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Reconfiguration-oriented opportunistic maintenance policy for reconfigurable manufacturing systems

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ABSTRACT

In today's highly competitive industrial market, reconfigurable manufacturing systems (RMSs) have been invented for diverse products, high quality and quick manufacturing. However, the changeable system structure brings new challenges for multi-unit maintenance scheduling. Thus, this research attempts to develop a novel dynamic maintenance strategy for those reconfigurable structures. In the machine-level decision-making, dynamical maintenance intervals are scheduled according to individual machine degradation. For responding rapidly to various system-level reconfigurations, RMS characters and maintenance opportunities are comprehensively considered. Then, a reconfigurable maintenance time window (RMTW) method is proposed to make real-time schedules for system-level opportunistic maintenance. This reconfiguration-oriented maintenance policy is demonstrated through the case study in a hydraulic steering factory. It is concluded that the proposed methodology can efficiently achieve rapid responsiveness and cost effectiveness for reconfigurable manufacturing systems.

1. Introduction

With the aggressive industrial market competition, industries and academics have focused on the reconfiguration concept for providing large product variety in demand and quick response to manufacturing adjustments [1–3]. Therefore, reconfigurable manufacturing systems (RMSs) have been invented with the characters as the dynamic adjustment of manufacturing capacity/functionality according to high market fluctuations for rapid changes in system structure, its machines and controls. RMS really helps to address future manufacturing system's flexibility and responsiveness [4,5]. On the other side of the coin, these novel characters of reconfigurable structures bring new challenges for multi-unit maintenance scheduling, which is essential for operating the system and its machines in good condition.

In traditional manufacturing systems for mass production, the system structures are rarely changed after the original design, thus the existing multi-unit maintenance strategies were normally presented in term of different stationary structures. Capturing the best characters of dedicated manufacturing lines (DMLs) and flexible manufacturing systems (FMSs), RMSs provide a modern production mode to take advantage of reconfigurable structures to make various products within limited time in a cost-effective manner [6,7]. However, unexpected failures will inevitably lead to a failure and corresponding downtime, and huge cost wastes will be caused by improper scheduling in realistic environments [8–10]. Therefore, other than classical system-level maintenance strategies, a novel opportunistic maintenance policy is required to efficiently achieve rapid responsiveness and cost effectiveness. In this decision-making process of interactive machine-level and system-level scheduling, changeable structures and maintenance opportunities should be comprehensively considered for responding rapidly to open-ended reconfigurations.

In an advanced RMS, various types of machines with different reliability parameters and degrading processes make up the reconfigurable structure. It is understood that reconfigurations include not only adding/removing machines to/from the system, but also replacing one machine with another machine in manufacturing systems [11]. Thus, individual machine degradation should be considered in the machine-level scheduling. As machinery maintenance technology emerged, diagnostics and prognostics gradually permeated all areas of mechanical engineering for condition-based maintenance (CBM) and prognostic and health management (PHM). Nowadays, there are many kinds of professional instruments, such as sensors, meters, controllers and computational devices, for conducting machine diagnostics and prognostics. These instruments can be used to acquire and

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analyze signals from a machine or process. More and more monitoring techniques of CBM and PHM are available to obtain machine degradation data [12–14]. Thousands of valuable machine-level maintenance studies have been published [15–18]. Here, the degradation based multi-attribute maintenance model integrating multiple attribute value theory, imperfect maintenance modelling and sequential scheduling mode is utilized to dynamically schedule maintenance intervals in the machine-level decision-making, which is the foundation of the system-level scheduling for the whole RMS.

As a modern production mode, the structure of RMS can be adjusted at the system level to meet various future products and changeable market demands. In other words, the main advantage of RMS is the adaptability to the uncertainties of the open system architecture with reconfigurable system structures. Many valuable studies dealing with RMS layouts and characteristics have been published [19,20]. Abdi [21] investigated RMS characteristics in order to identify the crucial factors influencing the machine selection and the machine (re)configuration, and changeover cost and changeover time were taken into account. Niroomand et al. [22] developed a decision model to explain how product life cycle and new product frequency could affect the system selection, while the ramp up time and reconfiguration period of RMS were incorporated as a function of the amount of added or removed capacity. Guan et al. [5] proposed a revised electromagnetism-like mechanism for the layout design of RMSs utilizing automated guided vehicle, where the main decision variables were the allocation variables for workstations to sites.

In the system-level scheduling, those diverse reconfigurations are caused by the changing needs in terms of capacity and functionality, while the production process will be separated into sequential manufacturing stages. Each manufacturing stage has its own system structure designed for its current production requirements. If the system-level maintenance strategy has to be rebuilt according to each different structure, the system responsiveness and flexibility will be obviously weakened. In fact, since the complexity (economic, stochastic and structural dependences) of system-level maintenance scheduling, even those researches related to this problem in term of different stationary structures are of high difficulty and value. For instance, Zhou et al. [23] proposed an opportunistic maintenance policy for multi-component systems with considering stochastic failures and disassembly sequence. Tan et al. [24] studied a parallel-machine maintenance scheduling problem to minimize the total completion time. Ruiz-Castro and Li [25] proposed a methodology for a k-out-of-n system subject to different failure types. For the maintenance scheduling for series-parallel systems, Zhou et al. [26] studied an effective approach to reducing strategy space for maintenance optimization of multistate series–parallel systems, which used the upper bound of expected system revenue difference under two different subsystem-level strategies as the criterion to reduce the strategy space. Xia et al. [27] developed a dynamic opportunistic maintenance methodology to make a cost-effective schedule for series-parallel systems. Azadeh et al. [28] proposed a combined Markovian simulation model to evaluate the condition-based maintenance effectiveness for series-parallel power generation system. In sum, it can be found that most previous works concentrate on the stationary system structure problems and may not be applied directly in the reconfigurable structure problem.

With the aim of developing proper maintenance policy for RMS, it is necessary to comprehensively consider maintenance opportunities and changeable structures to respond rapidly to various system-level reconfigurations. On the one hand, compared with the traditional group maintenance which delays the preventive maintenance (PM) actions until the preset value or time, opportunistic maintenance is a more aggressive strategy to keep the system in good condition and cost-effective manner. For related valuable research articles, see, e.g. [29–32]. Gu et al. [33] investigated hidden opportunities for performing proper maintenance tasks during production time without causing production losses, where failure-induced starvation or blockage time was defined as a passive maintenance opportunity window. Ni et al. [34] developed a prediction model to identify preventive maintenance opportunity windows for large production systems based on real-time factory information system data. When one machine in the system fails or is preventive maintained, PM opportunities arise for other machines. The advantage of opportunistic maintenance is to dynamically adjust related PM actions, decrease unnecessary system downtime, and save wasteful maintenance cost. On the other hand, considering the RMS characters such as customization, convertibility, scalability, modularity, integrability and diagnosability, the speed of responsiveness is a novel scheduling goal for advanced manufacturing systems [35–37]. Rapid responsiveness provides a key competitive advantage for RMS by adjusting production capacity when the market grows and adding functionality when the product changes.

Therefore, for achieving a responsive RMS with production capacity adjustable to product demand fluctuations while functionality adaptable to new products, it is imperative to develop a novel reconfiguration-oriented maintenance policy: (1) Real-time and sequential bi-level interactive scheduling, other than conventional long-term maintenance optimization, is presented as the decision-making mode; (2) Open-ended reconfigurations separate the production process into sequential manufacturing stages and cause immediate scheduling adjustments at the system level; (3) In each manufacturing stage with reconfigured system structure, rebuilt maintenance time window utilizes every PM opportunities to optimize the cost effect and decrease the scheduling complexity; (4) Systematic framework of reconfigurable maintenance time window (RMTW) helps to ensure the RMS responsiveness and the maintenance cost effectiveness during the whole production process.

This paper presents a reconfiguration-oriented opportunistic maintenance policy to achieve rapid responsiveness and cost effectiveness for future RMS manufacturing. In the machine-level scheduling, PM intervals are dynamically obtained through the degradation based multi-attribute maintenance model. In the system-level scheduling, by considering changeable structures and maintenance opportunities, a reconfigurable maintenance time window (RMTW) method is proposed to make real-time schedules in sequential manufacturing stages. RMTW is a dynamic time window that changes according to each real-time reconfiguration. During manufacturing stages, dynamic widths of RMTW are defined as the criteria to separate the PM actions in parallel subsystems and combine the PM actions in series subsystems when one machine has its downtime, which leads to PM opportunities for other non-failed machines. Numerical examples are also given to demonstrate that the proposed methodology can efficiently adapt to various system reconfigurations, decrease system-level scheduling complexity, avoid unnecessary RMS downtime and optimize maintenance cost effect.

