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Triple-level opportunistic maintenance policy for leasehold service network of multi-location production lines

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ABSTRACT

The huge investment of multiple devices and the popularization of service-oriented manufacturing have led to increasing requirements for leased production lines. The reliability and maintainability of these leased lines play an important role for an original equipment manufacturer (OEM). For promoting the maintenance outsourcing from a global perspective, this paper presents a triple-level network opportunistic maintenance (NOM) policy for multi-location production lines. At the machine level, sequential predictive maintenance (PM) intervals of every leased machines are dynamically scheduled based on its individual health evolution. At the system level, group PM sets for each multi-unit leased line are obtained by real-time leasing profit optimizations. At the network level, the global maintenance schemes for this leasehold service network are formulated by considering multiple locations of these lines and the maintenance central depot. This comprehensive policy utilizes the triple-level maintenance opportunities to integrate maintenance costs, lease contracts and geographical locations. The mechanism of our proposed policy can ensure the total maintenance cost reduction and significant performance in reliability and robustness for both the lessors and the multi-location manufacturing companies.

1. Introduction

With the intense market competition, a new trend has been happening for original equipment manufacturers (OEMs) that the entire production lines have been leased to multi-location manufacturing companies through product-service packages. These companies increasingly rely on OEMs to lease diverse physical assets and offer outsourcing maintenance services [1–3]. This partnership provides significant advantages for both. For the lessees (local manufacturing companies), leasing manner help companies save huge investment, focus on production, and acquire maintenance supports from OEM with specialized expertise on those machines. For the lessor (OEM), outsourcing maintenance service provides a new profit growth spot and an opportunity to strengthen the connections with lessees.

Under the product-service paradigm, this transformation also significantly increases the complexity of maintenance scheduling and routing decision-making for leasehold service network. On the one hand, service planning needs to determines the set of predictive maintenance (PM) actions, maintenance durations, and resources (including workforce, supplies, and spare parts) necessary to conduct maintenance actions [4]. On the other hand, in addition to assigning maintenance actions to the workforce, it is necessary to take into account the capacity of the workforce and arrange the order of their visits [5]. However, in reality, the lessor usually appoints the service planning to experienced maintenance teams, trusting in their intuition and knowledge. When they are arranged to routing maintenance actions manually, even the most experienced one can only consider a limited number of possibilities and need to invest a lot of time. Thus, the maintenance policy for leasehold service network become more interesting because they can obtain optimal service planning from a global perspective without spending amount of time.

In the past several decades, many researchers have studied the maintenance policies for a single machine [6–11]. In order to providing maintenance policies for a multi-unit production line, the models should further consider the dependences (economic, structural, stochastic and resource) between machines, and the real-time machines' conditions [12,13]. These two aspects are indispensable parts of modern manufacturing companies [14-20]. Xia et al. [21] proposed a lease-oriented maintenance methodology for multi-unit systems, which dynamically optimizes group PM actions. Zhou et al. [22] presented a maintenance model for multi-component systems by considering stochastic failures and disassembly sequences.

For supporting service-oriented manufacturing, most existing studies focus on either a single leased machine or assume simpler forms of

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Nomenclature

Sets

V	set of nodes (lessees and maintenance central depot)
A	set of arcs
L	set of lessees (production lines)
K	set of maintenance teams

Indices

i	index of machine-level PM cycles
u	index of system-level LPO cycles
d	index of network-level LNM cycles
j	index of the leased machines
z, z'	index of the lessees (leased lines)
k	index of the maintenance teams

Input parameters

N	number of lessees
M	number of maintenance teams
D	total number of machines $\mathrm{D} = \sum_{z=1}^{N} \mathrm{D}_z$
D_z	number of machines in lessee v_z
β_{zj}, η_{zj}	parameter in Weibull distribution of machine (z, j)
ε_{zj}	environmental factor for machine (z, j)
a_{zj}	Age reduction factor for machine (z, j)
C_{zj}^{P}	PM cost for machine (z, j)
C_{zj}^{R}	minimal repair cost for machine (z, j)
T_{zj}^{P}	time duration of a PM action for machine (z, j)
T_{zj}^{R}	time duration of a minimal repair for machine (z, j)
κ_{zj}	leasing rent of machine (z, j)
T_{z}^{L}	lease period of lessee v_z
δ_{zj}	rate of machine depreciation for machine (z, j)
V_{zj}^{S}	original value for machine (z, j) at leasing starting
V_{zj}^{E}	residual value for machine (z, j) at leasing ending
w_z	width of the service time-window of lessee v_z
(x_z, y_z)	location coordinates of lessee v_z
$t_{zz'}$	travel time between lessee v_z to $v_{z'}$
$c_{zz'}$	unit travel cost between lessee v_z to $v_{z'}$
$c_{zz'}^{\mathrm{W}}$	unit waiting cost between lessee v_z to $v_{z'}$
$c_{z'}^{\mathrm{P}}$	unit late penalty cost for starting maintenance of lessee $v_{z'}$ later than time window.
Q_k	capacity of maintenance team k
c_k	Maintenance team's visit cost of maintenance team k

Decision variable

$$Y_{zju} = \begin{cases} 1 & \text{if the PM action of machine } (z, j) \text{ is advanced at time point } e_{zu} \\ 0 & \text{otherwise} \end{cases}$$

$$X_{zz'kd} = \begin{cases} 1 & \text{if the maintenance team } k \text{ travels from lessee } v_z \text{ to } v_{z'} \text{ at } d \\ & \text{th network} - \text{level cycle} \\ 0 & \text{otherwise} \end{cases}$$

M_{zkd}	actual maintenance start time of lessee v_z performed by team k at dth network-level cycle

Auxiliary decision variable

$\lambda_{zji}(t)$	ith hazard rate function of machine (z, j)
T_{zji}^{*}	ith original PM interval of machine (z, j)
T_{zji}'	ith adjust PM interval of machine (z, j)
c_{zji}	ith cost rate for machine (z, j)
t_{zju}	PM time point of machine (z, j) at uth system-level cycle
e_{zu}	PM execution time point of production line v_z at uth system-level cycle
LPA_{zju}	leasing profit additions of PM advancement for machine (z, j) at uth system-level cycle
$\mathrm{LPA}_{zju}^{\mathrm{R}}$	machine rent saving of PM advancement for machine (z, j) at uth system-level cycle
$\mathrm{LPA}_{zju}^{\mathrm{M}}$	Unexpected failure saving of PM advancement for machine (z, j) at uth system-level cycle
LPR_{zju}	leasing profit reductions of PM advancement for machine (z, j) at uth system-level cycle
$\mathrm{LPR}_{zju}^{\mathrm{P}}$	extra PM spending of PM advancement for machine (z, j) at uth system-level cycle
$\mathrm{LPR}_{zju}^{\mathrm{D}}$	machine depreciation spending of PM advancement for machine (z, j) at uth system-level cycle
LPS_{zju}	leasing profit saving of PM advancement for machine (z, j) at uth system-level cycle
GP_{zu}	group PM actions of each lessee $v_z \in L$ at time point e_{zu}
$T_{zu}^{\max}$	maximum duration for PM actions combined at time point e_{zu}
$[a_{zu}, b_{zu}]$	service time-window expanded based on time point e_{zu}
s_{zd}	demand of maintenance capacity for lessee v_z at dth network-level cycle
τ_{zd}	service duration for lessee v_z at dth network-level cycle
$[t_{zd}^{\mathrm{S}}, t_{zd}^{\mathrm{E}}]$	time window for lessee v_z at dth network-level cycle
TC_d	total maintenance cost in dth network-level cycle
R_d	optimal routes of maintenance team in dth network-level cycle

coupling between machines in the scale of network routing activities [23-29]. Goel et al. [30] presented a combined scheduling and routing problem for periodic maintenance operations of electricity networks, where the downtimes of power lines and the travel effort of workers are minimized. López-Santana et al. [31] presented a problem of scheduling maintenance actions across distributed machines, which considers expected maintenance cost, routing cost and expected waiting time.

Above creative works are greatly promoting the development of the research on the integrated research filed of opportunistic maintenance scheduling and workforce routing. However, the common features of existing literature described above are that all maintenance actions are estimated and non-updated. Furthermore, in these works, the dependencies between machines and the capacity of maintenance teams do not count. Hence those maintenance policies cannot be well used in leasehold service network of multi-location production lines within the long lease period range. Therefore, the issue on dynamic consideration of maintenance scheduling and routing for leasehold service network with taking into account the dependencies between machines, geographical distributions and the capacity of maintenance teams remains widely open.

Motivated by the considerations of maintenance costs, lease contracts, geographical locations, and tried to be more practical for a complex leasehold service network consisting of multi-location production lines. We propose a triple-level network opportunistic maintenance (NOM) policy. Firstly, by scheduling two types of maintenance actions: PM and minimal repair, we obtain the sequential PM intervals of each leased machines based on its individual health evolution. Secondly, by pulling these PM intervals, we opportunistically advance future scheduled PM of several machines to obtain group PM sets for each leased line with leasing profit optimizations. Thirdly, based on real-time group PM sets, we provide a global maintenance scheme for this leasehold service network by considering multiple locations of these lines and the maintenance central depot. In a cycle by cycle manner, PM interval adjustments of each machine are updated and the NOM policy is executed again with new information as input. This cyclic decision-making process continues until the leased machines exceeds the lease period range.

The remainder of this paper is organized as follows: Section 2 presents the problem statement for a leasehold service network of multi-location production lines. Section 3 dedicates the mathematical formulations in the proposed triple-level NOM policy. Section 4 illustrates the cyclic decision-making process of NOM programing. Section 5 presents numerical experiments by applying the proposed methodology to demonstrate its effectiveness for a leasehold service network. The simulation results can effectively prove the effectiveness of this triple-level network opportunistic maintenance policy. Section 6 discusses the dynamic characteristics of various routing parameters. Finally, Section 7 provides some concluding remarks and future works.

