is intended to alleviate the failure effects. Maintenance policy optimization has always been the research emphasis for reliability analysis of manufacturing systems (Ding & Kamaruddin, 2015). However, maintenance optimization should be directed at a certain object. Thus failures are handled or prevented in a passive mean without involving the composition of the maintenance object. Note that process routes of parts determine the composition of manufacturing systems to some extent. Little research is focused on reliability analysis methods to reduce failure effects in the initial stage of system design activities such as process planning. Maintenance activities are scheduled to ensure that machines are operating reliably. Compared with maintenance activities, machining process oriented reliability optimization is a more active procedure for better system performance by rational adjustment of process routes. In fact, it is a continuous improvement process for reliability growth between maintenance optimization and construction modification of systems. Thus, it is meaningful of machining process oriented reliability optimization from the source of system construction formation.

Process planning is the key work in a job shop. It is concerned with determining the sequence of individual manufacturing operations needed to produce a given part or product. The result of process planning is documented on a form (typically referred to as a route sheet) containing machining operations, process sequences, associated machine tools, tooling and fixtures. In this paper, process sequences and associated machine tools are only considered. In a real job shop, there could be multiple process routes for a given part, owing to machine flexibility and operation flexibility. Hence, it is difficult to obtain optimal process routes. Generally, machines are considered to be reliable, and the final process routes are selected to achieve a certain objective of job scheduling, such as minimizing the make-span of all jobs. However, system reliability is another important evaluating factor, when determining the final process routes.

Most of the literature of reliability analysis for machining and manufacturing systems are aimed at individual equipment based on failure and repair data for months, such as the CNC lathes (Wang *et al.,* 1999), machining centers (Dai & Jia, 2001), food production lines (Tsarouhas et al. 2009) as well as the piston production line (Zhang *et al*., 2014). In the case of analytic models for manufacturing systems, Aldaihani & Savsar (2005) and Savsar & Aldaihani (2008) have proposed reliability models for flexible manufacturing cells, and system performance under variation of reliability indicators is evaluated. Besides, system configuration and redundancy allocation for serial-parallel systems have been focus of other research (Sheikhalishahi *et al*., 2013; Ebrahimipour *et al*., 2013). Nevertheless, machining tasks allocation and connections among machines are often overlooked from a system reliability perspective.

Unreasonable task allocation on machines can lead to frequent failures of unreliable or overused equipment, which caters to the theme of cask effect, since a chain is only as strong as its weakest link. A high reliable manufacturing system is not always the combination of reliable machines. Task allocation problem has been studied and its effectiveness is validated in flexible manufacturing systems (FMS) (Tripathi *et al.*, 2005) and holonic manufacturing systems (Zhao *et al.*, 2007) under dynamic production environment. However, it does not mean that machining tasks should be allocated to more reliable machines simply because of less maintenance costs. Interaction between system reliability and maintenance activities is introduced in Ahmadi(2014). Reliability and cost are isolated in definitions, but they must be weighed when carrying out reliability analysis for repairable production systems (Zhang & Ge, 2015; Zhang *et al.*, 2015).

Components' reliabilities are often considered as a fixed value during reliability analysis of electronic parts. In contrast, reliability assessment of machine tools is more difficult, owing to variable machining tasks and working conditions. Doubtlessly, a machine fails easily, if it is used more frequently than another machine of the same type. In addition, multiple failure modes exist during the uptime, which can be divided into time-dependent failures and operation-dependent failures. Failures of subsystems like spindle, feeding system, tools and magazine are heavily related with machining operations. Thus failures of these subsystems are classified as operation-dependent failures. On the other hand, even if machines are idle between jobs, much of energy is consumed by subsystems such as power module and fans, controlling and lubricating systems (He *et al.*, 2012); hence failures of these subsystems are classed as time-dependent ones. Generally, uncertainty of lifespan of mechanical devices is much larger than electronic devices because of complex serving conditions, which make normal statistical descriptions (e.g. mean time between failures and average failure rate) inaccurate.

The machining process oriented reliability evaluation is helpful for decision-making on alleviation of failure effects in production management. Currently, a common misunderstanding evolved from reliability evaluation for electronic devices is that a system is more likely to fail, if it is composed of more serial components. For mechanical systems, however, the machining time is an important factor for the calculation of system reliability. Besides, interactions between machines are usually accompanied with unloading and loading movements of material handling systems (MHS) such as AGVs, gantry robots or manpower. Reliability assessment of a MHS should be different from that of machine tools. Reliability of a MHS should be calculated according to its delivery times instead of working hours, because it generally fails when grasping a part.