The remainder of this paper is organized as follows: Section 2 discusses the framework of the reconfiguration-oriented opportunistic maintenance policy. In Section 3, the degradation based multi-attribute maintenance model at machine level is briefly presented; then the decision-making analysis of system-level reconfiguration is outlined; based on these, the reconfigurable maintenance time window method at system level is developed. Section 4 gives numerical examples of RMS in a hydraulic steering factory to illustrate the effectiveness of the proposed policy. Finally, some concluding remarks are provided in Section 5.

2. Research statement and methodology

As known, according to changeable market demands and manufacturing adjustments, diverse reconfigurations bring new system structures in sequential manufacturing stages. In the traditional multi-unit maintenance scheduling manner, we have to rebuild new system-level policies for these various stationary structures. This traditional manner not only causes intractable scheduling complexity, but also weakens the rapid responsiveness, which is one of the core

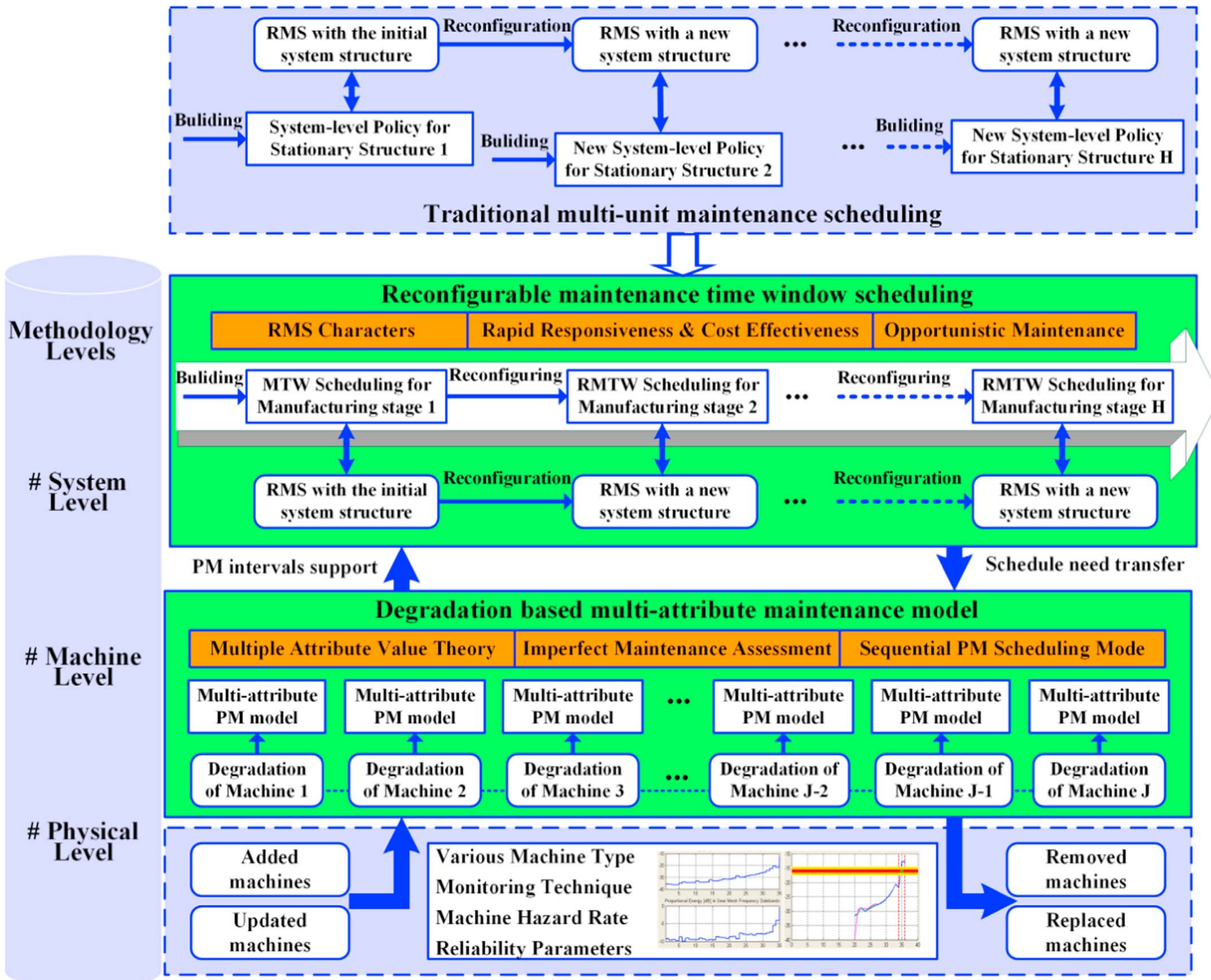

Fig. 1. Framework of reconfiguration-oriented opportunistic maintenance policy.

advantages in RMS characters. Therefore, a reconfiguration-oriented opportunistic maintenance policy is applied as the decision-making process to deal with the dynamic maintenance of RMS. This novel manner provides reconfigurable maintenance time windows (RMTW) to dynamically utilize maintenance opportunities based on machine-level schedules, and its framework is sketched by Fig. 1. Other than the traditional manner, the proposed manner focuses on reconfiguring scheduling criteria within a uniform method for rapidly adapting to new reconfigurable system structures.

As a whole, the proposed reconfiguration-oriented opportunistic maintenance methodology consists of following levels:

(1) Physical level: An advanced RMS with various types of machines is defined as the decision object. The reconfigurable structure, as well as the information of its machines (various machine type, monitoring technique, hazard rate and reliability parameters), will be required and analyzed. It should be noticed that the physical level not only concerns the machines in the initial system, but also follows those added or updated machines after each reconfiguration.

(2) Machine level: With the degradation information gathered in the previous level, PM intervals are dynamically obtained through the degradation based multi-attribute maintenance model. Multiple attribute value theory, imperfect maintenance assessment and sequential PM scheduling mode contribute to the development of the machine-level dynamic PM model. Two kinds of maintenance actions are considered to reduce unanticipated downtime: PM action, as imperfect maintenance, improves the machine condition but not makes it as good as new; while minimal repair, which only recovers the machine to the failure rate that it had when it failed, is used when the machine fails between successive PM actions.

(3) System level: By transferring schedule needs and pulling the real-time PM intervals, RMTW method is presented to optimize maintenance schedules with rapid responsiveness and cost effectiveness for the whole RMS. Other than rebuilding new system-level policies for various stationary structures, RMTW utilizes every downtime caused by one machine to perform PM on non-failed machines all along, thus unnecessary downtime of the whole RMS could be avoided. Facing different system structures in sequential manufacturing stages, this methodology focuses on changeable structures and maintenance opportunities to reduce the total system maintenance cost and avoid unnecessary downtimes resulting from excessive maintenance actions.

To validate that the proposed policy can efficiently adapt to diverse system reconfigurations, decrease system-level scheduling complexity,

Table 1
Notation.

j: Index of machine S	h: Index of manufacturing stage MS_h
i: Index of PM cycles in machine level	k: Index of PM cycles in system level
$\lambda_{ij}(t)$: Hazard rate function prior to the ith PM	t_{jk}: PM time point of Sj in system level
C_{pij}: Cost of PM action	t_k: PM execution point in system level
C_{fij}: Cost of minimal repair	t_{Rh}: Time point of the hth reconfiguration
T_{pij}: Time duration of PM action	T_{Rh}: Time duration of the hth reconfiguration
T_{fij}: Time duration of minimal repair	T_{Wh}: Time width of RMTW in MS_h
T_{oij}: PM interval of machine level	$T_{pk\ \max}$: Maximum PM duration at t_k
c_{dj}: Downtime cost rate	$\Theta(j, t_k)$: Maintenance decision for Sj at t_k
MC_{kj}: Maintenance cost of the kth cycle for Sj	TMC: Total maintenance cost for the RMS

avoid unnecessary RMS downtime and optimize maintenance cost effect, this reconfiguration-oriented opportunistic maintenance methodology will be introduced and demonstrated in detail. The notation used in this paper is listed in Table 1.