2. Problem statement

This paper proposes a triple-level network opportunistic maintenance (NOM) policy specifically designed for leasehold service network, where original equipment manufacturer (lessor) lease multi-unit production lines to their global client companies (lessees). Each lessee has a production line consisting of multiple individual machines in series, which are independent regarding their degradation rates. Under the lease contract, the lessor needs to dispatch maintenance teams to provide seasonable maintenance actions of geographically distributed lessees, in order to decrease the downtime and prevent the occurrence of failures. Therefore, our framework extends opportunistic maintenance to multi-location production lines by integrating maintenance costs, lease contracts and geographical locations. And the interactions between the lessor and the lessees are also taken into account. The design of our triple-level maintenance framework is illustrated in Fig. 1.

Thus, this problem consists of optimizing real-time global maintenance and routing schemes for a leasehold service network that minimize the total maintenance cost. The problem can be defined in a directed complete graph $G = (V, A)$ with a set of nodes $V = \{v_0, v_1, \cdots, v_N\}$ and the arc set $A = \{(v_z, v_{z'}) | v_z, v_{z'} \in V, v_z \neq v_{z'}\}$. A single maintenance central depot indexed by vertex v_0 is utilized as the point of departure and also final destination for all the maintenance teams. And the remaining vertices of V, denoted by $L = \{v_1, v_2, \cdots, v_N\}$, represent N production lines to be served. Each production line $v_z \in L$ consists of diverse leased machines. And the arc set A represent the links between all pairs of vertices. To reduce unforeseen failures, as well as help lessor to effectively minimize the total maintenance cost, a set of maintenance teams $K = \{k_1, k_2, \cdots, k_M\}$ is dynamically scheduled to cover a number of production lines to perform group PM actions within corresponding soft time windows from a global perspective. The assumptions and conditions of the problem are summarized as follows:

- The machines have different degradation rates.
- After the PM, the machines are restored to a better state, but start in not as good as new condition at the next cycle.
- In the event of an unexpected failure, minimal repair is performed to bring back the failed machine to its operation state, and minimal repair does not improve its hazard rete.
- The maintenance parameters (the hazard rate, the degradation factors, the maintenance actions' durations and costs, etc.) of leased machines are estimated by lessor.
- The lease parameters (the lessees and their location, the machine original/residual values, the lease rent, the depreciation rate, etc.) of production lines are obtained according to lease contract.
- The machines of multi-location production lines have a service time-window, and the production lines will not start maintenance before this earliest time.
- The travel distance is deterministic and fulfill the triangle inequality.
- Every route originates and ends at the maintenance central depot.
- Once the PM action begins to be performed, it will not be interrupted until the maintenance operation is completed.

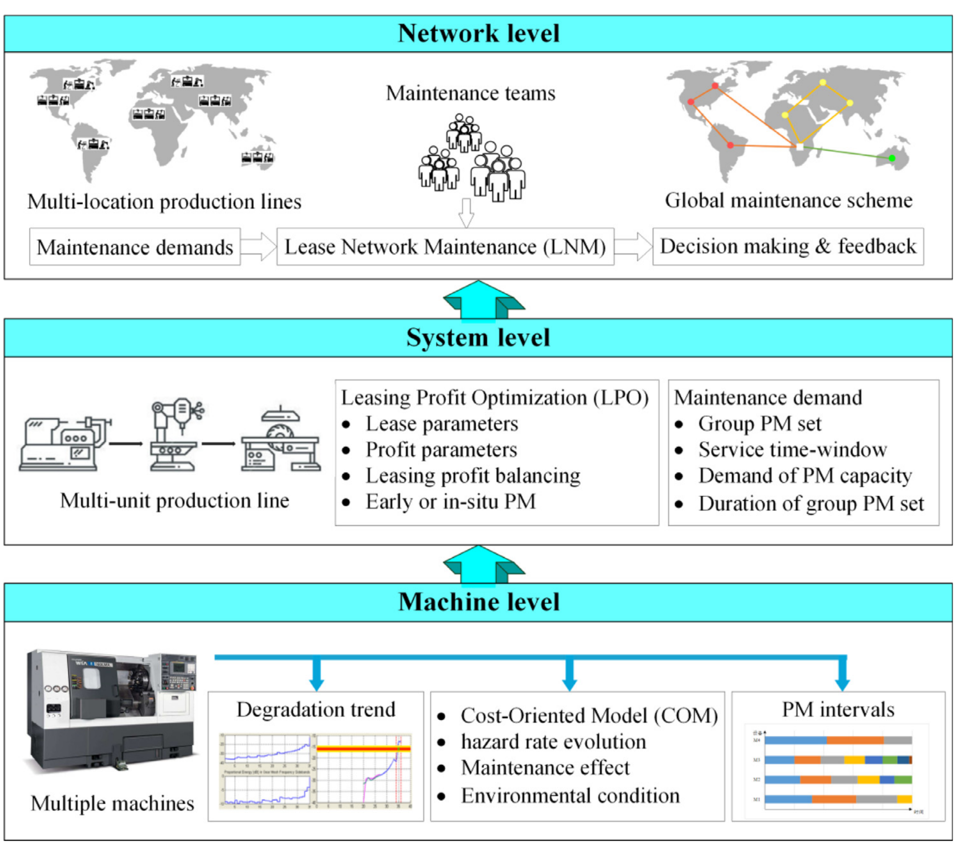


Fig. 1. Illustration of triple-level network opportunistic maintenance policy.

Triple-level NOM policy consists in solving three levels iteratively, as shown in Fig. 2:

(1) Machine level: In view of the multiple leased machines, we consider two types of maintenance actions: PM and minimal repair. The PM actions are maintenance actions before a failure occurs, thus makes the machine unavailable only during the maintenance. The minimal repairs are performed to restore the machine of unexpected failure to its operation state. And a failed machine stays down until minimal repair is conducted. Based on the above mechanism, by inputting the maintenance parameters, we utilize a cost-oriented model (COM) to schedule the PM intervals that are calculated by minimizing the individual total maintenance costs per unit time. And the outputs are sequential PM intervals of each leased machines.
(2) System level: For a multi-unit production line, the series system operation will be interrupted due to maintenance actions. Therefore, one machine fails or predictively maintained will arise PM opportunities for other non-repair machines. By pulling the original PM intervals and lease parameters of each machine as input, leasing profit optimization (LPO) model dynamically optimizes real-time group PM sets. It utilizes every PM opportunity as grouping PM time point to only consider sequential or advanced maintenance not delayed maintenance to keep the machines' proper operation and avoid more economic loss due to the system downtime. The outputs consist of the group PM sets, the durations of group PM sets and corresponding service time-windows.
(3) Network level: In the leasehold service network, a maintenance team should be present at a lessee when there are some machines at that location need performed maintenance. Thus, we should consider the capacity of each team in terms of how many machines they can maintain, travel distance between lessees, and the costs associated with waiting, late penalty, maintenance team's visit in network level. This level takes the outputs from system level, routing parameters and the directed graph corresponding to the geographical location of these production lines as inputs. A lease network maintenance (LNM) model is built to schedule cost-effective maintenance schemes for the whole network. The outputs include the actual start time of each PM action, routes of each maintenance team, the total maintenance cost. And LNM decisions will be fed back to the next machine-level COM scheduling cycle to update corresponding PM interval, and to the next system-level LPO optimization cycle to update PM time point.

3. Mathematical formulation

In this triple-level NOM policy, the COM model is utilized to obtain sequential PM intervals for each leased machine at the machine level; the LPO model is then presented to provide group PM sets for each production line at the system level; while the LNM model is proposed to optimize global maintenance schemes for the whole leasehold service network.

3.1. Sequential PM intervals for each leased machine

We consider a leasehold service network consisting of a set of leased machines. J machines are distributed among N multi-location lessees, and each lessee (say, lessee $v_z \in L$) has $D_z(D_z > 1)$ series machines. To better describe the proposed model, the jth machine at lessee z is abbreviated as machine (z, j). Each machine is assumed to be operating continuously except when there is a scheduled PM or an unscheduled breakdown. We consider both the lessor's maintenance effect factor and the lessee's environmental condition factor in the health modeling. Thus, the relationship between the hazard rates before and after the ith PM action of machine (z, j) is defined by:

$$\lambda_{zj(i+1)}(t) = \begin{cases} (\beta_{zj}/\eta_{zj})(t/\eta_{zj})^{\beta_{zj}-1} & i = 0 \\ \varepsilon_{zj}\lambda_{zji}(t + a_{zj}T'_{zji}) & i > 0 \end{cases} \tag{1}$$

where $t \in (0, T'_{zji+1})$, and the lifetime distribution of each machine follows a Weibull distribution at the first machine-level cycle ($i = 0$). ε_{zj} is the environmental factor that captures the effect of the lessee's environment on the machine (z, j), and $\varepsilon_{zj} > 1$ indicates that the environment lead to machine accelerated degradation. a_{zj} is the age reduction factor for imperfect maintenance, where $0 < a_{zj} < 1$ reflects the internal maintenance capacity of machine (z, j). T'_{zji} is the updated length of the ith PM interval of machine (z, j). The machine-level PM interval output T^*_{zji} may be shortened or extended into the group PM action at the system level, then lead to routing different period of PM at the network level. Therefore, for the next $i + 1$th machine-level cycle, T'_{zji} is used to calculate the hazard rate after the last imperfect PM action.