Yusof & Latif (2014) have reviewed the current problems and trends of computer-aided process planning (CAPP). Numerous research efforts have been done in this area. Generally, there are two basic approaches to CAPP: variant and generative.

As a retrieval approach, the success of variant CAPP depends on group technology (GT) and database retrieval. A generic process plan is selected from the existing mature process plans developed for each part family. In contrast, generative CAPP can generate an optimal process plan according to part's features and manufacturing requirements based on process knowledge and artificial intelligence techniques (Shen *et al*., 2006). In general, reliability information and failure effects of individual equipment are overlooked during normal process planning in the job shop. Reliability centered process planning could be of great importance to failure-prone manufacturing systems, which need to be certified in the following analysis.

The ultimate purpose of determining process schemes is to improve production efficiency in scheduling period. Scheduling is used to determine the most appropriate moment to execute each operation for the launched production orders, taking into account the due date of these orders (usually with the objective of minimizing make-span). However, process planning and job scheduling are separate tasks in two periods. Process schemes of jobs have been determined during process planning period, based on which the scheduling of these jobs is performed in the job shop by another department. Hence, improper selection of process schemes would result in reduction of efficiency during scheduling optimization. Integrated process planning and scheduling (IPPS) has been researched to address this question (Guo *et al*., 2008; Qiao & Lv, 2012). However, most of them concentrate on optimization of multiple intelligent algorithms (genetic algorithm, particle swarm algorithm, ant colony algorithm, etc.). System reliability is rarely thoughtfully analyzed compared to other considerations like cost and machining time.

Reliability, defined as the ability against failures, is one of the important capabilities of machines. However, reliability constraint is considered only during preventive maintenance optimization and its integrated model with production planning (Kouedeu *et al*., 2015), while it is neglected in the initial program like process planning. This paper proposes a modeling method of machining process oriented reliability optimization to highlight the dependence of failure frequency on alternative process schemes in dynamic manufacturing environment. The influence of alternative process routes on alleviation of failure effects is analyzed in this work. Considering that manufacturing operations can be conceived as a set of discrete events triggered by process flow, an event graph methodology is exploited to model the reliability evaluation of the manufacturing system. One contribution of this paper is to provide a valuable insight to understand the process-dependent failure principle for the decision-making on the potential for reliability optimization and efficiency gain of manufacturing systems. The other contribution is to afford a reliability evaluating tool for determining process schemes during the process planning period. It is noted that the selected process schemes may not be the optimal ones during scheduling period. However, this paper does provide an efficient mean to analyze system reliability elaborately, and the obtained reliability can be directly used as the optimization objective of IPPS algorithms.

This paper is organized as follows. The next section clarifies the relation of system reliability and process planning, and a modeling method for machining process oriented reliability optimization is also given. Subsequently, the simulation analysis of a case study is exhibited. Conclusions and future work is discussed at the end.

THEORY AND METHOD

Failure characteristics driven by multiple process schemes

Products are manufactured through multiple workstations and transport systems with a prescribed process route. There are various process schemes during the planning period owing to flexible capabilities of equipment and technology. On the other hand, process schemes vary a lot in the failure effects owing to the diversities of equipment in reliability and maintainability levels. Thus it is essential to allocate machining tasks and manufacturing resources properly, especially for deteriorated manufacturing systems after multiple major repairs.

The flexibility of process routing greatly influences the failure characteristics of failure-prone manufacturing system. An example is exhibited to show the influence of two alternative production schemes in Figure 1. As shown in Figure 1, the process routing of scheme 1 is from M1 to M3, while process routing of scheme 2 goes through M1, M2 and M3. Transitions of parts' location are carried out by the MHS. On the surface, reliability of scheme 1 is higher than that of scheme 2 because more serial elements are included. However, processing time is neglected, when calculating failure rates of machines. Such a computing method is quite different from that of serial electronic components. The mission time of electronic components is identical, but the processing time of machines is different. Failure probabilities of machine tools are dominated by the states transition and respective time duration of each state. In the case of MHS like a robot, there is a direct proportional relationship between the failure probability and switching times of loading and unloading movements.