General assumptions:

(1) At time t=0, the RMS original design can be seen as the first reconfiguration ($T_{R1} = 0$), and the system enters operation with the initial system structure. According to the changing needs in terms of capacity and functionality, open-ended reconfigurations separate the following production process into sequential manufacturing stages.
(2) The machines in the RMS are independent with individual machine degradations. The rate of deterioration increases as the machine ages if there is no maintenance intervention. The maintenance resources (crews, tools and so on) are sufficient at all times.
(3) At the beginning of each manufacturing stage, the reconfiguration may include adding new machines to increase the capacity, moving machines from the system, replacing machines for functionality adjustment, and so on. Various reconfigurations could be designed.
(4) The production operations of the whole system continue except machine unavailability due to PM, minimal repair, failure or reconfiguration. The changeable machines in the RMS are flexibly interconnected according to each new system structure.
(5) System-level reconfigurations imply adding/removing machines to/from the RMS, and replacing one machine with another. These layout adjustments and machine relocations affect maintenance actions, thus PM actions are not performed during the reconfiguration period.

3. Reconfiguration-oriented opportunistic maintenance policy

In the proposed dynamic maintenance methodology for reconfigurable structures of RMS, PM intervals are dynamically scheduled according to individual machine degradation. By pulling these machine-level outputs, RMTW makes real-time opportunistic maintenance schedules in system level. In this section, firstly, the maintenance model for machine-level scheduling is presented by taking advantages of multiple attribute value theory, imperfect maintenance assessment and sequential PM scheduling mode. Secondly, the decision-making analysis of system-level reconfiguration is outlined, while the illustration of RMS production scenarios is provided. Thirdly, the procedures of the developed RMTW method for system-level scheduling will be demonstrated in detail; Dynamic widths of RMTW are defined as the criteria to separate the PM actions in parallel subsystems and combine the PM actions in series subsystems for reconfigurable structures. This RMTW optimum aims to not only adapt to even complex series-parallel structures, but also achieve rapid responsiveness and cost effectiveness for future RMS manufacturing.

3.1. Degradation based multi-attribute maintenance model

In machine level, the duration between two successive PM actions is defined as one PM cycle. Imperfect PM actions and minimal repairs are conducted to lengthen the useful lifetime by reducing cumulative failure risk in sequential PM cycles for every machine. An availability model and a cost model are combined to develop the multi-attribute maintenance model to plan availability-effective and cost-effective PM intervals. The procedures of the degradation based PM model can be described as follows:

Procedure 1: For each machine Sj, assess the reliability parameters (T_{pij}, T_{fij}, C_{pij}, C_{fij}), the maintenance effect and the initial hazard rate function $\lambda_{1j}(t)$ from the physical level of RMS. Start the scheduling from the cycle i=1 (the first PM cycle).

Procedure 2: Separately solve the availability model and the cost rate model as the process of single-attribute scheduling. Output the solutions of the ith PM cycle (A_{ij}^*, T_{aij}^*, c_{rij}^*, T_{cij}^*):

$$\text{Availability model: } A_{ij} = \frac{T_{aij}}{T_{aij} + (T_{pij} + T_{fij}\int_0^{T_{aij}} \lambda_{ij}(t)\mathrm{d}t)} \tag{1}$$

$$\text{Cost rate model: } c_{rij} = \frac{C_{pij} + C_{fij}\int_0^{T_{cij}} \lambda_{ij}(t)\mathrm{d}t}{T_{cij} + T_{pij} + T_{fij}\int_0^{T_{cij}} \lambda_{ij}(t)\mathrm{d}t} \tag{2}$$

In the availability model, the numerator equals to the useful time (PM interval), and the denominator equals to the PM cycle duration, where $\int_0^{T_{ij}} \lambda_{ij}(t)\mathrm{d}t$ is the expected frequency of failures. In the cost rate model, the numerator equals to the total maintenance cost. For the ith PM cycle, the optimal T_{aij}^* for the maximum A_{ij}^* and the optimal T_{cij}^* for the minimum c_{rij}^* can be obtained by:

$$(dA_{ij}/dT_{aij})|_T = 0 \tag{3}$$

$$(dc_{rij}/dT_{cij})|_T = 0 \tag{4}$$

Procedure 3: Transfer the A_{ij}^* and c_{rij}^* into the multi-attribute maintenance model. For integrating the availability model and the cost rate model, we use A_{ij}/A_{ij}^* and c_{rij}/c_{rij}^* to eliminate differences of unit and quantity. For each attribute, the values of A_{ij}/A_{ij}^* and c_{rij}/c_{rij}^* are preferred to be 1, which means the corresponding attribute achieves the best level as in single-attribute scheduling. Besides, since a large A_{ij} and a small c_{rij} are preferred, $-A_{ij}/A_{ij}^*$ is utilized to ensure the minimization of the overall objective. This is the process of multi-attribute optimal scheduling for the ith PM cycle.

$$\text{Multi-attribute model: } V_{ij} = -w_{1ij}\frac{A_{ij}}{A_{ij}^*} + w_{2ij}\frac{c_{rij}}{c_{rij}^*} \tag{5}$$

In this function, the machine-level PM interval, denoted by T_{oij}, takes place of T_{aij} and T_{cij}. The solution is the machine-level PM interval T_{oij}^*, which can be obtained by minimizing the overall objective V_{ij}. We can have $\min(T_{aij}^*, T_{cij}^*) \le T_{oij}^* \le \max(T_{aij}^*, T_{cij}^*)$ by:

$$(dV_{ij}/dT_{oij})|_T = 0 \tag{6}$$

Prolongation: Assume there are L objectives (O_1, O_2, … ,O_L). The overall objective function is minimized to obtain the optimal PM interval. If a small O_{lij} (like c_{rij}) is preferred, $\Delta_l = 0$; if a large O_{lij} (like A_{ij}) is preferred, $\Delta_l = 1$. Thus, the multi-attribute PM model becomes:

$$V_{ij} = w_{1ij}\frac{(-1)^{\Delta_1}O_{1ij}}{O_{1ij}^*} + w_{2ij}\frac{(-1)^{\Delta_2}O_{2ij}}{O_{2ij}^*} + \dots + w_{Lij}\frac{(-1)^{\Delta_L}O_{Lij}}{O_{Lij}^*} \tag{7}$$

where the attribute weights $w_{1ij} + w_{2ij} + \dots + w_{Lij} = 1$. The relative importance of the objectives is measured by these attribute weights.

In practice, there are various methods developed to evaluate the weights for different objectives, such as Delphi method, Analytic Hierarchy Process (AHP), Entropy method, Fuzzy Cluster Analysis and Cellular Automaton model [38–40].

Procedure 4: Find whether cumulative intervals go beyond the mission lifetime T_{LIFE}: No, turn to Procedure 5 and schedule the next cycle; Yes, turn to Procedure 6 and stop the procedures.

Procedure 5: Assign i=i+1 and turn back to Procedure 2 to schedule the next cycle. Model the imperfect maintenance based on age reduction factor. The age reduction factor $a_{ij} \in (0, 1)$ indicates that PM reduces machine's initial failure rate to $\lambda_{ij}(a_{ij}T_{ij})$, other than $\lambda_{(i+1)j}(0) = 0$. Thus, the relationship of hazard rates between successive PM cycles can be defined as:

$$\lambda_{(i+1)j}(t) = \lambda_{ij}(t + a_{ij}T_{ij}) \tag{8}$$

where $t \in (0, T_{(i+1)j})$.

Procedure 6: Output the last PM cycle $T_{oIj} = T_{\text{LIFE}} - \sum_{i=1}^{I-1}(T_{oij}^{*} + T_{pij} + T_{fij}\int_0^{T_{oij}^{*}} \lambda_{ij}(t)\mathrm{d}t)$. These real-time PM intervals will support the system-level scheduling, and be updated with RMTW decision feedbacks in Procedure 5 for the next cycle.

3.2. Decision-making analysis of system-level reconfiguration

It is understood that the machine-level PM intervals don't mean the optimum maintenance schedules for the whole RMS. The structural dependences in a stationary system structure already bring PM conflicts and cause unnecessary downtime, no matter in an advanced RMS experiencing various system-level reconfigurations. In practice, an RMS usually consists of different types of machines, which suffer increasing degradation at different rates. Besides, system-level reconfigurations imply adding/removing machines to/from the RMS, and replacing one machine with another machine. Therefore, the decision-making analysis of system-level reconfigurations concentrates on an opportunistic maintenance methodology that not only reflects individual machine degradations, but also responses rapidly to reconfigurable structures.