Based on the hazard rate, the COM model is built to schedule

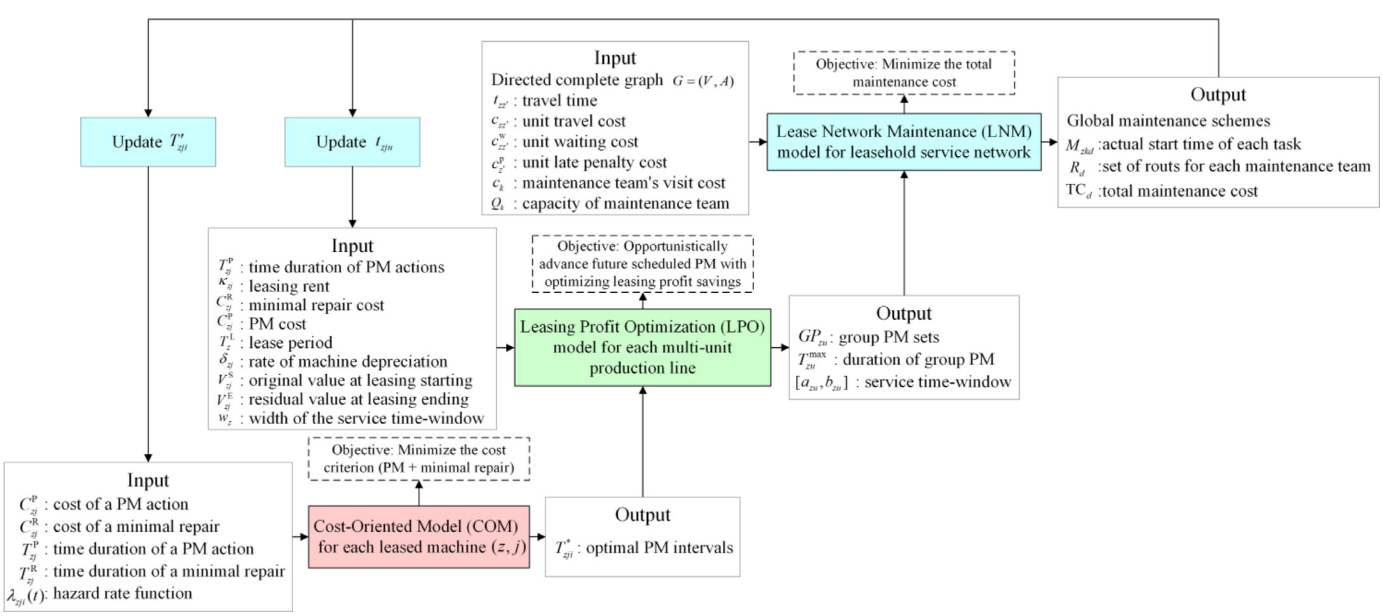


Fig. 2. Interactive decision-making of triple-level maintenance scheduling.

sequential PM intervals of each leased machine. The objective that minimizes the maintenance cost per unit time of the ith PM cycle for machine (z, j) is given by:

$$c_{zji} = \frac{C_{zj}^{\mathrm{P}} + C_{zj}^{\mathrm{R}} \int_0^{T_{zji}} \lambda_{zji}(t)\mathrm{d}t}{T_{zji} + (T_{zj}^{\mathrm{P}} + T_{zj}^{\mathrm{R}} \int_0^{T_{zji}} \lambda_{zji}(t)\mathrm{d}t)} \tag{2}$$

where the numerator indicates the maintenance cost of a cycle. $\int_0^{T_{zji}} \lambda_{zji}(t)\mathrm{d}t$ is the expected failure frequency. C_{zj}^{P} is the cost of a PM action and C_{zj}^{R} is the cost of a minimal repair for machine (z, j). The denominator indicates the total duration of this cycle. T_{zj}^{P} is the time duration of a PM action and T_{zj}^{R} is the time duration of a minimal repair for machine (z, j). The PM intervals T_{zji}^{*} for machine (z, j) at the ith machine-level cycle are scheduled sequentially by solving derivative function $dc_{zji}/dT_{zji} = 0$. These are the inputs of the system level in the next section.

3.2. Group PM sets for multi-unit production line

For a multi-unit production line of the leasehold service network, a scheduled PM event creates an opportunity for the non-repair machines at the system level [21]. The LPO model is designed to dynamically analyze leasing profit savings to decide between advancing a PM action or performing it on schedule (Early PM or In-situ PM) for every machine while maximizing leasing profits. By opportunistically considering to advance several PM actions when one PM action firstly happens, the risk of unexpected failures can be decreased and the number of maintenance team assignments can be reduced. The system level is processed with the following mechanism: For a D_z-unit leased production line $v_z \in L$, pull real-time PM interval T_{zji}^{*} from the machine level for each unit and choose the earliest unit to be performed PM firstly. Define its PM time point t_{zju} as an PM execution time point e_{zu} of production line $v_z \in L$ in the uth system-level cycle. For all the other units of this system, the lessor will use LPO model to calculate leasing profit savings in order to decide whether to advance their original PM actions at time point e_{zu}. If Early PM can lead to positive profit savings, the PM action of this machine will be performed in current group PM set GP_{zu} at e_{zu}.

According to the series structure and lease contracts, leasing profit additions of Early PM (the machine (z, j) is performed PM in advance at time point e_{zu}) consist of two parts: the machine rent saving $\mathrm{LPA}_{zju}^{\mathrm{R}}$ and the unexpected failure saving $\mathrm{LPA}_{zju}^{\mathrm{M}}$. First, the Early PM can avoid the extra PM breakdown (time duration of PM action), which means the rent saving for the lessor. Second, the updated PM interval of machine reduce the cumulative failure risk, which means cost of minimal repairs for unexpected failures can be saved. Meanwhile, performing a PM action in advance will also lead to leasing profit reductions: the extra PM spending $\mathrm{LPR}_{zju}^{\mathrm{P}}$ and the machine depreciation spending $\mathrm{LPR}_{zju}^{\mathrm{D}}$. First, the Early PM will cause the fact that more PM actions will be needed during the lease period. Thus, the lessor has to spend more cost of PM actions. Second, more PM actions will also cause accelerating depreciation in the view of machine's value. Based on the above real-time calculations, the lessor can dynamically obtain the leasing profit saving LPS_{zju} of each non-repair machine (z, j) at the uth system-level cycle:

$$\begin{aligned}\mathrm{LPS}_{zju} &= \mathrm{LPA}_{zju} - \mathrm{LPR}_{zju}\\ &= \mathrm{LPA}_{zju}^{\mathrm{R}} + \mathrm{LPA}_{zju}^{\mathrm{M}} - \mathrm{LPR}_{zju}^{\mathrm{P}} - \mathrm{LPR}_{zju}^{\mathrm{D}}\\ &= (T_{zj}^{\mathrm{P}}\kappa_{zj}) + \left(\left[\int_0^{T_{zji}^{*}} \lambda_{zji}(t)\mathrm{d}t - \int_0^{T'_{zji}} \lambda_{zji}(t)\mathrm{d}t\right] C_{zj}^{\mathrm{R}}\right)\\ &\quad - \left(\frac{t_{zju} - e_{zu}}{T'_{zji}} C_{zj}^{\mathrm{P}}\right) - \left(\frac{t_{zju} - e_{zu}}{T_z^{\mathrm{L}}} \delta_{zj}(V_{zj}^{\mathrm{S}} - V_{zj}^{\mathrm{E}})\right)\end{aligned} \tag{3}$$

where κ_{zj} is the leasing rent of machine (z, j). t_{zju} is the PM time point from the cumulative PM intervals of machine (z, j) at the uth system-level cycle. $e_{zu} = \min(t_{zju})$ is the PM execution time point of the production line $v_z \in L$ at the uth system-level cycle. T_z^{L} is the is the lease period of the production line $v_z \in L$. δ_{zj} is the rate of machine depreciation of machine (z, j). V_{zj}^{S} is the original value at the lease starting, and V_{zj}^{E} is the residual value at the lease ending of machine (z, j).

If the leasing profit saving $\mathrm{LPS}_{zju} > 0$, which means leasing profit additions are larger than leasing profit reductions, an Early PM action will be taken. Otherwise, In-situ PM will be the choice. The lessor can dynamically make LPO decisions Y_{zju} for machine (z, j) at each system-level opportunity e_{zu} to statistic whether to advance their original PM actions or not. Arrange the leased machines all $Y_{zju} = 1$ in the current group PM sets GP_{zu}, the lessor can execute PM actions on these machines at time point e_{zu} together. And the maintenance duration of group PM set GP_{zu} is the maximum durations for PM actions combined at e_{zu}.

$$Y_{zju} = \begin{cases} 1 & \mathrm{LPS}_{zju} > 0 \quad (\text{Early PM}) \\ 0 & \mathrm{LPS}_{zju} \le 0 \quad (\text{In} - \text{situ PM}) \end{cases} \tag{4}$$

The width of the service time-window w_z of a production line is determined on the lease contract. For the uth system-level cycle, the lower bound a_{zu} equals to maintenance opportunity e_{zu} minus the width of the service time-window w_z, as $a_{zu} = e_{zu} - w_z$. And the upper bound b_{zu} equals to the maintenance opportunity e_{zu}, as $b_{zu} = e_{zu}$. Based on a_{zu} and b_{zu}, we denote the lower and upper bounds of the service time-window for this production line $v_z \in L$ at the uth system-level cycle. Thus, we expended the PM time point e_{zu} to the service time-window $[a_{zu}, b_{zu}]$ while keeping the LPO decision Y_{zju} unchanged.

In summary, for a multi-unit leased production line $v_z \in L$, we obtain the LPO decisions Y_{zju} for machine (z, j) at each system-level opportunity e_{zu} by balancing between the leasing profit additions and reductions. The group PM set GP_{zu}, the duration of group PM set $T_{zu}^{\max}$, and the service time-window $[a_{zu}, b_{zu}]$ are the inputs of the network-level optimizations in the next section.

3.3. Global maintenance schemes for leasehold service network

In this subsection, the network-level routing problem expends the scale of maintenance actions further to consider geographically distributed multi-location production lines. This routing problem of outsourcing maintenance service can be described as follows: at the dth network-level cycle, there are a set of lessees $L = \{v_1, v_2, \cdots, v_{\mathrm{N}}\}$ waiting for the maintenance service. Each lessee (production line) $v_z \in L$ has complete information about its location, demand of the maintenance capacity, and time window requirements from system level. On the one hand, the lessor needs to determine how many maintenance teams are to be dispatched in this cycle. On the other hand, the lessor also needs to determine which lessees' maintenance will be carried out by each maintenance team, and the sequence in which these group PM sets must be performed. Under the above circumstances, the LNM model tries to minimize the total maintenance cost of the leasehold service network.