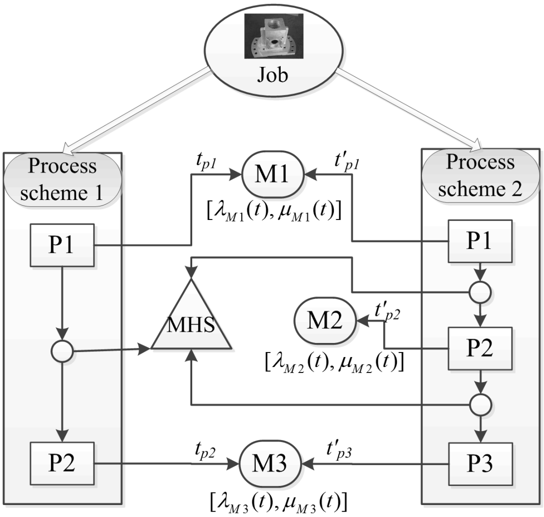

Fig. 1. Influence of process plans on reliability evaluation

As shown in Figure 2, multiple manufacturing jobs exist in the sequential production planning periods. In the first production period, Jobs 1, 2, and 3 are required to be performed. In the beginning of the second period, Job 4 is added into the machining tasks, and Job 1 is finished, the production is rescheduled in this period. Job 2 is finished at the end of the second period, which leads to another new scheduling plan. System reliability greatly depends on job types during the production. Note that process schemes of the same task may be different in two independent production periods. Dynamic jobs and alternative process schemes greatly influence the total failure times and induced costs.

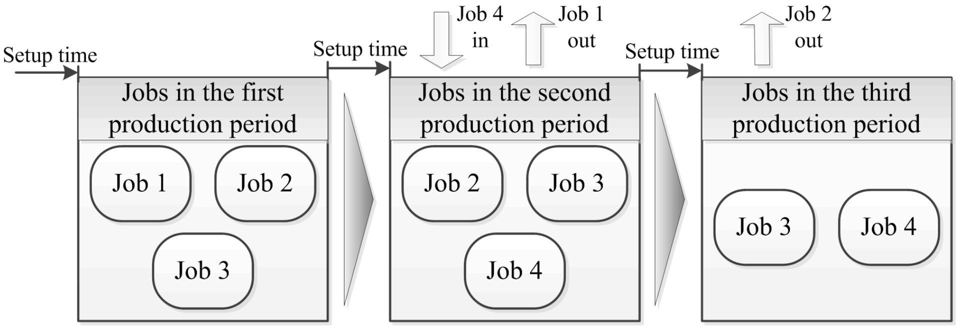

Fig. 2. Dynamic task flow in production processes

Modeling the machining process oriented reliability optimization

A manufacturing system can be conceived as a set of discrete events triggered by the state changes. In this paper, the event graph modeling approach is used to capture the dynamics of state changes. The system dynamics are characterized by events that change the state of the system and logical and temporal relationships among events (Savage *et al.*, 2005). As shown in Figure 3, three states are included to describe the working process of a single machine. In normal statistical procedures of failure data, total uptime of machine tools is counted, when calculating failure rates or mean time between failures (MTBF). Such a computing method is inherited from that of electronic systems. Nevertheless, individual uniqueness is lost, when applying the same computing method to mechanical systems, especially to machine tools with discrete tasks. Therefore, the idle state is separated in Figure 3, and the failure rate during this state is considered to be different from that of the processing time on account of different working subsystems.

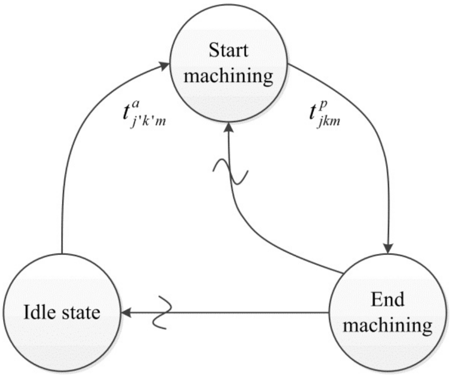

Fig. 3. Basic event graph model for a single machine

Based on the basic graph, the event graph model for system reliability evaluation is developed in Figure 4. Eight kinds of events related with the machining processes are used in the system model. They are *start event*, *process planning event*, *prepared machine event*, *start machining event*, *end machining event*, *idle waiting event*, *available MHS event* and *end event*. After the setup time between production periods, the *start event* occurs. Meanwhile, the job set is updated. A process scheme is determined during *process planning event*. Subsequently, available machine and MHS initiate the *start machining event*. Note that MHS is assumed to be always available here. Once *start machining event* occurs, two reliability operators are launched, namely, reliability operator for MHS and reliability operator in the machining time. Similarly, when *idle waiting event* is triggered, the reliability operator in the idle time is initiated. The *prepared machine event* is triggered after a time delay of $t^a_{j'k'm}$. Machining process oriented system reliability can be evaluated in terms of this model, which contributes to the decision-making on reliability optimization and production efficiency gains.