In this situation, the reconfigurable maintenance time window (RMTW) method is presented to utilize every downtime caused by one machine to perform PM on non-failed machines, thus unnecessary downtime of the whole RMS could be avoided. If we have a further research on system-level reconfigurations, the following RMS characters can be noticed: the RMS is designed to be operational for a production lifetime during which the products that it produces will change; new product adjustment will cause the reconfiguration to change functionality, while increasing product demand leads to the reconfiguration to increase capacity; these diverse reconfigurations separated the production process into sequential manufacturing stages, while each stage has its new system structure designed for its current production requirements; and during the lifetime, the RMS will evolve constantly as it adapts itself to the market through rapid reconfiguration cycles (manufacturing stages). The schematic illustration of RMS production is shown in Fig. 2.

Many valuable researches have been devoted to redesign RMS structures by considering the impacts of reconfiguration cost. The research presented by Bruccoleri et al. [2] focused on understanding whether the reconfiguration ability of RMSs could be used and coupled with the routing flexibility in the error handling process, further increasing its cost-effectiveness. Bensmaine et al. [7] investigated RMS design by considering two main objectives respectively the minimization of the costs (production cost, reconfiguration cost, tool changing cost and using cost) and the total completion time. Abdi [21] took changeover cost and changeover time into account in the study of the crucial factors influencing RMS selection and (re)configuration.

This study focuses on the reconfiguration-oriented opportunistic maintenance policy to achieve rapid responsiveness and cost effectiveness for the constantly rebuilt RMS with new structures. No matter what reconfiguration the RMS goes through in the light of functionality/capacity demand, its new structure still consists of different parallel subsystems or series subsystems. Parallel structure, series structure and series-parallel structure can be viewed as three configuration clusters. Thus, in sequential manufacturing stages, the RMTW can be applied as criteria to separate the PM actions in parallel structure and to combine the PM actions in series structure, while PM separations and PM combinations are integrated for series-parallel structure by analyzing the redesigned system configuration. The dynamic RMTW scheduling aims to reduce the total system maintenance cost by dynamically utilizing the maintenance opportunities and avoiding unnecessary downtimes resulting from excessive maintenance actions.

The RMS production scenarios in Fig. 2 can be taken as an example to illustrate the RMTW scheduling for system-level reconfigurations. After the original design, the RMS enters service at time t=t_{R1}=0 with its initial system structure (5 machines are connected in series-parallel). In this first manufacturing stage MS_1, the time width of RMTW T_{W1} is defined as a criterion to separate PM actions in parallel subsystems and combine PM actions in series subsystems based on those machine-level PM intervals.

At the reconfiguration time t_{R2}, the system structure needs to be redesigned for entering the second manufacturing stage MS_2 according to market demands. In the time duration of this reconfiguration T_{R2}, machine 1 is replaced with a new machine 6, and machine 7 is added in parallel with machine 5. Then, the RMS continues production with a new structure, while a redefined time width of RMTW T_{W2} is applied for reconfigured parallel subsystems and series subsystems to minimize the total system maintenance cost.

Similarly, in the next reconfiguration before MS_3, machine 3 is removed, while machine 8 is added in parallel with machines 2 and 4. In contrasted to the traditional manner of rebuilding new system-level policies for different structures, RMTW scheduling focuses on reconfiguring scheduling criteria T_{Wh} within a uniform method for rapidly adapting to new structures. The structure analysis of each manufacturing stage is essential for RMTW scheduling. The composition operators $\oplus$ and $\otimes$ are defined for the parallel and series connections of the machines, thus we can have the following RMS structure analysis in Table 2.

Based on the RMS structure analysis about redesigned parallel subsystems and series subsystems, the procedures of RMTW scheduling for system-level reconfigurations will be presented next in detail.

3.3. Reconfigurable maintenance time window scheduling

In system level, reconfiguration-oriented opportunistic maintenance policy is presented to achieve rapid responsiveness and cost effectiveness for the constantly rebuilt RMS with new structures. For a parallel subsystem, PM actions performed on all its units at the same time lead to the downtime of other machines located upstream or downstream, thus the RMTW is applied as the criteria to separate the PM actions for avoiding unnecessary downtime of the whole RMS. For a series subsystem, a PM action performed on one unit means the maintenance opportunity for others, so the RMTW provides a criterion to combine the PM actions for reducing the total RMS maintenance cost. Furthermore, considering diverse reconfigurations would separate RMS production into sequential manufacturing stages with different structures designed for current functionality and capacity requirements, RMS structure analysis is essential to extract reconfigured parallel subsystems and series subsystems in each manufacturing stage. The flowchart of the proposed RMTW method is shown in Fig. 3.

The detailed procedures of the system-level RMTW scheduling can be described as follows:

Procedure 1: According to the existing machines in the current RMS, pull the real-time PM intervals from the degradation based

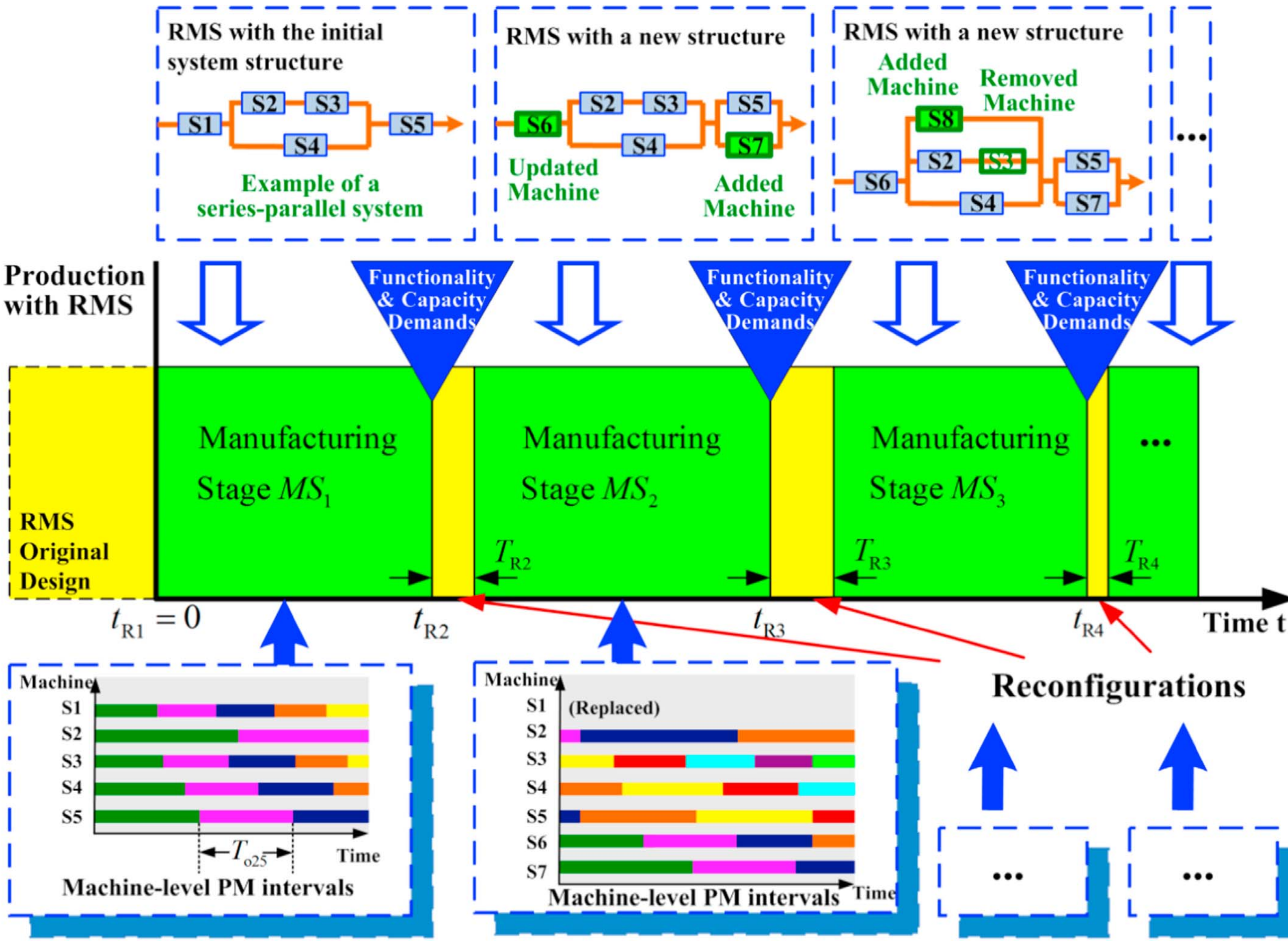

Fig. 2. Schematic illustration of RMS production scenarios.