From the system-level LPO model, pull the group PM sets GP_{zu}, the durations of group PM sets $T_{zu}^{\max}$ and the service time-windows $[a_{zu}, b_{zu}]$ of each lessees $v_z \in L$ cyclically. Then define the number of repairable machines in GP_{zu} as the demand of the maintenance capacity s_{zd}, which means that the number of repairable machines is arranged for the lessee v_z at the dth network-level cycle. In addition, we define the $T_{zu}^{\max}$ as the service duration τ_{zd}, and define the $[a_{zu}, b_{zu}]$ as the time windows $[t_{zd}^{\mathrm{S}}, t_{zd}^{\mathrm{E}}]$ of the lessee v_z at the dth network-level cycle.

Each lessee $v_z \in L$ is associated with a demand of the maintenance capacity s_{zd}, an on-site service duration τ_{zd}, and a time window $[t_{zd}^{\mathrm{S}}, t_{zd}^{\mathrm{E}}]$ at the dth network-level cycle. Each lessee $v_z \in L$ is with a two-dimensional location coordinate (x_z, y_z). And each arc $(v_z, v_{z'}) \in A$ has an associated travel time $t_{zz'}$, which represent the travel time of maintenance teams from the lessee v_z to $v_{z'}$. Moreover, with each arc $(v_z, v_{z'}) \in A$, a travel cost per unit time $c_{zz'}$, a waiting cost per unit time

$c^{\mathrm{w}}_{zz'}$, and a late penalty cost per unit time $c^{\mathrm{p}}_{z'}$ is associated. In addition, each maintenance team $k \in K$ is associated with a maximal maintenance capacity Q_k and a maintenance team's visit cost c_k.

For the LNM model, binary variables $X_{zz'kd}$ takes the value 1 only if the maintenance team $k \in K$ travels from lessee v_z to $v_{z'}$ at the dth network-level cycle, where $v_z \neq v_{z'}$; and take the value 0, otherwise. And the time variables M_{zkd} defines the actual maintenance start time of the lessee v_z when performed by maintenance team $k \in K$ at the current dth network-level cycle.

The LNM model can be formally described using the following set of equations:

$$\begin{aligned} \min \mathrm{TC}_d = & \sum_{z\in V}\sum_{z'\in V}\sum_{k\in K}(c_{zz'}t_{zz'})X_{zz'kd} \\ & + \sum_{z\in V}\sum_{z'\in V}\sum_{k\in K}\left(c^{\mathrm{w}}_{zz'}\left[M_{z'kd} - \left(M_{zkd} + \tau_{zd} + t_{zz'}\right)\right]^*\right)X_{zz'kd} \\ & + \sum_{z\in V}\sum_{z'\in V}\sum_{k\in K}\left(c^{\mathrm{p}}_{z'}\left[M_{z'kd} - t^{\mathrm{E}}_{z'd}\right]^*\right)X_{zz'kd} \\ & + \sum_{z'\in L}\sum_{k\in K} c_k X_{v_0 z'kd} \end{aligned} \tag{5}$$

subject to

$$\sum_{z'\in V}\sum_{k\in K} X_{zz'kd} = 1, \quad \forall\, z \in V \tag{6}$$

$$\sum_{z\in V} X_{zz'kd} - \sum_{o\in V} X_{z'okd} = 0, \quad \forall\, z' \in L, \quad \forall\, k \in K \tag{7}$$

$$\sum_{z\in L} X_{v_0 zkd} = 1, \quad \forall\, k \in K \tag{8}$$

$$\sum_{z\in L} X_{zv_0kd} = 1, \quad \forall\, k \in K \tag{9}$$

$$\sum_{z\in L}\sum_{z'\in V}\left(s_{zd}X_{zz'kd}\right) \le Q_k, \quad \forall\, k \in K \tag{10}$$

$$M_{zkd} \ge t^{\mathrm{S}}_{zd}, \quad \forall\, z \in L, \quad \forall\, k \in K \tag{11}$$

$$X_{zz'kd} \in \{0, 1\}, \quad \forall\, z, z' \in V, \quad k \in K \tag{12}$$

Where $[\cdot]^*$ indicates $\max(\cdot, 0)$. The objective function (5) minimizes the total maintenance cost TC_d. Which includes the travel cost, the waiting cost, the late penalty cost, and the maintenance team's visit cost. Constraint (6) ensures that each PM action is executed exactly once during the current network-level cycle. Constraint (7) ensures that after a maintenance team arrives at the lessee z' and completes the maintenance operation, it has to leave to another destination. Constraint (8) and (9) indicate that each maintenance team must leave the central depot and finally arrive at the central depot (vertex v_0). Constraint (10) depicts for the current network-level cycle, maximum number of production lines that can be served, depending upon the maintenance capability of each maintenance team. Constraint (11) requires that the actual start time must be later than the lower bound of the time window. Constraint (12) imposes binary conditions on the flow and indicator variables.

After optimizing the LNM model, the effective allocation sequence of each maintenance team obtained in the optimal solution. In general, we obtain the global maintenance scheme for the multi-location leasehold service network at the dth network-level cycle, including the actual start time M_{zkd}, the routes of each maintenance team R_d, and the total maintenance cost TC_d. When the global maintenance scheme is implemented, the PM intervals T'_{zji} and PM time point t_{zju} of machine (z, j) will be updated for the next machine-level cycle and system-level cycle, respectively.

4. Decision-making process of triple-level NOM policy

To obtain cost-effective global maintenance schemes for the leasehold service network, the triple-level NOM policy seamlessly integrates the COM model at the machine level, the LPO model at the system level, and the LNM model at the network level. The information of maintenance decision-makings, lease contracts and geographical locations is interacted and updated among these three levels. Here, the cyclic decision-making process during the lease period are presented for achieving the total maintenance cost minimization.

***Step 1 (Machine-level PM pulling)*:** During the lease period of the leasehold service network of multi-location production lines, start the maintenance scheduling and routing from the first machine-level cycle $i = 1$. Pull the original PM intervals T^*_{zji} of each machine (z, j) from the machine-level COM model.

***Step 2 (Time points assignment)*:** Based on the outputs of the machine level, assign the machines' PM intervals T^*_{zji} to theirs corresponding PM time points t_{zju} at the first system-level cycle $u = 1$, as $t_{zju} = T^*_{zji}$. And after the first system-level cycle, $u > 1$, the PM time points t_{zju} will be updated from Step 13.

***Step 3 (Maintenance opportunity choice)*:** For a multi-unit production line $v_z \in L$, the PM action of one machine creates an opportunity for other non-repair machines. From the first system-level cycle $u = 1$, choose the PM execution time point e_{zu} for LPO model by $e_{zu} = \min(t_{zju})$.

***Step 4 (Real-time LPS calculation)*:** At the system-level time point e_{zu} for the production line $v_z \in L$, calculate the leasing profit savings of non-repair machines by comparing leasing profit additions and leasing profit reductions.

Step 5 (system-level LPO decision): Based on the above real-time calculations, the lessor can dynamically obtain the leasing profit saving LPS_{zju} of each machine. If $\mathrm{LPS}_{zju} = \mathrm{LPA}_{zju} - \mathrm{LPR}_{zju} > 0$, the LPO decision $Y_{zju} = 1$, which means the PM action of machine (z, j) will be performed in advance at e_{zu}. Otherwise, $Y_{zju} = 0$ and the PM action of machine (z, j) will be performed on schedule.

***Step 6 (Group PM arrangement)*:** Arrange all the leased machines with $Y_{zju} = 1$ in the current group PM set GP_{zu} of the production line $v_z \in L$. Then output the duration of group PM set GP_{zu} which is the maximum duration for PM actions combined at e_{zu}, as $T^{\max}_{zu} = \max(T^{\mathrm{P}}_{zji})$, and the service time-window $[a_{zu}, b_{zu}]$.

***Step 7 (Lessee parameters generation)*:** Pull the group PM sets GP_{zu}, the duration of group PM sets $T^{\max}_{zu}$ and the service time-window $[a_{zu}, b_{zu}]$ from system level, routing parameters and the directed graph $G = (V, A)$ as inputs. From the first network-level cycle $d = 1$, each lessee v_z is associated with a demand of the maintenance capacity s_{zd}, a service duration τ_{zd}, and a time window $[t^{\mathrm{S}}_{zd}, t^{\mathrm{E}}_{zd}]$.

Step 8 (Network-level LNM optimization): Allocate the group PM sets of leasehold service network to the maintenance teams, and repeat this procedure until all PM actions are scheduled to find a preliminary solution. Then search the global solution space to obtain feasible solutions that satisfy constraint conditions. Finally, global maintenance schemes for the leasehold service network is the feasible solution with lowest total maintenance cost.

Step 9 (Maintenance schemes decision-making): output the global maintenance scheme for the multi-location leasehold service network at the dth network-level cycle, including the actual start time M_{zkd}, the routes of each maintenance team R_d, and the total maintenance cost TC_d.