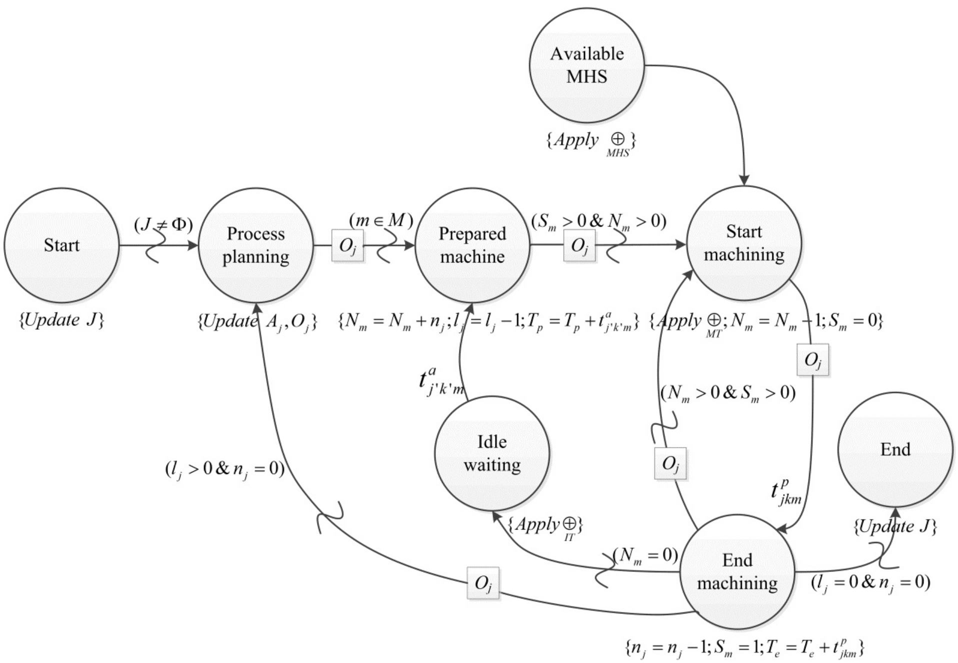

Fig. 4. Event graph model of machining process oriented reliability optimization

The notations of the event graph are listed as following:

$J=\{j\}$ job set

$A_j=\{a_{jk}\}$ process set of the job j

$O_j=\{l_j, n_j, m\}$ parameter set of job j; l_j is the number of processes for job j; n_j is the batch number of job j and m is the index for machine tool

M machine tool set satisfying the machining task of a_{jk}

N_m the number of tasks on machine m

S_m state of the machine m, it equals 1 if machine m is idle, and 0 if it is working

t^p_{jkm} the processing time of process a_{jk} on machine m

$t^a_{j'k'm}$ the time delay of the idle state for process $a_{j'k'}$ on machine m($a_{j'k'}$ is the next task after a_{jk} during machine m)

T_e, T_p the dynamic time point of the previous *end machining event* and *prepared machine event* of machine m

$h^m_p(t)$ failure rate function of the working machine m

$h^m_a(t)$ failure rate function of the idle machine m

P_S the accumulated failure times of the system

λ_{MHS} the failure rate for a transition of the part's location between processes (a combination of unloading and loading movements)

Accordingly, the detailed description of the events and transitions is provided in Table 1.