Table 2
RMS structure analysis of manufacturing stages.

Manufacturing stage	Parallel subsystem	Series subsystem
MS_1	S2⊕S4; S3⊕S4	S1⊗S2⊗S3⊗S5; S1⊗S4⊗S5
MS_2	S2⊕S4; S3⊕S4; S5⊕S7	S6⊗S2⊗S3⊗S5; S6⊗S4⊗S5; S6⊗S2⊗S3⊗S7; S6⊗S4⊗S7
MS_3	S2⊕S4⊕S8; S5⊕S7	S6⊗S8⊗S5; S6⊗S2⊗S5; S6⊗S4⊗S5; S6⊗S8⊗S7; S6⊗S2⊗S7; S6⊗S4⊗S7
MS_h(h=4, 5, ...)	...	...

multi-attribute maintenance model in machine level. Evaluate the RMTW value T_{Wh} ($\forall\, T_{pij}\&T_{Wh}\&\,\forall\, T^*_{oij}$) and start from the cycle $i = 1, k = 1$. Assign the PM intervals T^*_{oij} to the PM time points t_{jk} of each unit for the system-level RMTW scheduling. In the first cycle, the PM time points are given by:

$$t_{jk} = T^*_{oij}\ (i = 1,\ k = 1) \tag{9}$$

Procedure 2: RMTW-separation of parallel subsystems in the manufacturing stage MS_h (h=1, 2, 3, ...). For a reconfigured N-unit parallel subsystem, an updated time width of RMTW T_{Wh} is applied to separate the PM actions for avoiding unnecessary downtime of the whole RMS. The RMTW value $T_{Wh}\&\,\forall\, T_{pij}$ ensures that RMTW-separation of parallel subsystems will not be interfered by a long PM duration. Delayed PM action according to an adequate T_{Wh} can avoid unnecessary downtime of other machines located upstream or downstream.

2-1. Check moment choice: In the kth cycle for the subsystem, choose the first machine that reaches its PM interval as j=$m1$ and assign $T_{pk(m1)} = T_{pi(m1)}$. The check moment can be chosen by:

$$t_k = t_{(m1)k} = \min(t_{jk})\ (0\&j \le N) \tag{10}$$

2-2. Reconfiguration time point check: Identify whether the check moment is greater than or equal to the next reconfiguration time point $t_{R(h+1)}$. If yes, the current manufacturing stage MS_h is over, turn to Procedure (2–7) and end the scheduling. Otherwise, turn to Procedure (2–3) and implement RMTW-separation check.

2-3. RMTW-separation check: Identify whether for all other units $t_{jk} \le t_k + T_{pk(m1)}$ $(0\&j \le N,\ j \ne m1)$, which means the downtime of this parallel subsystem. If yes, choose another S_{m2} $(m2 \ne m1)$, turn to Procedure (2–4) for PM separation. Otherwise, turn to Procedure (2–5) for the next cycle; meanwhile take S_{m1} to Procedure (2–6) for PM execution.

2-4. PM separation: Separate the PM action of S_{m2} according to the RMTW criterion by the following expression. Feedback this PM separation decision to the machine-level schedule of S_{m2}. Then, for the next cycle, assign $k = k + 1$, $t_{jk} = t_{(m2)(k-1)}$. Return to Procedure (2–1).

$$t_{jk} = t_{(m2)k} = t_k + T_{Wh} \tag{11}$$

2-5. For the next system-level PM cycle, assign $k = k + 1$, $t_{jk} = t_{j(k-1)}$ $(j \ne m1,\ j \ne m2)$. Return to Procedure (2–1).

2-6. PM execution: Execute the PM action of S_{m1}. For the next cycle, assign $k = k + 1$, $i = i + 1$, then update the system-level PM time point of S_{m1}. Return to Procedure (2–1).

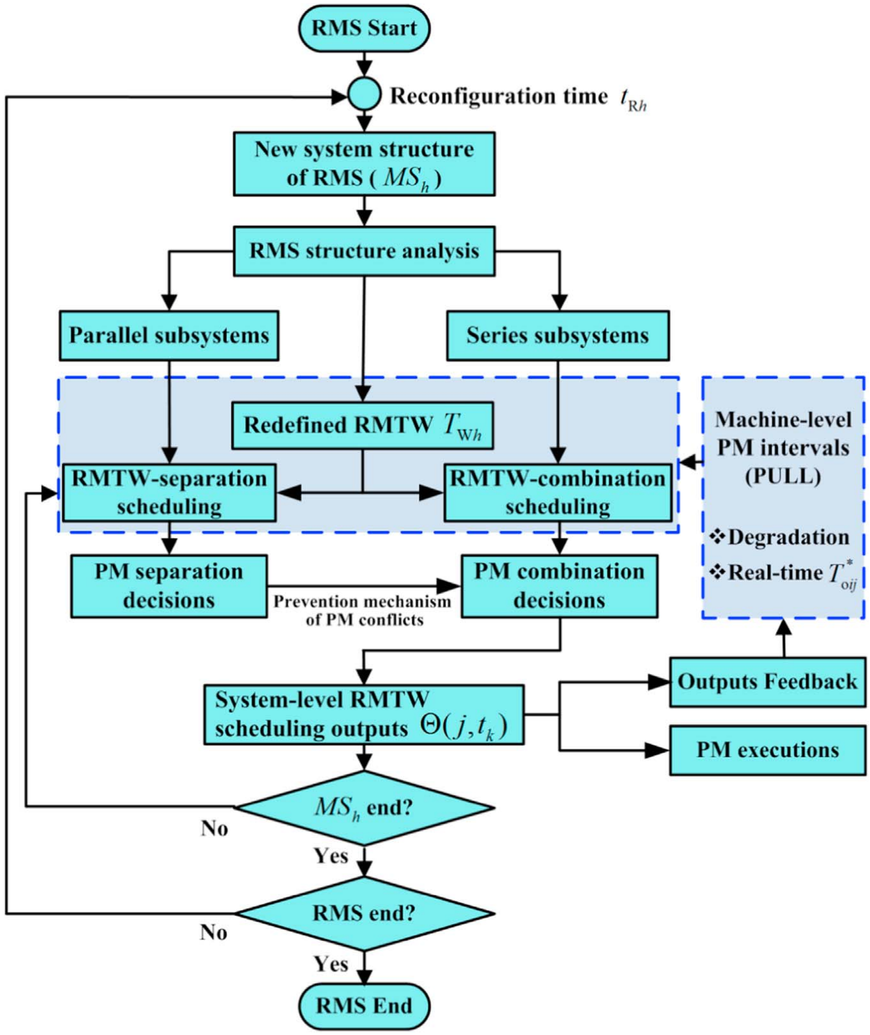

Fig. 3. Flowchart of RMTW scheduling for RMS.

$$t_{jk} = t_{(m1)k} = t_{(m1)(k-1)} + T_{p(k-1)(m1)} + T^*_{oi(m1)} \tag{12}$$

The new system-level PM time point equals to the current PM time point adding the PM duration and the new PM interval.

2–7. End the RMTW-separation programming in the current manufacturing stage MS_h. Turn to Procedure 4 to experience the reconfiguration and adjust the machines for $MS_{(h+1)}$.

Procedure 3: RMTW-combination of series subsystems in the manufacturing stage MS_h (h=1, 2, 3, ...). For a reconfigured M-unit series subsystem, an updated time width of RMTW T_{Wh} is applied to combine the PM actions for reducing the total RMS maintenance cost. The RMTW value T_{Wh}& $\forall\ T^*_{oij}$ ensures RMTW-combination of series subsystems will not be interfered by a short PM interval. A suitable time window T_{Wh} can avoid repeated PM actions on one machine at the same time.