***Step 10 (PM intervals adjustment)*:** Since the network-level LNM optimization adjusts PM intervals of machines, the new machine-level PM intervals will be adjustment. Feedback the network-level PM intervals of the global maintenance scheme to the next machine-level COM scheduling.

$$T'_{zji} = \begin{cases} T^*_{zji} & Y_{zju} = 0 \\ T^*_{zji} - (t^{\mathrm{E}}_{zd} - M_{zkd}) & Y_{zju} = 1 \end{cases} \tag{13}$$

***Step 11 (Machine-level periods check)*:** When the machine-level PM intervals of each leased machine are calculated, the machine level starts the next cycle. Thus, we need to identify whether the cumulative PM intervals within the current cycle i' are out of lease period range T_z^{L}. If the answer is YES, end the NOM optimizations of this machine. Otherwise, continue to step 12 and formulate the hazard rate after a PM action, and the decision formulation is:

$$T_{zji'}^{*} + \sum_{i=1}^{i'-1} T'_{zji} > T_z^{\mathrm{L}}? \tag{14}$$

***Step 12 (Hazard rates evolution)*:** After the first machine-level cycle $i = 2, 3, \cdots$, the hazard rates also need be updated according to diverse deteriorations by integrating the environmental factors ε_{zj} (lessee's environmental condition), the age reduction factors a_{zj} (lessor's maintenance effect), and the adjusted PM intervals T'_{zji}.

***Step 13 (system-level periods check)*:** For the next system-level cycle, first identify whether these PM time points t_{zju} are out of lease period range T_z^{L}. If the answer is YES, end the NOM optimizations of this production line (lessee). Otherwise, continue to Step 14 to update the PM time points and turn back to Step 3 to choose the maintenance opportunity for this production line.

***Step 14 (Time points update)*:** Meanwhile, same as Step 10, the network-level LNM optimization also updates the PM time points of machines. Therefore, update the new PM time points t_{zju} for each machine (z, j) based on the global maintenance schemes and sequential PM intervals. If $Y_{zju} = 0$, it means that machine (z, j) is not performed PM in advance and the new PM time point are $t_{zju} = t_{zju} + \tau_{zd}$. And if $Y_{zju} = 1$, the new PM time point are$t_{zju} = M_{zkd} + \tau_{zd} + T_{zj(i+1)}^{*}$. Then feedback the new PM time points to the next system-level LPO optimization.

$$t_{zju} = \begin{cases} t_{zju} + \tau_{zd} & Y_{zju} = 0 \\ M_{zkd} + \tau_{zd} + T_{zj(i+1)}^{*} & Y_{zju} = 1 \end{cases} \tag{15}$$

***Step 15 (network-level periods check)*:** For the next network-level for LNM optimization, assign $d = d + 1$. Identify whether the actual maintenance start times M_{zkd} are out of lease period range T_z^{L}. If the answer is YES, end the NOM optimizations of leasehold service network. Otherwise, return back to the Step 7 and resolve the routing problem to determine the global maintenance scheme for the next cycle. This procedure is repeated until all the lessees of the leasehold service network are out of lease period range. This cyclic triple-level NOM policy is shown in Fig. 3.

5. Numerical experiments

In this section, applicability of the formulated model and the decision-making approach are validated. In doing so, we first present the formulating process of global maintenance schemes during sequential cycles to show the validity of our results. As well as benchmarking the NOM policy with two conventional maintenance policies for multi-location production lines to show the effectiveness of our policy for future service-oriented manufacturing.

5.1. Test instances

We consider the leasehold service network consisting of five lessees, where each lessee leases a three-unit series production line as the illustrative example. Each production line may consist of different machines, such as CNC center, lathe machine, drilling machine, milling

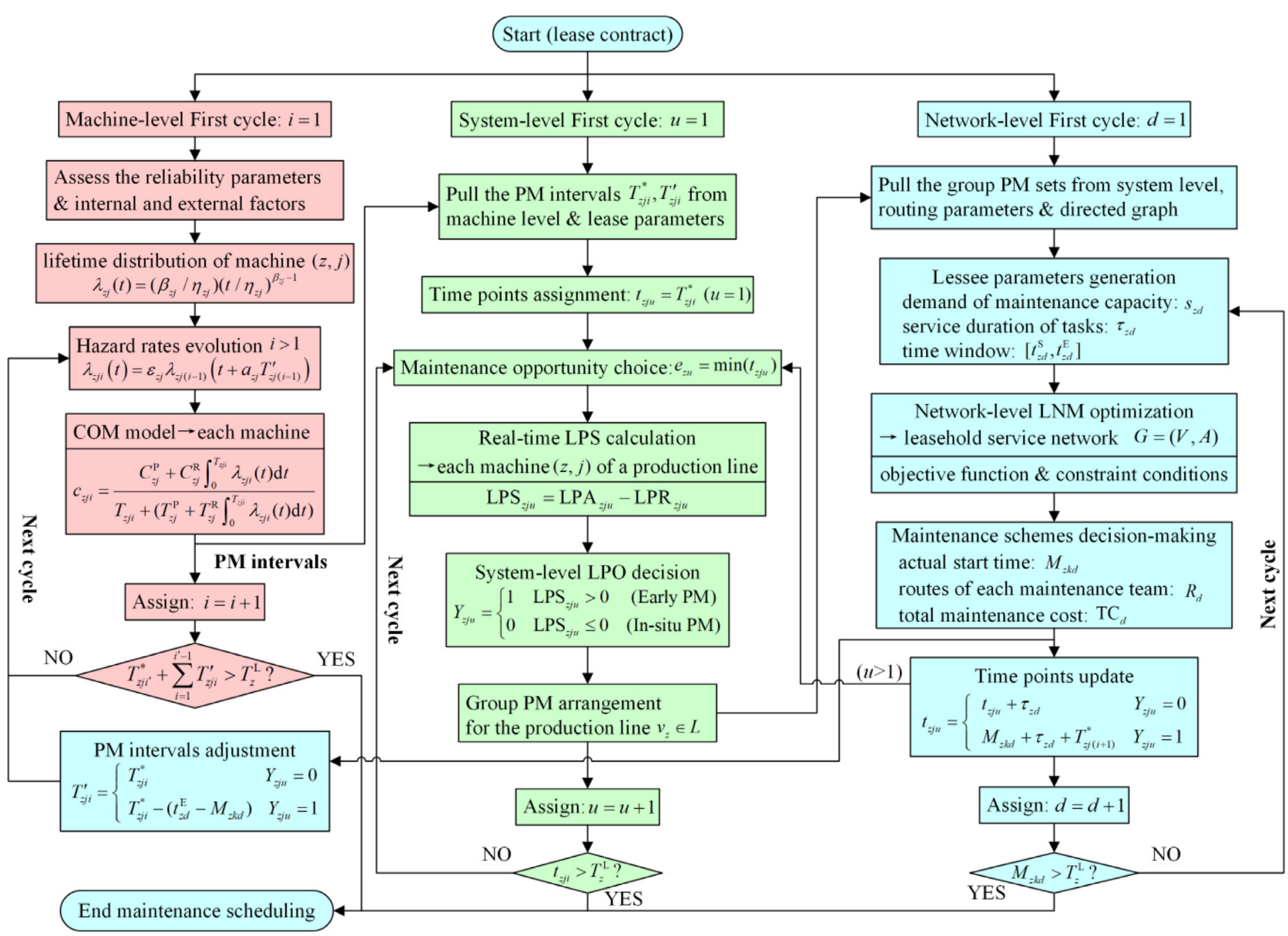


Fig. 3. Flowchart of opportunistic maintenance based on NOM policy.

machine, grinding machine and so on. And the reliability information of each production line can be collected with cooperative enterprise. For providing outsourcing maintenance schemes, the maintenance parameters (the hazard rate, the degradation factors, as well as the maintenance durations and costs) are estimated by OEM reliability engineers and listed in Table 1.

To demonstrate that the NOM policy can provide cost-effective outsourcing maintenance schemes for the lessor (OEM) and lessees (users of multi-location leased lines), in-depth investigations on sequential COM scheduling and real-time saving calculations during a two-year lease period T_z^{L}=17520h (730 days, three shifts during the 24-h period) of each lessee v_z have been presented and analyzed. Table 2 provides the lease parameters (the vertex and its location, the travel time, the machine original/residual values, the lease rent, and the depreciation rate) of multi-location production lines according to the lease contracts.

5.2. Analysis of triple-level NOM decision-making

This study focuses on the cost-effectiveness of the triple-level NOM policy for the leasehold service network under the product-service paradigm. By pulling original PM intervals from the machine level, when one machine is scheduled to be stopped for PM action, the system-level LPO programming analyzes the leasing profit saving to choose the PM adjustments (Early PM or In-situ PM) for each leased machine. Table 3 illustrates the decision-making of production lines at the first cycle in LPO programing (u = 1).

In the LPO programming at the first cycle, M4 is scheduled to be first performed the PM action in the L2. Define its PM time point t_{zju}=1949 as the system-level PM execution point e_{z1}. Then calculate the leasing profit additions and reductions for the other machines. For example, M5 has LPA_{251}=\$1382 and LPR_{251}=\$763. Thus, $\mathrm{LPS}_{251} = \mathrm{LPA}_{251} - \mathrm{LPR}_{251}$ = \$619 means that Early PM can lead to more profit saving. Therefore, the PM action of M5 is advanced to the current group PM set GP_{z1}.

Based on cyclic group PM sets from the multi-location production lines, we consider the capacity of maintenance teams and the distribution of each lessee to analyze the routing problem at the network level. Each leased line has a width of the service time-window as w_z = 25h according to the service contract. The travel cost $c_{zz'}$ and the waiting cost $c_{zz'}^{\mathrm{w}}$ are set to \$150 and \$50 per unit time, respectively. Besides, the penalty cost $c_{z'}^{\mathrm{p}}$ for starting the maintenance of lessee v_z later than t_{zd}^{E} is \$20 per unit time, the cost of the maintenance team visit c_k is \$1500, and the capacity of maintenance team Q_k is 6 unit/time. Table 4 presents the global maintenance scheme at the first network-level cycle (d = 1).

At each network-level cycle, the total maintenance cost TC_d in LNM programming is optimized to schedule all maintenance teams. And at this network-level cycle, in order to route teams to satisfy requests for all PM actions and consider corresponding time windows, lessor arranges two maintenance teams to serve every production line over the planning horizon. It can be seen that both teams start and end at the vertex v_0, one team serves the lessee v_2 and another team serves the lessees v_4, v_5, v_3 and v_1 successively. The total maintenance cost of this cycle is TC_1 = \$81930.