Table 1. Description of the event graph model

Events	Description	State changes	Required conditions
Start	A new job arrives	Update the job set J	
Process planning	A process scheme is determined for the job	Update the process set A_j and the parameters l_j, n_j, m in the set O_j	Job set $J \neq \Phi$, or the number of processes $l_j>0$ and the batch number $n_j=0$
Prepared machine	The machine is prepared for its missions	Increase by n_j of the number of tasks on machine $m(N_m=N_m+n_j)$; Decrease by 1 of the number of processes for job $j(l_j=l_j-1)$; Increase by $t^{a}_{j'k'm}$ of T_p ($T_p=T_p+ t^{a}_{j'k'm}$)	The machine m can satisfy the machining of a_{jk} ($m \in M$)
Start machining	The process is started to be machined	Decrease by 1 of the total number of tasks($N_m=N_m-1$); Set S_m to be 0; Applied the reliability operator in the machining time	The number of tasks $N_m>0$ and the machine is in idle state($S_m>0$)
End machining	The process is finished	Decrease by 1 of the batch number of process $a_{jk}(n_j=n_j-1)$; Increase by t^{p}_{jkm} of T_e ($T_e=T_e+t^{p}_{jkm}$)	The processing time t^{p}_{jkm} passes
Available MHS	The MHS is prepared	Applied the reliability operator for MHS	MHS is assumed to be always available
Idle waiting	The machine m is idle	Applied the reliability operator in the idle time	The number of processes $N_m=0$
End	Job j is finished	Update the job set J	The number of processes $l_j>0$ and the batch number $n_j=0$

Description for the above three reliability operators is listed as following Equation (1) to Equation (3). Delivery times of unloading and loading movements are counted for reliability calculating use. P_{MHS} is assumed to be a constant value in this paper. Thus P_S can be updated as the sum of the former P_S and P_{MHS}. The reliability operator for MHS is denoted as $\underset{MHS}{\oplus}$, and the reliability operator for processing a_{jk} can be shown as

$$\underset{MHS}{\oplus}(a_{jk}):P_S \leftarrow P_S+\lambda_{MHS} \tag{1}$$

the reliability operator in the machining time is represented by $\underset{MT}{\oplus}$. The operator for processing a_{jk} can be obtained as

$$\underset{MT}{\oplus}(a_{jk}):P_S \leftarrow P_S+\int_{T_e}^{T_e+t_{jkm}^{p}} h_p^m(t)dt \tag{2}$$

Similarly, the reliability operator in the idle time for processing $a_{j'k'}$ is shown as

$$\underset{IT}{\oplus}(a_{j'k'}):P_S \leftarrow P_S+\int_{T_p}^{T_p+t_{j'k'm}^{a}} h_a^m(t)dt\,. \tag{3}$$

SIMULATION ANALYSIS

Flexible process scheme is an important characteristic of modern manufacturing system. To some extent, the decision-making on a suitable process scheme can mitigate the negative effects of unreasonable system configuration, such as a wrong arrangement of an unreliable machine. On the other hand, an adaptive decision for process planning is increasingly important with the degeneration of equipment. In this paper, the proposed machining process oriented reliability optimization method is employed to analyze and select the flexible process routes on the purpose of reducing failure effects and improving system efficiency.

The proposed method is tested and verified in a shop floor that produces high-voltage electrical apparatus. Job types and their volume sizes are shown in Figure 2. Four jobs are required to be planned during three production periods. For example, the total processing tasks for Job 1, Job 2 and Job 3 during the first production period are 1200, 1500 and 1000, respectively, which are determined according to the due date of orders. Alternative process schemes and machining time of processes are exhibited in Figure 5.

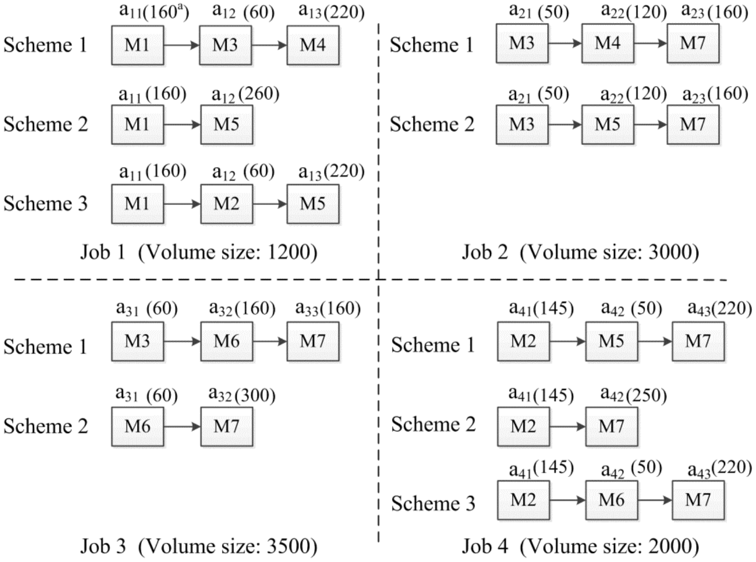

Fig. 5. Alternative process schemes of jobs (^{a} the unit of the processing time is sec)