3-1. Combination moment choice: PM action of a unit creates opportunities for other units. Based on machine-level PM intervals and system-level PM separation decisions, the PM combination moment for a series subsystem can be chosen by the first machine that reaches its PM interval:

$$t_k = \min(t_{jk})\ (0\&j \le M) \tag{13}$$

3-2. Reconfiguration time point check: Identify whether the PM combination moment is greater than or equal to the next reconfiguration time point $t_{R(h+1)}$. If yes, the current manufacturing stage MS_h is over, turn to Procedure (3–5) and end the scheduling. Otherwise, turn to Procedure (3–3) and implement RMTW-combination check.

3-3. RMTW-combination execution: Identify whether the other units $j \in \{1, 2, \ldots, M\}$ are expected to be performed PM actions within $[t_k, t_k + T_{Wh}]$. Accordingly, schedule the system-level PM decision at the combination moment t_k. Assuming that $\Theta(j, t_k) = 0$ means no PM is needed on S_j; while $\Theta(j, t_k) = 1$ means the PM action is combined to perform in advance and assign $t_{jk} = t_k$ to perform, thus the following definition could be applied:

$$\Theta(j, t_k) = \begin{cases} 0 & t_{jk}\&t_k + T_{Wh} \\ 1 & t_{jk} \le t_k + T_{Wh} \end{cases} \tag{14}$$

3-4. For the next system-level PM cycle, assign $k = k + 1$, the new PM time points t_{jk} $(0\&j \le M)$ can be provide by the following expression. Assume that $T_{p(k-1)\max}$ is the maximum time for PM actions combined in the last cycle, which is also the down time for this series subsystem during $[t_{k-1}, t_{k-1} + T_{p(k-1)\max}]$.

$$t_{jk} = \begin{cases} t_{j(k-1)} + T_{p(k-1)\max} & \Theta(j, t_{k-1}) = 0 \\ t_{(k-1)} + T_{p(k-1)\max} + T^*_{oij}(i = i+1) & \Theta(j, t_{k-1}) = 1 \end{cases} \tag{15}$$

Feedback this PM combination decision to the machine-level schedule of the combined units. Then return to Procedure (3-1) for scheduling the next PM combination moment.

3-5. End the RMTW-combination programming in the current manufacturing stage MS_h. The PM combination moments t_k

(t_{Rh}&$t_k \le t_{R(h+1)}$) could be outputted as the system-level PM schedules for the whole RMS. Turn to Procedure 4 to experience the reconfiguration and adjust the machines for $MS_{(h+1)}$.

Procedure 4: At the reconfiguration time $t_{R(h+1)}$ (h=1, 2, 3, ...), the system structure will be redesigned for the next manufacturing stage MS_{h+1}. Within the time duration of the (h+1)th reconfiguration $T_{R(h+1)}$, some machines will be remained, while some others are added or removed according to new functionality & capacity demands. Thus, in the current kth system-level PM cycle, the PM time points of all the machines in RMS should be updated. Then, these newly added or removed machines will be considered by the RMS structure analysis in Procedure 5 for the next manufacturing stage.

(1) For a remained machine, the PM time point after the reconfiguration can be obtained by:

$$t_{jk} = t_{jk} + T_{R(h+1)} \tag{16}$$

(2) For a newly added machine, the beginning-operation moment of S_j is recorded as

$$t_{j\mathrm{IN}} = t_{\mathrm{R}(h+1)} + T_{R(h+1)} \tag{17}$$

Thus, the PM time point of the newly added machine can be obtained by:

$$t_{jk} = t_{j\mathrm{IN}} + T^*_{oij}\ (i = 1,\ k = k) \tag{18}$$

(3) For a removed machine, its ending-operation moment is $t_{j\mathrm{OUT}} = t_{\mathrm{R}(h+1)}$, thus its operational lifetime can be recorded as:

$$t_{j\mathrm{LIFE}} = t_{j\mathrm{OUT}} - t_{j\mathrm{IN}} \tag{19}$$

Procedure 5: After each system-level reconfiguration, the RMS structure analysis about redesigned parallel subsystems and series subsystems will be implemented according to the new system structure. This structure analysis has been illustrated in Section 3.2. Besides, a redefined time width of RMTW $T_{W(h+1)}$ can be applied for rapidly adapting to the new structure. Return to Procedures 2 and 3 for RMTW scheduling in the new manufacturing stage MS_h ($h = h + 1$).

Procedure 6: RMS performance by using this reconfiguration-oriented opportunistic maintenance policy is evaluated based on the system-level RMTW scheduling outputs. Assuming that $\Theta(j, t_k) = 0$ means no PM action on S_j but this unit has to be down, the unit's cost is only caused by downtime for PM duration in this cycle; $\Theta(j, t_k) = 1$ means the PM action is combined to be performed in advance, the unit's cost includes PM cost, expected minimal repair cost and downtime cost; $\Theta(j, t_k) = 2$ means no PM and this unit continues working, there is no cost for this unit. Thus the expected maintenance cost of the kth cycle for S_j is obtained by:

$$MC_{kj} = \begin{cases} c_{\mathrm{d}j}\cdot T_{pk\ \max} & \Theta(j,\ t_k) = 0 \\ C_{\mathrm{p}ij} + C_{\mathrm{f}ij}\int_0^{T^*_{oij}-(t_{jk}-t_k)} \lambda_{ij}(t)\,\mathrm{d}t + c_{\mathrm{d}j}\cdot T_{pk\ \max} & \Theta(j,\ t_k) = 1 \\ 0 & \Theta(j,\ t_k) = 2 \end{cases} \tag{20}$$

Thus, the total maintenance cost for the RMS in its sequential manufacturing stages can be evaluated by the following expression. One main goal of the proposed RMTW methodology is to achieve cost effectiveness for RMS maintenance scheduling.

$$TMC = \sum_{k=1}^{K}\left(\sum_{j=1}^{J} MC_{kj}\right) + \sum_{h=1}^{H}\left(\sum_{j=1}^{J} c_{\mathrm{d}j}\cdot T_{\mathrm{R}h}\right) \tag{21}$$

It should be noticed that another goal is to achieve rapid responsiveness for future RMS manufacturing. In each manufacturing stage, compared with traditional opportunistic maintenance that calculates the expected cost-savings of all possible PM combinations at every PM time point (its scheduling complexity grows exponentially with the machine number), the scheduling complexity of RMTW is reduced to be polynomial with the machine number, thus even an RMS consists of many machines can be handled. Furthermore, in sequential manufacturing stages, other than rebuilding new system-level policies for various stationary structures, RMTW scheduling utilizes changeable structures and maintenance opportunities to constantly redefine reconfiguring scheduling criteria within a uniform methodology for rapidly adapting to new system structures, which is more suitable for the practical application in reconfigurable manufacturing systems.

4. Numerical example and discussion

To validate the proposed reconfigurable maintenance time window (RMTW) methodology, a complex RMS consists of various machines is considered here. The decision-making process should not only reflect individual machine degradations, but also response rapidly to reconfigurable structures. Thus, for dynamically scheduling the reconfiguration-oriented opportunistic maintenance, both reconfiguration information of RMS and maintenance information of machines are synthetically collected in a hydraulic steering factory.

In the reconfiguration information of RMS, diverse reconfigurations separate the production process into sequential manufacturing stages, while each manufacturing stage has its new system structure designed for its current production demands. In practice, the RMS will evolve constantly as it adapts itself to the market through rapid reconfiguration cycles, and we take the first three manufacturing stages as the numerical example. Corresponding RMS structures, reconfiguration time points and durations are given in Fig. 4.