Based on Tables 3 and 4 ($e_{z1} \rightarrow t_{z1}^{\mathrm{E}}$, $GP_{z1} \rightarrow s_{z1}$, $T_{z1}^{\max} \rightarrow \tau_{z1}$), the decision-makings (M_{zk1}, R_1 and TC_1) for all the lessees at the first network-level cycle can be obtained. Similarly, LPO programming will be sequentially performed at each PM execution points e_{zu} for each lessee and LNM programming will be applied to cover the outsourcing maintenances of leasehold service network.

5.3. Output of cyclic global maintenance schemes

During the lease period T_z^{L}, the NOM policy is designed for the leasehold service network through a global perspective by minimizing the total maintenance cost cycle by cycle. The lessor can calculate TC_d of each feasible scheme and obtain the optimal one cyclically. And for each leased machine (z, j), the updated PM intervals T'_{zji} from LNM optimization will be fed back to the machine level for the next COM scheduling. Like the examples at the first network-level cycle, the NOM policy dynamically optimizes the total maintenance cost to formulate cost-effective outsourcing maintenance schemes. The global maintenance schemes of sequential network-level cycles are shown in Table 5.

At each network-level cycle, TC_d values are optimized to schedule the optimal routes of maintenance teams R_d. Multiple maintenance teams of lessor perform PM actions for each lessee in a specific time period according to the optimal routes. This in turn leads to corresponding arrival time M_{zkd}, thereby updates the machine-level PM interval and the system-level time point of each leased machine. Furthermore, it can be seen that only lessees v_1, v_4, and v_5 have their actual start times at the ninth cycle. It is because that the machines' PM time points t_{zju} of lessees v_2 and v_3 have exceeded their corresponding lease period. In sum, based on the real-time global maintenance schemes, the lessor can arrange relevant number of maintenance teams to perform all outsourcing maintenances circularly.

5.4. Effectiveness of network opportunistic maintenance policy

To illustrate the effectiveness, we make a comparison of this triple-level NOM policy with two maintenance policies normally used in real manufacturing companies. (1) Individual preventive maintenance (IPM) policy: PM actions of each leased machine are individually performed by a maintenance team according to their original PM intervals from the machine level. IPM is applied based on machines' individual deteriorations without considering system structure interactivities. (2) Leasing profit optimization (LPO) policy: Whenever one machine is scheduled to have a PM action, the others are considered whether to be performed PM actions together. And a maintenance team will perform PM actions of one production line without considering the network routing problem.

Fig. 4 shows the cumulative total maintenance cost (CTMC) values during the lease period of above three maintenance polices. It can be seen that the cumulative total maintenance cost of the IPM policy is CTMC = \$3188700, while the LPO policy can cost CTMC = \$2091900 in this case. In comparison, based on the cumulative total maintenance cost of cyclic optimal maintenance schemes in Table 5, the CTMC of this NOM policy is \$971,420, since the proposed framework combines maintenance and routing optimizations in depth. This CTMC-value comparison with two conventional maintenance policies can demonstrate the cost-effectiveness of the NOM policy for multi-location leasehold service network.

Table 1
Maintenance parameters of diverse leased machines.

v_z	j	(β_{zj}, η_{zj})	(a_{zj}, ε_{zj})	T_{zj}^{P}(h)	T_{ij}^{R}(h)	C_{ij}^{P}(\$)	C_{ij}^{R}(\$)
1	1	(3.1,4000)	(0.025,1.035)	20	66	6500	18,000
	2	(1.8,4400)	(0.016,1.042)	25	74	8000	30,000
	3	(2.5,5500)	(0.018,1.044)	14	48	6000	17,000
2	4	(2.1,3200)	(0.023,1.054)	10	38	3400	8800
	5	(1.9,3400)	(0.038,1.032)	12	68	9600	28,000
	6	(2.3,5600)	(0.048,1.041)	8	18	4000	6800
3	7	(1.9,3400)	(0.038,1.032)	12	68	9600	28,000
	8	(1.7,6500)	(0.036,1.052)	10	22	9800	16,000
	9	(2.3,5600)	(0.048,1.041)	8	18	4000	6800
4	10	(2.1,3200)	(0.023,1.054)	10	38	3400	8800
	11	(1.9,3400)	(0.038,1.032)	12	68	9600	28,000
	12	(1.7,6500)	(0.036,1.052)	10	22	9800	16,000
5	13	(1.9,3400)	(0.038,1.032)	12	68	9600	28,000
	14	(2.5,5500)	(0.018,1.044)	14	48	6000	17,000
	15	(3.1,4600)	(0.036,1.037)	16	40	7000	13,000

Table 2
Lease parameters of multi-location production lines.

V	(x_z, y_z)	$t_{zz'}$(h)						j	V^{S}_{zj}($)	V^{E}_{zj}($)	κ_{zj}($/h)	δ_{zj}
		0	1	2	3	4	5					
0	(0,0)	0	52	87	71	83	62	–	–	–	–	–
1	(−25,45)	52	0	46	76	131	91	1	700,000	660,000	14	0.11
								2	960,000	860,000	18	0.15
								3	520,000	400,000	16	0.13
2	(−70,−50)	87	46	0	120	169	135	4	400,000	350,000	10	0.12
								5	860,000	700,000	20	0.22
								6	330,000	250,000	18	0.16
3	(50,50)	71	76	120	0	102	37	7	860,000	700,000	20	0.22
								8	750,000	600,000	22	0.28
								9	330,000	250,000	18	0.16
4	(65,−50)	83	131	169	102	0	66	10	400,000	350,000	10	0.12
								11	860,000	700,000	20	0.22
								12	750,000	600,000	22	0.28
5	(60,15)	62	91	135	37	66	0	13	860,000	700,000	20	0.22
								14	520,000	400,000	16	0.13
								15	600,000	550,000	12	0.14

6. Discussion

To validate the proposed triple-level NOM policy, and this decision-making process in the dynamic opportunistic maintenance strategy, we conduct some sensitivity analyses and perform some further investigations from the numerical results on the whole-network optimization for leasehold service network.

6.1. Impact of the width of time window

We first analyze how the width of the service time-window affects lessor's maintenance schemes. If w_z is large, the time window $[t^{S}_{zd}, t^{E}_{zd}]$ becomes wide, while if w_z is small, the time window becomes tight. To focus on the effects of w_z, we assume the other routing parameters that the lessor pays $3000 for every maintenance team when it recruits, while the capacity of a maintenance team is 6 unit/time. The unit costs associated with the maintenance travel, the waiting, and the late arrive penalty are set as $c_{zz'} = \$150$, $c^{W}_{zz'} = \$50$, and $c^{P}_{z'}$=$20 correspondingly. To investigate how width of time window affect the global maintenance schemes, various values of the time window are investigated. Thus, cyclic global maintenance schemes with w_z = 25, 50, 100h are shown in Fig. 5(a), (b), (c), respectively.

It can be seen that the time windows $[t^{S}_{zd}, t^{E}_{zd}]$ with different widths w_z will impact the number of maintenance teams and the ordered sequences of each group maintenance. Results of the total maintenance costs will thus be different during the lease period T^{L}_{z}. From the global maintenance scheme with w_z = 100h given in Fig. 5(c), it is visible that a longer time window can make more lessees maintained by a maintenance team. For example, in the 4th network-level cycle, the PM actions of lessee v_1 and v_5 are combined. This results in less demand for maintenance team in this cycle. Therefore, as the width of time window gradually increases, there are more opportunities to integrate the PM actions of multiple lessee to a team. Effective maintenance integration will decrease the number of PM actions and the total maintenance cost within the lease period.

It is clear that when the width of time window is large, multiple lessees maintained in advance will lead to less PM actions, thus reducing the total maintenance cost. However, more PM actions performed on the machines can decrease unnecessary downtimes. In sum, neither too small nor too large width of time window should be applied. The suitable value of w_z is essential to reach the cost-effective whole-network optimization.

Table 4
Global maintenance scheme at the 1st network-level cycle.

v_z	s_{z1}	t^{S}_{z1}	t^{E}_{z1}	τ_{z1}(h)	M_{zk1}	RT_1	TC$_1$($)
1	2	2244	2269	25	2244	$[v_0 \to v_2 \to v_0]$	81,930
2	2	1924	1949	12	1924		
3	1	2034	2059	12	2083		
4	2	1924	1949	12	1924	$[v_0 \to v_4 \to v_5 \to v_3 \to v_1 \to v_0]$	
5	1	2034	2059	12	2034		

Table 3
LPO programing at the 1st system-level cycle.

v_z	j	t_{zj1}	e_{z1}	LPA$_{zj1}$($)	LPR$_{zj1}$($)	LPS$_{zj1}$($)	Y_{zj1}	T^{P}_{zji}(h)	GP_{z1}	T^{max}_{z1}(h)
1	1	2269	2269	–	–	–	1	20	{1,2}	25
	2	2384		1345	504	841	1	25		
	3	3086		2531	2888	−357	0	14		
2	4	1949	1949	–	–	–	1	10	{4,5}	12
	5	2059		1382	763	619	1	12		
	6	3969		2889	5622	−2733	0	8		
3	7	2059	2059	–	–	–	1	12	{7}	12
	8	6014		12,895	28,306	−15,411	0	10		
	9	3969		2800	5106	−2306	0	8		
4	10	1949	1949	–	–	–	1	10	{10,11}	12
	11	2059		1382	763	619	1	12		
	12	6014		113,113	30,185	−17,072	0	10		
5	13	2059	2059	–	–	–	1	12	{13}	12
	14	3086		2960	3908	−948	0	14		
	15	2969		2728	3458	−730	0	16		

Table 5
Global maintenance schemes of sequential network-level cycles.