In order to investigate failure effects during different periods of the system's life cycles, we present the reliability and cost parameters for each machine in Table 2. Weibull distribution $\lambda_m(t) = (\alpha_m / \beta_m)(t / \beta_m)^{\alpha_m - 1}$ is proved to fit the machining failure data of machines, wherein α_m and β_m are the shape and scale parameter, respectively. Exponential distribution is applied to fit these time-dependent failures such as power systems, wherein λ_m represents failure rate of machine m in the idle state (i.e., $h_a^m(t)=\lambda_m$). The failure rate of MHS is also supposed to be a constant.

It is well-known that a manufacturing system is subject to degradation due to imperfect maintenance activities. In order to illustrate the failure effects during different periods of the system's life cycle, a hybrid hazard rate evolution is adopted based on the age reduction method and the hazard rate increase method (Zhou *et al.*, 2007). The relationship between the hazard rate functions before and after the *i*th preventive maintenance (PM) can be defined as

$$h_{m(i+1)}(t) = b_{mi} h_{mi}(t + a_{mi} T_i) \quad \text{for} \quad t \in (0, T_{i+1}) \tag{4}$$

where $0<a_{mi}<1$ and $b_{mi}>1$ are the age reduction factor and the hazard rate increase factor, respectively. Both the factors need to be deduced from the history of maintenance data and condition monitoring (Xia *et al.*, 2012; Zhou *et al.*, 2007). T_i is the time interval for *i*th PM. For simplicity, it is set to be a constant value with the aim of investigating the failure effects under different system reliability levels.

Table 2. Reliability and cost information of machine tools

	α_m	β_m	$\lambda_m(\times 10^{-3})$	a_{mi}	b_{mi}
M1	1421	1.85	0.15	$i/(25i+5)$	$(17i+1)/(16i+1)$
M2	1228	2.11	0.15	$i/(20i+20)$	$(18i+3)/(17i+3)$
M3	1033	1.98	0.17	$i/(16i+14)$	$(21i+1)/(20i+1)$
M4	1022	2.14	0.14	$i/(20i+25)$	$(19i+2)/(18i+2)$
M5	1526	2.07	0.15	$i/(24i+20)$	$(27i+1)/(26i+1)$
M6	998	2.51	0.15	$i/(30i+20)$	$(17i+1)/(16i+1)$
M7	984	2.12	0.18	$i/(20i+15)$	$(19i+2)/(18i+2)$

Suppose that scheme 1 of all jobs is selected. Then, system failure rate (the sum of failure rates for all individual equipment) can be obtained as shown in Figure 6 by applying the proposed method to the processing tasks in Figure 2, where T_i is set to be 400 hours and failure rate of MHS is 0.25×10^{-3} for every delivery time. The event graph model is simulated with Simulink tool in MATLAB. Average failure rate of the system increases sharply as PM cycles owing to degradation. For instance, the system failure rate is 0.041 when i=20, which means there are about 4.1 failures per 100 hours. System performance would be badly influenced by those failures owing to the corresponding maintenance cost and extra production loss during the repair time.

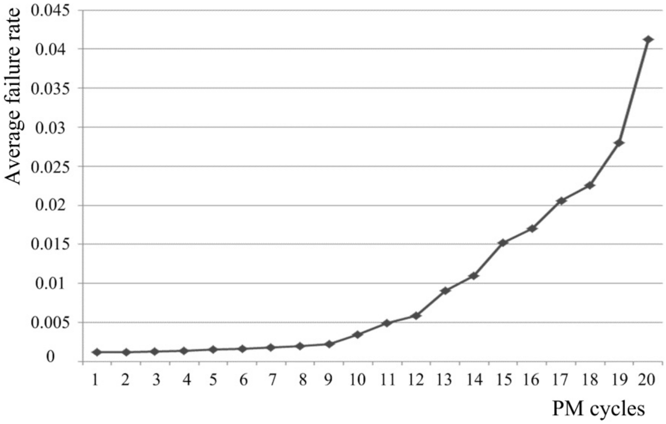

Fig. 6. Description of average failure rate during different periods of system's life cycle (T_i=400 hours)

Based on the previous analysis, there are different system reliability levels under different process schemes owing to the diversity of total processing contents (such as a hole can be finished by a boring machine or a drilling machine) and failure characteristics of machines. For testing purpose, the method is applied to a failure-prone manufacturing system in the 15th PM cycles (i.e., i=15) to illustrate the effects of alternative process schemes on reliability optimization. In the first production period in Figure 2, there can be 12 scenarios by selecting any one of the process schemes of a job. Each process scheme is scheduled to minimize the makespan based on the method proposed in Ponnambalam *et al.* (2000). The results of total failure probabilities and makespan for 12 scenarios are exhibited in Figure 7.