In the maintenance information of machines, both the original machines and those newly added/removed machines should be considered. Corresponding reliability parameters, machine hazard rates,

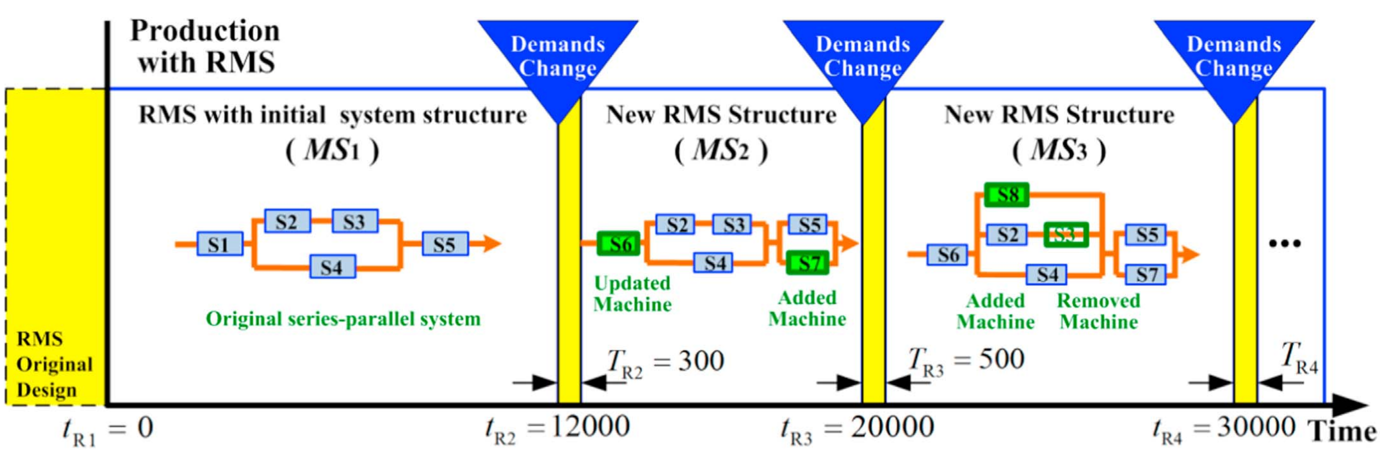

Fig. 4. System-level reconfigurations of RMS.

Table 3
Maintenance information of machines.

Sj			(m_j, η_j)	a_{ij}	T_{pij}	T_{fij}	C_{pij}	C_{fij}	c_{dj}
*MS*1	*MS*2	*MS*3							
S1			(2.8, 9000)	0.046	180	800	6000	22,000	75
S2	S2	S2	(1.7, 7000)	0.028	100	360	4000	9000	40
S3	S3		(1.8, 11,000)	0.032	120	500	2800	11,000	35
S4	S4	S4	(3.0, 15,000)	0.055	140	660	7300	18,000	65
S5	S5	S5	(1.5, 8000)	0.038	220	1000	5500	20,000	90
	S6	S6	(2.6, 7500)	0.017	240	700	4000	15,000	80
	S7	S7	(1.9, 13,000)	0.039	125	400	3000	8500	30
		S8	(2.2, 12,000)	0.025	150	570	4500	12,000	50

and maintenance effects are collected according to individual machine degradation. The reliability of each machine is formulated by a Weibull failure probability function:

$$\lambda_{1j}(t) = (m_j/\eta_j)(t/\eta_j)^{m_j-1} \quad (22)$$

which has been widely used to fit repairable equipment in electronic and mechanical engineering. These parameters are estimated by maintenance engineers in manufacturing processes and presented in Table 3.

4.1. RMTW optimization for reconfigured system structure

Based on those machine-level PM intervals of various machines, this study focuses on the reconfiguration-oriented opportunistic maintenance policy for RMS. We program the system-level maintenance schedule through the RMTW method. In the first manufacturing stage (*MS*1), T_{W1}=800 is applied for the RMTW programming as an example, while T_{W2}=600 and T_{W3}=1000 are taken for *MS*2 and *MS*3 separately. Table 4 shows the RMTW scheduling results for reconfigured system structures. At each system-level PM execution point t_k, $\Theta(j, t_k) = 0$ (IN YELLOW) means no PM action but this machine will be down according to the system structure; $\Theta(j, t_k) = 1$ (IN RED) indicates a PM action is combined to be performed; while $\Theta(j, t_k) = 2$ (IN GREEN) evinces no PM and this machine continues working. Newly added or removed machines are considered in each manufacturing stage.

According to the RMTW scheduling, in the fist cycle of *MS*1, S1, S2 and S5 of the series subsystem (S1⊗S2⊗S3⊗S5) are maintained together, where S2 and S5 are maintained in advance at t_k=4587. Besides, it can be seen that in *MS*2, the PM actions of the parallel subsystem (S3⊕S4) are separated at t_k= 18,437, which avoids the unnecessary downtime of other machines. Furthermore, in the last cycle of *MS*3, the PMs of parallel subsystems (S2⊕S4⊕S8) and (S5⊕S7) are performed at the same time t_k= 27,538, it's because the PM of the bottleneck machine S6 means maintenance opportunities for the whole RMS. The influence of T_{Wh}-value will be further discussed followed.

4.2. System-level schedules under static MTW

Within the reconfiguration-oriented opportunistic maintenance policy, the value of T_{Wh} directly impacts on the whole-RMS maintenance schedule. It can be understood that static MTW is a special and low-grade form of RMTW methodology. To find out how the RMS maintenance programming is influenced, different values of static MTW are investigated. In the comparative analysis, same set of parameters as that with the RMTW (T_{W1}=800, T_{W2}=600 and T_{W3}=1000) is used, and Table 5 and Table 6 give the results of RMS maintenance scheduling with static smaller T_{Wh}=400 and larger T_{Wh}=1200 for the system-level PM separation/combination decision.

In Table 5, from the RMS maintenance schedule with a smaller T_{Wh}-value, it can be seen that a shorter maintenance time window causes more individual maintenance actions of the machines. For instance, at t_k=4587, S2 and S5 are not maintained together with S1, which directly leads to unnecessary downtimes of other machines, and correspondingly increases the total maintenance cost for RMS. Thus, it is a viable way to combine as many PMs as possible based on the RMTW methodology for decreasing the *TMC*.

In Table 6, from the RMS maintenance schedule with a larger T_{Wh}-value, it is visible that a longer maintenance time window can combine more PM actions at each maintenance opportunities. On the positive side, it can efficiently decrease unnecessary downtimes of the whole RMS. On the negative side, too many PMs in advance may lead to extra maintenance. For example, before the fourth reconfiguration t_{R4}= 30,000, S2 and S5 have been performed six PM actions, which is more than with a smaller T_{Wh}-value and also increases the *TMC*.

Therefore, we can have the conclusion that neither too large nor too small T_{Wh}-value should be applied in the RMTW scheduling. Dynamic and suitable values of T_{Wh} are essential to reach the cost-effective whole-RMS maintenance schedule. For each manufacturing stage with diverse system structure, a redefined time width of RMTW T_{Wh} (h=1, 2, 3, ...) for minimizing the *TMC* can be applied for rapidly adapting to the new structure.

4.3. Effectiveness of reconfiguration-oriented opportunistic maintenance

To validate the proposed bi-level methodology of reconfiguration-oriented opportunistic maintenance for reconfigurable manufacturing

Table 4
RMS maintenance scheduling with RMTW.

$\Theta(j,t_k)$	*MS*1				*MS*2					*MS*3		
t_k	4587	6042	9033	10251	12563	16012	18437	19147	19978	21955	24188	27538
S1	1*	2	1	0	-	-	-	-	-	-	-	-
S2	1	0	0	1	0	1	2	0	0	1	0	1
S3	0	1*	0	0	1*	0	2	1*	0	-	-	-
S4	0	2	1*	0	2	0	1*	2	0	2	0	1
S5	1	2	0	1*	2	1*	2	2	0	1*	0	1*
S6	-	-	-	-	2	1	2	2	1*	2	1*	1
S7	-	-	-	-	2	0	2	2	1	2	0	1
S8	-	-	-	-	-	-	-	-	-	2	0	1

* means the PM that creates system-level maintenance opportunities

Table 5
RMS maintenance scheduling with static MTW=400 h.

$\Theta(j,t_k)$	MS1					MS2					MS3						
t_k	4587	5539	6222	9213	11243	12783	16065	17242	18657	19427	20531	21223	23283	24428	28052	28837	29628
S1	1*	0	2	1	0	-	-	-	-	-	-	-	-	-	-	-	-
S2	0	1*	0	0	1	0	0	1	2	0	0	2	1	0	0	1	2
S3	0	0	1*	0	0	1*	0	0	2	1*	-	-	-	-	-	-	-
S4	0	0	2	1*	0	2	0	2	1*	2	0	2	2	0	0	1*	2
S5	0	1	2	0	1*	2	0	1*	2	2	0	2	1*	0	0	1	2
S6	-	-	-	-	-	2	1*	2	2	2	1*	2	2	1*	1	2	2
S7	-	-	-	-	-	2	0	2	2	2	0	1*	2	0	0	2	1*
S8	-	-	-	-	-	-	-	-	-	-	0	2	2	0	1*	2	2

* means the PM that creates system-level maintenance opportunities

Table 6
RMS maintenance scheduling with static MTW=1200 h.