d	M_{zkd}					RT_d	TC_d($)
	v_1	v_2	v_3	v_4	v_5		
1	2244	1924	2083	1924	2034	$[v_0 \to v_2 \to v_0][v_0 \to v_4 \to v_5 \to v_3 \to v_1 \to v_0]$	81,930
2	3086	3809	3956	3809	2956	$[v_0 \to v_5 \to v_1 \to v_0][v_0 \to v_4 \to v_3 \to v_0][v_0 \to v_2 \to v_0]$	102,550
3	4473	5644	5960	5791	4073	$[v_0 \to v_2 \to v_4 \to v_0][v_0 \to v_1 \to v_0][v_0 \to v_3 \to v_0][v_0 \to v_5 \to v_0]$	109,690
4	6115	7432	7816	7579	5839	$[v_0 \to v_2 \to v_4 \to v_0][v_0 \to v_1 \to v_0][v_0 \to v_3 \to v_0][v_0 \to v_5 \to v_0]$	107,250
5	8229	9175	9792	9322	7831	$[v_0 \to v_2 \to v_4 \to v_0][v_0 \to v_1 \to v_0][v_0 \to v_3 \to v_0][v_0 \to v_5 \to v_0]$	107,250
6	9087	10,875	11,577	11,022	8638	$[v_0 \to v_1 \to v_4 \to v_0][v_0 \to v_2 \to v_5 \to v_0][v_0 \to v_3 \to v_0]$	107,250
7	10,309	12,534	13,539	12,681	9823	$[v_0 \to v_2 \to v_4 \to v_0][v_0 \to v_1 \to v_0][v_0 \to v_3 \to v_0][v_0 \to v_5 \to v_0]$	107,250
8	11,982	14,154	15,249	14,301	11,358	$[v_0 \to v_2 \to v_4 \to v_0][v_0 \to v_1 \to v_0][v_0 \to v_3 \to v_0][v_0 \to v_5 \to v_0]$	107,250
9	13,959	–	–	15,883	13,324	$[v_0 \to v_1 \to v_0][v_0 \to v_4 \to v_0][v_0 \to v_5 \to v_0]$	63,600
10	14,824	–	–	–	14,004	$[v_0 \to v_1 \to v_0][v_0 \to v_5 \to v_0]$	37,200
11	–	–	–	–	15,302	$[v_0 \to v_5 \to v_0]$	20,100
12	–	–	–	–	16,580	$[v_0 \to v_5 \to v_0]$	20,100

6.2. Impact of the maintenance team's visit cost

We next analyze the impact of the maintenance team's visit cost onto the maintenance schemes. We set the width of time window as w_z = 50h, use the capacity of the maintenance team, the cost associated with the maintenance travel, the waiting and the late arrive penalty as in the previous subsection. We conduct the second case to assess the impact of c_k (the lessor pays for every maintenance team when it recruits) on global maintenance schemes. The triple-level NOM policy ensures dynamically how aggressive whether it should group the maintenances together in an effort to balance out the team visit costs. To study this effect, we changed the cost as c_k=$1500, $3000, and $6000, as illustrated in Fig. 6(a), (b), (c).

It can be observed that the total maintenance cost has an increasing pattern when c_k becomes large. More importantly, we can observe that as the visit cost increases, the NOM policy makes more of an effort to decide whether to limit the number of maintenance teams or change the sequence of routing results. For example, in the 4th network-scheduling cycle, the maintenance scheme of c_k = $6000 given in Fig. 6(c) is different from the others. If the maintenance scheme is same as before that use four maintenance teams to cover all the PM actions, it will cost $125,250. But the optimal global maintenance scheme uses three maintenance teams that lessor will only need spend $122,640 at this cycle.

The results in Fig. 6 indicate that as the maintenance team's visit cost increases, the lessor will minimize the number of maintenance teams while meeting the maintenance demands. That is to say, human resources will be saved during the lease period. However, these improvements also decrease the number of visits, which become increasingly important as their associated cost rises. And too large c_k-value will cause human resources to be the primary constraint. Therefore, the correct description of the payment for each maintenance team can contribute to the optimality of the global maintenance schemes.

6.3. Impact of the late penalty cost

In the last case, we study the effects of the late penalty cost $c_{z'}^{p}$. Generally, the group PM sets of each production line should start within the corresponding time windows. However, there also can be two possibilities: (1) the maintenance team may arrive much before the starting of the time window and (2) it may arrive well after the ending of the time window. In the triple-level NOM policy, for the first condition, a waiting cost is charged for waiting outside the time window. And in the second condition, a late penalty cost is incurred depending upon the number of hours operated outside the time window to counter such violation. With the increase of the late penalty cost, lessor would rather increase the number of maintenance teams, even if the capacity of the maintenance team is still overplus.

In order to highlight the effects of the late penalty cost onto the routing results, we set the width of time-windows as w_z = 100h and use the capacity of maintenance team, the costs associated with the maintenance travel and the waiting as in the previous subsection. We set that the lessor pays up to $6000 for every maintenance team when it recruits and change the late penalty cost as $c_{z'}^{p}$=$20, $100, and $500 per hour, as illustrated in Fig. 7(a), (b), (c).

Based on the results in Fig. 7, it can be found that even with a large maintenance team's visit cost as c_k = $6000, as the cost of the late penalty increased, the NOM policy prefers to choose more maintenance

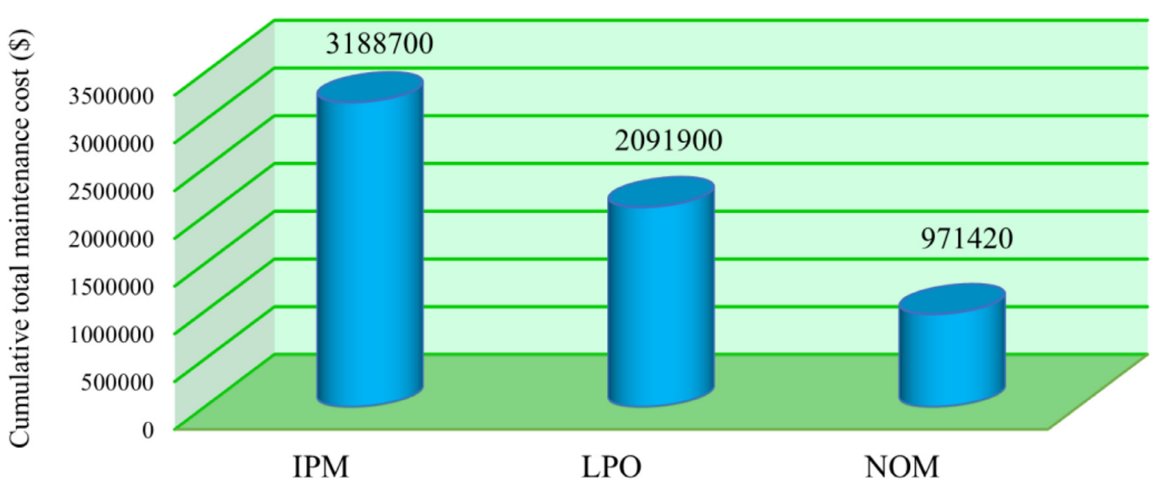
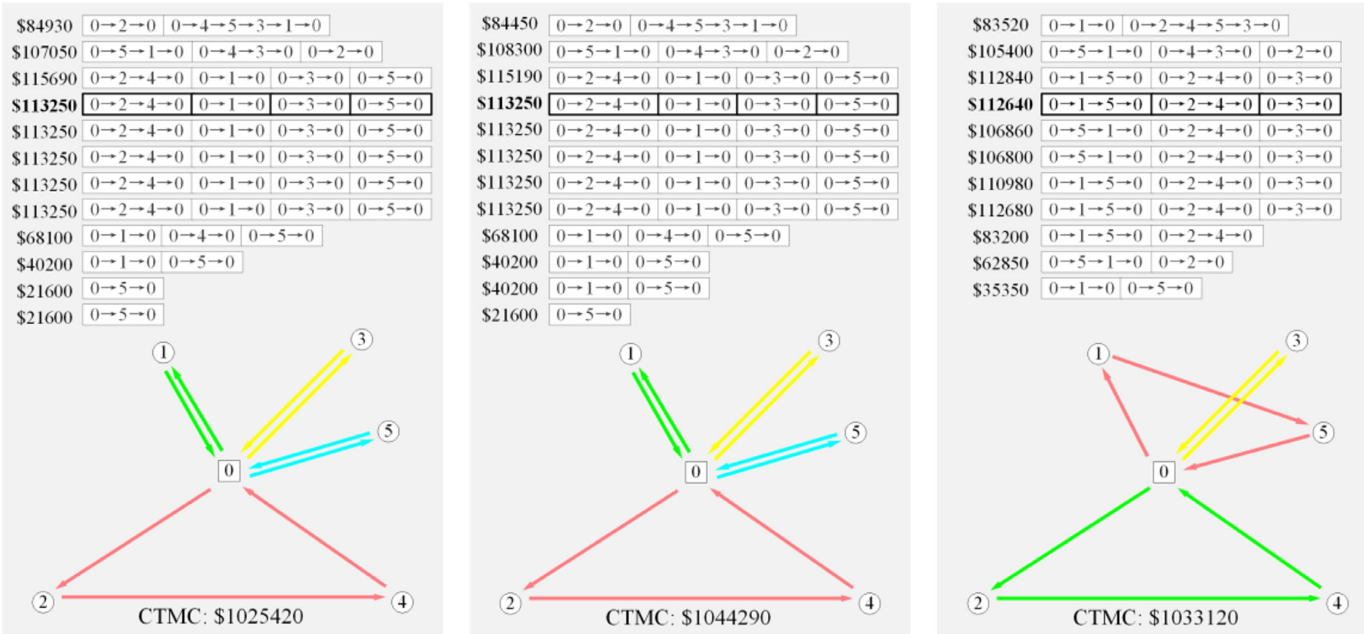


Fig. 4. Cumulative total maintenance cost comparison of three policies.