As shown in Figure 7, the system failure rate varies from 0.0114 (S6) to 0.0186 (S2), which is approximately a range of 63.16% variation. Therefore, it obviously indicates that there can be a significant role in reliability optimization with alternative processes for the same jobs. In this case, scenario 6 obtains the minimum system failure rate as well as the minimum makespan. However, there is actually trade-off between system reliability and makespan, which is not obviously concluded in this paper. Besides, further reliability optimization can be achieved by an insight into the constitution for the system failure rate of scenario 6. In the case of Scenario 6 (Job 1: M1->M5, Job 2: M3->M4->M7, Job 3: M6->M7), the failure rate M7 is 0.0065 hour^{-1}. It is clear that more reliability and maintenance improving effort should be put on M7 to obtain a better system performance. The smart workload allocation can help to mitigate the load unbalance between machines and achieve reliability optimization.

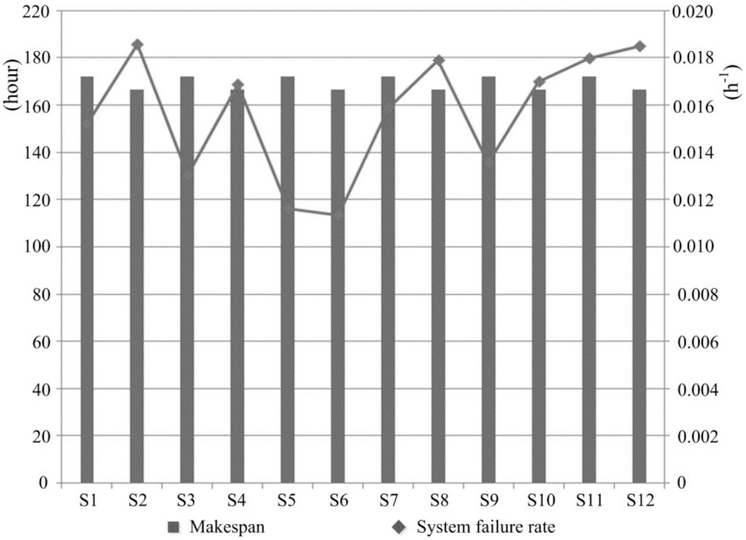

Fig. 7. Results of system failure rate and makespan for 12 scenarios (i=15)

The above job shop is merely applied for verification purpose. When we need to design the scheduling of jobs for a more complex system in IPPS algorithms, the two objectives (i.e., system reliability and make-span of all jobs) may be conflicting. Then it turns to be a double-objective optimization problem, which is another research issue in the future work.

CONCLUSIONS AND FUTURE WORK

This paper proposes a machining process oriented reliability optimization method for manufacturing system. Reliability of mechanical system is closely related with its operation states, based on which an event graph is used as the system reliability analysis model. Subsequently, system reliability is surveyed under different life cycles; it is inferred that reliability based process planning is of great importance for efficiency growing of failure-prone manufacturing systems. However, this paper fails to afford a trade-off strategy between reliability and make-span from the perspective of scheduling optimization.

Understanding and characterizing the machining process oriented reliability analysis for failure-prone manufacturing system essentially contributes to explore potential reliability optimization and efficiency improvement. Most of the literature for reliability analysis of machining and manufacturing systems is aimed at individual equipment based on failure and repair data for months. Besides, Maintenance policy optimization and maintenance resources allocation have always been the research focus of reliability assurance for manufacturing system. Compared to these growth measures of individuals' reliabilities, process planning affords a more convenient way from the machining processes perspective. It offers a solution for reliability optimization by rational use of manufacturing resources, instead of more expensive activities like reconfiguration or redundancy allocation.

A highly reliable manufacturing system does not always consist of highly reliable equipment, but the result of effectively coupled interaction of system configuration, production planning and maintenance strategy. Thus configuration optimization, spare parts prediction and smart workload allocation during production would be interesting to pursue in further research.

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