$\Theta(j,t_k)$	MS1			MS2			MS3			
t_k	4587	9033	10325	14794	16065	18297	20531	24459	27637	29767
S1	1*	1	2	-	-	-	-	-	-	-
S2	1	0	1*	1	0	2	1	1	0	1
S3	1	0	1	0	1	2	-	-	-	-
S4	0	1*	2	2	0	1*	0	0	1*	2
S5	1	1	2	1*	0	2	1	1	0	1*
S6	-	-	-	2	1*	2	1*	1*	1	2
S7	-	-	-	2	0	2	1	0	1	2
S8	-	-	-	-	-	-	0	0	1	2

* means the PM that creates system-level maintenance opportunities

systems, we investigate the total maintenance cost (*TMC*) achieved by RMTW programming (T_{W1}=800, T_{W2}=600 and T_{W3}=1000) as the best choice in $T_{Wh} \in [300, 2000]$ with $\Delta T_{Wh} = 100$ ($\forall\ T_{pij}$ & T_{Wh} & $\forall\ T^*_{oij}$) for RMS. Besides, we compare the *TMC* of RMTW methodology with other opportunistic maintenance policies to show the significant cost reduction. The *TMC* values with different methods and corresponding *TMC*-saving rates are given in Fig. 5 and 6 respectively.

Three common types of opportunistic maintenance methods are compared to validate the RMTW scheduling in the same horizon of 30,000 h (three manufacturing stages of RMS):

(1) Individual maintenance mode (IMM): PM is conducted on a machine only when it reaches its original PM intervals (Namely T_{Wh}=0);
(2) Simultaneous maintenance mode (SMM): When one of the machines reaches its intervals, PM actions are carried out on all machines (Namely T_{Wh}= 30,000);
(3) Static maintenance time window (SMTW): One machine's PM arises PM opportunities of non-failed machines within a static time window (Examples of T_{Wh}=200, 400, 800, 1000, 1200, 1400).

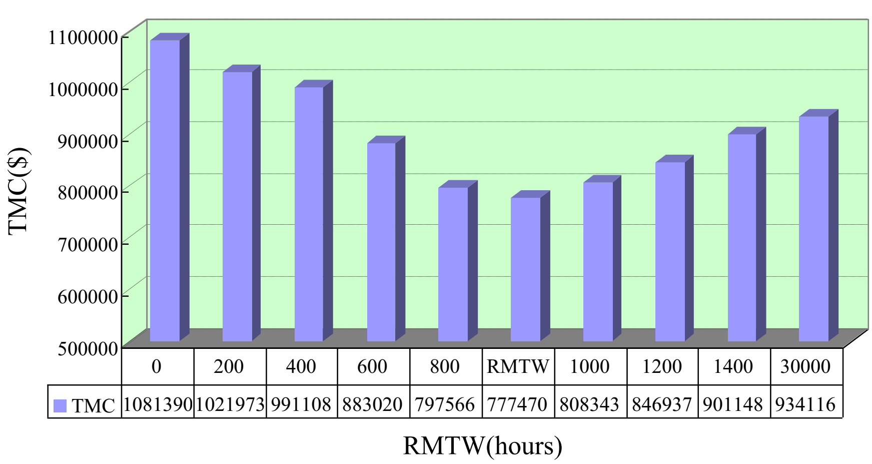

Fig. 5. *TMC* of the RMS with various maintenance methods.

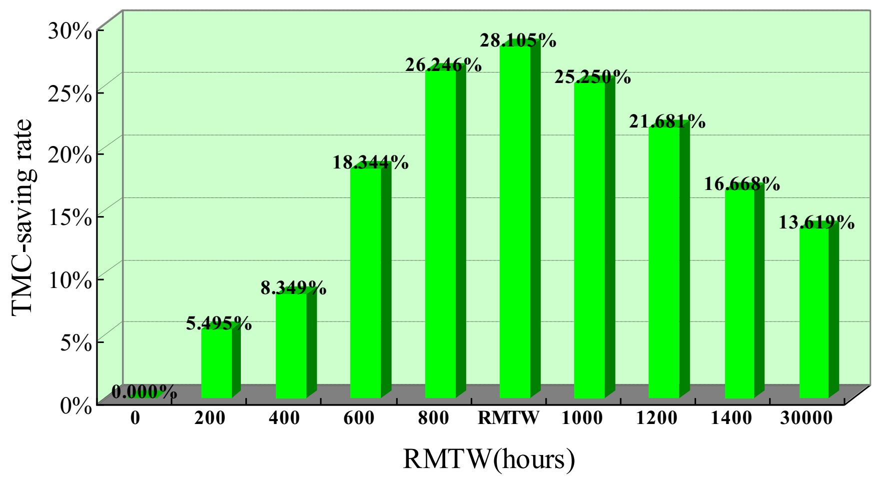

Fig. 6. *TMC*-saving rate comparison with various methods.

Based on the *TMC* sensitiveness in Fig. 5, it can be found that the *TMC* of the RMTW methodology is 777,470, which is the lowest in different opportunistic maintenance policies. Besides, when the static T_{Wh}-value increases from 200 to 800, *TMC* is decreasing; while T_{Wh} extends to 1400, *TMC* will be increasing correspondingly. This proves the conclusion that suitable values of T_{Wh} are essential to reach the cost-effective system-level maintenance schedule. Furthermore, if we define the *TMC* of IMM (T_{Wh}=0) as the baseline, it can be seen in Fig. 6 that RMTW brings the *TMC*-saving rate 28.105%, which is higher than traditional opportunistic maintenance policies (IMM, SMM and SMTW). This comparison result indicates the significant cost effectiveness of the RMTW methodology.

In the general sense, the proposed reconfiguration-oriented opportunistic maintenance policy can efficiently adapt to various system reconfigurations, decrease system-level scheduling complexity, avoid unnecessary RMS downtime and optimize maintenance cost effect with various reconfiguration information of RMS and maintenance information of machines. Different RMSs with various machine reliabilities and changeable system-level reconfigurations would lead to different *TMC*-saving rates. However, RMTW method is exactly designed to redefine the time width of T_{Wh} for minimizing the *TMC* in each manufacturing stage (h=1, 2, 3, ...). Therefore, this optimization mechanism ensures that RMTW methodology can not only be rapidly adapt to new diverse system structures, but also achieve cost effectiveness for the whole-RMS maintenance scheduling.

5. Conclusions

This paper presents a novel dynamic maintenance strategy for the reconfigurable structure, other than stationary system structures. A reconfiguration-oriented opportunistic maintenance policy is developed for efficiently achieving rapid responsiveness and cost effectiveness for RMS. In this proposed decision-making process of interactive bi-level scheduling, changeable structures and maintenance opportunities are comprehensively considered for responding rapidly to open-ended reconfigurations. In the machine-level scheduling, PM intervals T_{oij}^{*} are dynamically obtained through the degradation based multi-attribute maintenance model. In the system-level scheduling, the RMTW methodology has been proposed to make real-time schedules $\Theta(j, t_k)$ in sequential manufacturing stages.

Numerical examples are used to demonstrate that the proposed methodology can efficiently adapt to various system reconfigurations, decrease system-level scheduling complexity, avoid unnecessary RMS downtime and optimize maintenance cost effect. Other than rebuilding new system-level policies for various stationary structures, RMTW utilizes every downtime caused by a machine to perform PM on non-failed machines all along, thus unnecessary downtime of the whole RMS could be avoided. Results indicate that the *TMC*-saving rate achieved by RMTW scheduling is much higher than traditional opportunistic maintenance policies (e.g. IMM, SMM and SMTW). It can be concluded that proposed RMTW methodology is a viable and effective policy to achieve rapid responsiveness and cost reduction for future RMS manufacturing.

In the current study, the RMTW is a dynamic time window that will change according to each real-time reconfiguration. We would try to study variable RMTW even in one manufacturing stage if we could handle the increasing scheduling complexity. For further application, we can also investigate reconfiguration cost of RMS redesigns besides maintenance cost of changeable structures. Besides, how to integrate the reconfiguration scheduling responding to market changes and the RMTW scheduling based on dynamic structures will be considered in future work.

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