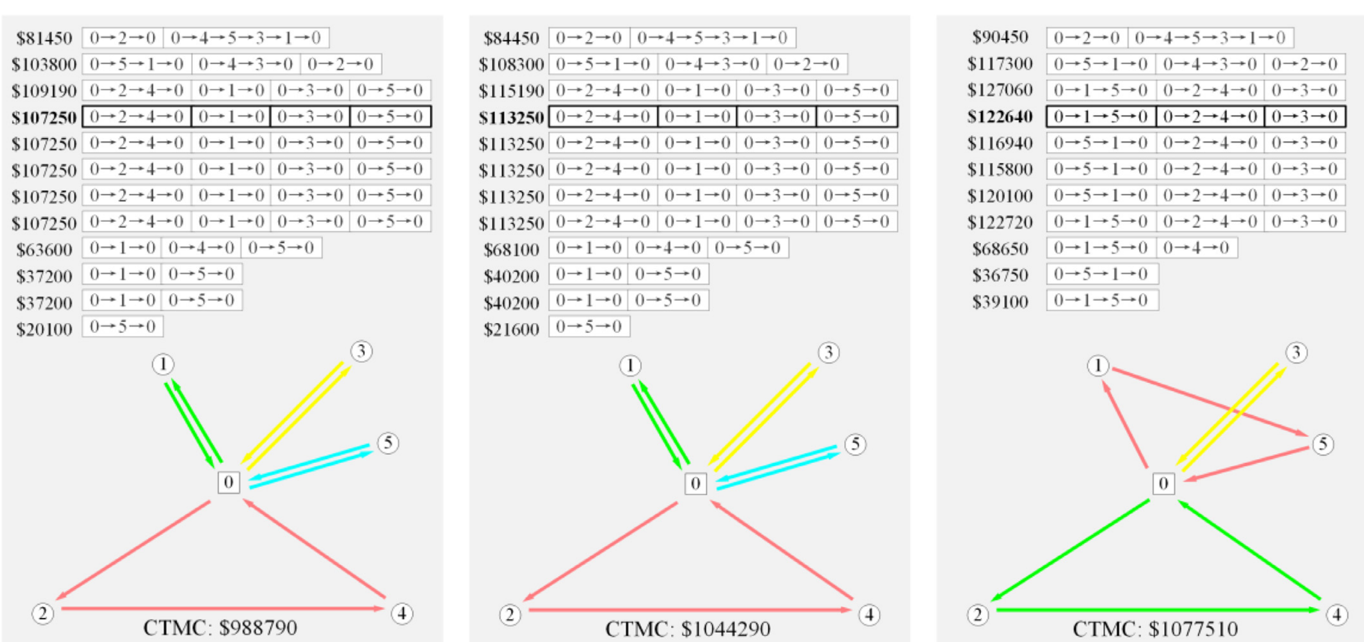


(a) (b) (c)

Fig. 5. Global maintenance schemes with different widths of service time-window.

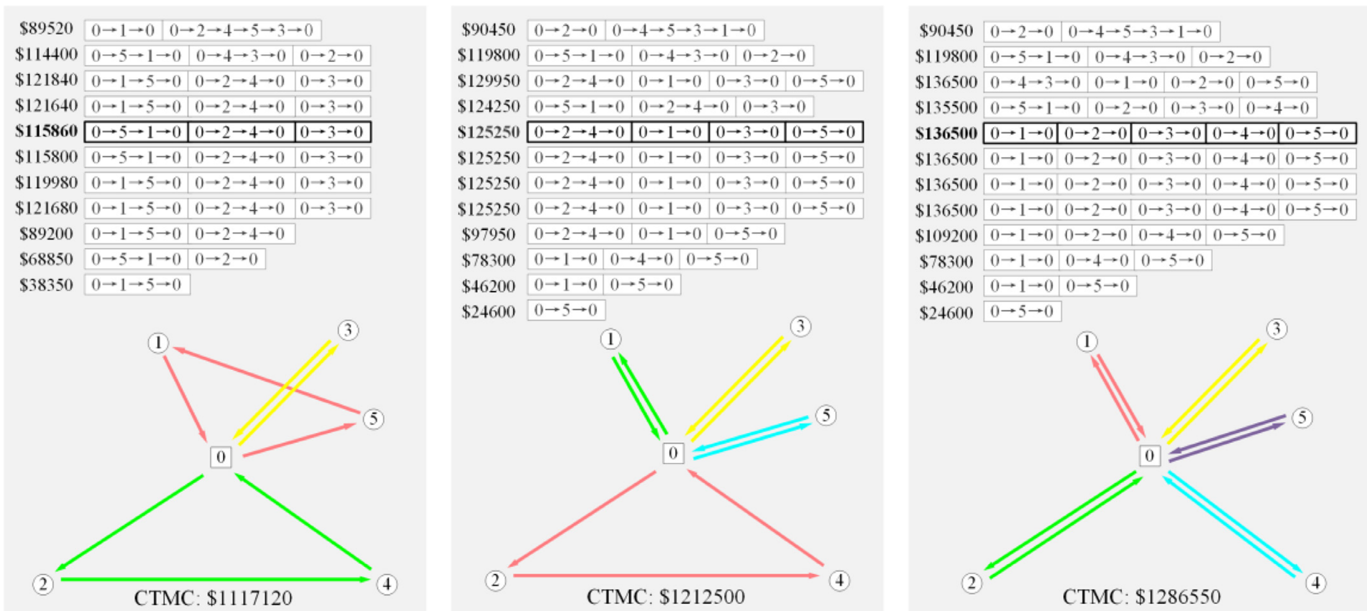
teams to perform all the maintenances. It is because that the larger $c_{z'}^{p}$-values enables the hard time windows of each group PM actions, which means the late penalty becomes the primary constraint.

Furthermore, facing multi-location maintenance optimization problem, the opportunistic maintenance scheduling, logistics path planning and human resource routing should be considered comprehensively. Therefore, we decompose this problem into several subproblems (corresponding to different levels) in this paper. In the machine level, we not only consider the degradation information from the whole population but also consider the unique information from each individual machine. In the system level, tradition opportunistic maintenance strategies consider all the possible machine combinations and calculate the corresponding maintenance cost savings. Thus, the scheduling complexity for a D-unit manufacturing system will be at least $O(2^{(D\text{-}1)})$, which means the complexity grows exponentially with the machine number. This LPO model utilizes the downtime caused by the first machine's PM action as a maintenance opportunity to calculate the leasing profit saving of the other machines. And the scheduling complexity will be reduced to O(D-1). In the network level, the network-level routing problem is a capacity-constrained vehicle routing problem with time windows (VRPTW). We use the tabu search to solve the routing problem. Therefore, triple-level NOM policy can handle a larger



(a) (b) (c)

Fig. 6. Global maintenance schemes with different maintenance team's visit costs.



(a) (b) (c)

Fig. 7. Global maintenance schemes with different late penalty costs.

leasehold service network, even its machine and lessees number increase, to dynamically output efficient global maintenance schemes.

In the general sense, NOM policy can efficiently avoid unnecessary system downtime, achieve total maintenance cost reduction and overcome complexity of networked maintenance and routing with various maintenance date flow and lease date flow. Different distributed manufacturing systems with various machine reliabilities and geographical locations would lead to different global maintenance schemes and corresponding total maintenance costs. However, the mechanism of the NOM policy can ensure the dynamic networked maintenance and routing performance. On the one hand, with sequential PM advancement or performed on schedule, this cost-driven opportunistic maintenance strategy avoids unnecessary system downtime by utilizing the group maintenance opportunity caused by the first PM action. On the other hand, the network-level dynamically compares the total maintenance costs and chooses the global maintenance scheme with the lowest maintenance cost at each network-level cycle. It makes full use of the capacity of each maintenance team and reduces the number of maintenance team assignments. This sequential decision-making process ensures that the minimization of total maintenance cost can be achieved, which make NOM more effective than traditional maintenance policies normally used in real manufacturing companies (e.g. IPM and LPO). In sum, the NOM policy achieves significant total maintenance cost reduction of the whole-network, because it not only makes the PM adjustment according to the profit saving for every machine at each group maintenance opportunity, but also considers the capacity of the maintenance team and routing sequence optimization.

7. Conclusion and prospects

In this paper, we propose a triple-level network opportunistic maintenance policy for the leasehold service network of multi-location production lines by effectively integrating maintenance costs, lease contracts and geographical locations. The machine-level COM model based on reliability evolution is proposed to obtain the sequential PM intervals of each leased machine. The system-level LPO model is then presented, which utilizes the stop of the entire production line caused by the first PM action to determine whether to advance the PM actions on other machines. And outputs the group PM sets of each production line. While ensuring the reliability of each leased machine, the network-level LNM model is presented to minimize the total maintenance cost, which includes travel cost, waiting cost, late penalty cost, and maintenance team's visit cost. And in this model, the allocation sequence of each maintenance team and the PM planning of each geographically distributed lessee are concurrently determined.

Cumulative total maintenance cost minimized by applying NOM policy has been demonstrated in a leasehold service network of various multi-unit production lines. Results on practical instances illustrate a balance among the total maintenance costs, the service capacities and the maintenance demands. Comparison experiments between our policy and other two maintenance policies show that our policy can help the lessor to effectively achieve lower cumulative total maintenance cost. The contribution of this paper is that this policy not only reduces the complexity of whole-network optimization for leasehold service network, but also ensures the minimization of total maintenance cost. It can be concluded that this NOM policy can scale well to future service-oriented networked manufacturing.

In future work, the extension of this proposed policy is to consider a dynamic stochastic failure condition, in which unplanned failures occur on the leased machines and the maintenance teams need to be rescheduled to cover these failures in real time. Also, for larger instances and real-world global business, this study can also be extended by involving other kinds of system structure, such as parallel system, series-parallel system and k-out-of-N system.

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