Tangbin Xia
Mem. ASME
State Key Laboratory of Mechanical System and Vibration,
Department of Industrial Engineering,
School of Mechanical Engineering,
Shanghai Jiao Tong University,
Shanghai 200240, China;
H. Milton Stewart School of Industrial and Systems Engineering,
Georgia Institute of Technology,
765 Ferst Drive,
Atlanta, GA 30332
e-mails: xtbxtb@sjtu.edu.cn; txia60@gatech.edu

Lifeng Xi[1]
State Key Laboratory of Mechanical System and Vibration,
Department of Industrial Engineering,
School of Mechanical Engineering,
Shanghai Jiao Tong University,
Shanghai 200240, China
e-mail: lfxi@sjtu.edu.cn

Ershun Pan
State Key Laboratory of Mechanical System and Vibration,
Department of Industrial Engineering,
School of Mechanical Engineering,
Shanghai Jiao Tong University,
Shanghai 200240, China

Xiaolei Fang
H. Milton Stewart School of Industrial and Systems Engineering,
Georgia Institute of Technology,
765 Ferst Drive,
Atlanta, GA 30332

Nagi Gebraeel
H. Milton Stewart School of Industrial and Systems Engineering,
Georgia Institute of Technology,
765 Ferst Drive,
Atlanta, GA 30332

Lease-Oriented Opportunistic Maintenance for Multi-Unit Leased Systems Under Product-Service Paradigm

With many industries increasingly relying on leased equipment and machinery, many original equipment manufacturers (OEMs) are turning to product-service packages where they deliver (typically lease) the physical assets. An integrated service contract will be offered for the asset. A classic example being Rolls Royce power-by-the-hour aircraft engines. Service contracts offered by original equipment manufacturers have predominantly focused on maintenance and upkeep activities for a single asset. Interestingly enough, manufacturing industries are beginning to adopt the product-service paradigm. However, one of the unique aspects in manufacturing settings is that the leased system is often not a single asset but instead a multi-unit system (e.g., an entire production line). In this paper, we develop a lease-oriented maintenance methodology for multi-unit leased systems under product-service paradigm. Unlike traditional maintenance models, we propose a leasing profit optimization (LPO) policy to adaptively compute optimal preventive maintenance (PM) schedules that capture the following dynamics: (1) the structural dependencies of the multi-unit system, (2) opportunistic maintenance of multiple system components, and (3) leasing profit savings (LPSs). We demonstrate the performance of our multi-unit maintenance policy by using a leased automotive manufacturing line and investigate its impact on leasing profits.
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1 Introduction

Outsourcing maintenance activities has been a growing trend in many industries. In 1980, Rolls Royce practically coined the phrase power-by-the-hour for their jet engines. Operators were provided with a complete engine overhaul after a fixed number of flying hours, thus relieving the airline operators from performing delicate maintenance on the engine and carrying large amounts of spare stocks for their entire fleet. Other original equipment manufacturers, such as GE and Pratt & Whitney quickly followed suit. Airline industries embraced the idea because they acknowledged the fact that equipment manufacturers who designed and manufactured the engines are arguably the best source for maintaining these assets over their lifecycles.

A similar trend is taking place in the manufacturing industry where entire production lines are being leased to companies through a product-service package. The original equipment manufacturer leases the physical assets and offers an integrated service contract for maintaining the assets throughout the lease period [1]. With the increasing product diversification, manufacturing industries tend to embrace the leasing option and either renew or lease a different production line configuration based on customer demands and preferences. Similar to the airline sector, maintenance of leased machines is provided by the lessor (the original equipment manufacturer who owns the system). However, the systems in the manufacturing sector often consist of multiple units, i.e., multiple machines constituting a production line. Thus, performing maintenance becomes more interesting because it is likely to benefit from an opportunistic maintenance policy.

Normally, two types of maintenance actions, corrective maintenance (CM) and PM, are performed to maintain the upkeep of the leased system [2–5]. Corrective maintenance typically takes the form of minimal repair actions to bring back a failed machine to

[1]Corresponding author.
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its operational state without changing its failure rate. In contrast, preventive maintenance focuses on reducing the possibility of unexpected failures. Numerous valuable PM models have been proposed in the literature [6–11]. Many models assume that perfect PM, which brings a machine to the "as good as new" state, may be plausible in practice [12,13]. Imperfect PM that makes the machine younger is applied in this paper. PM actions are scheduled by balancing the costs of PM routines and unexpected failure events [14]. In addition to the regular maintenance costs, others aspects (such as lease period, rental cost, and penalty cost for prolonged downtime) need to be considered when dealing with maintenance of leased equipment.

Leasing manufacturing equipment has led to some new issues in maintenance scheduling. These issues are specified in the lease contract for both the lessor and the lessee, such as the lease period, the rent cost, the penalty cost, and the maintenance cost. There have been numerous studies devoted to this topic. For example, Jaturonnatee et al. [15] developed a model to determine the optimal parameters of a preventive-maintenance policy, which considers some cost aspects with the goal of minimizing total expected cost to the lessor. Pongpech and Murthy [16] focused on a periodic preventive-maintenance policy, which achieves a tradeoff between the penalty for failures occurring over the lease period without timely rectifications and maintenance. Yeh and Chang [17] and Yeh et al. [18] investigated several important optimal preventive-maintenance policies for leased equipment, where PM actions were performed sequentially with a fixed maintenance degree, and the fixed failure-rate-reduction method was adopted to describe the degree of PM. Chang and Lo [19] studied the influence of the length of the lease period on the maintenance policy, while a machine's residual value after the lease was considered for machine reuse and reclaiming channels. Schutz and Rezg [20] developed two maintenance strategies for leased equipment: preventive maintenance was triggered when the system reliability reached a prespecified threshold in the first policy, while the second policy focused on the effectiveness degree of PM to determine the cost of PM actions.

The existing literature has focused almost exclusively on maintenance decision-making for a single leased machine. Our framework builds on the existing literature and tries to solve the difficulties to perform the extension to multi-unit leased systems: (1) economic dependences of multiple leased machines should be considered to optimize machine-level PM intervals; (2) group maintenance opportunity caused by one machine should be utilized for others to avoid unnecessary system downtime and dispatching cost; (3) the designed system-level PM optimization should be interactive with the machine-level PM scheduling in real time; and (4) PM adjustments based on real-time calculations of leasing profit savings should reduce the maintenance scheduling complexity for a multi-unit leased system. Specifically, we propose a systematic framework for lease-oriented maintenance methodology that targets multi-unit leased systems. The key distinction being that different machines (units) in the system will require different maintenance intervals, thus giving rise to a setting that can benefit tremendously from an opportunistic maintenance paradigm. In addition, to investigating the dynamics between opportunistic maintenance and leasing profits, our framework also considers the impact of system structure. The conception of opportunistic maintenance is utilized to solve the complexity of multi-unit leased system scheduling, which refers to the optimal maintenance scheme that PM actions are carried out at opportunities [21–25]. For a manufacturing line, when one leased machine is preventive maintained, PM opportunities arise for other ones [26–29]. The advantage of applying opportunistic maintenance is that one PM combination with several PM actions advanced can save much maintenance cost for the lessor. However, classical opportunistic maintenance policies just adjust PM actions according to the time window of maintenance opportunities and do not consider PM optimizations in a leasing profit-maximizing manner. Thus, they can only be called maintenance-driven opportunistic maintenance. Due to innovation requirements of the product-service paradigm, we develop a novel type of opportunistic maintenance. It not only considers the degradation of each machine but also integrates system structure interactivities, advanced maintenance opportunities, and leasing profit savings.

In this paper, a lease-oriented maintenance methodology is proposed for the lessor and the lessee to service multi-unit leased systems by integrating both individual machine degradation and the product-service paradigm. During the lease period, original machine-level PM actions are dynamically scheduled to reduce failures of diverse machines cycle by cycle ($i = 1, 2, 3\ldots$). By pulling these outputs, a leasing profit optimization (LPO) policy in the system level is developed to obtain real-time PM optimizations (early PM) for the whole system by utilizing each maintenance opportunity ($u = 1, 2, 3\ldots$). And the system-level LPO results will be fed back to schedule the subsequent PM cycle in real time. This bilevel programing interactively calculates the leasing profit savings to make real-time schedules on whether to advance PM actions of nonfailure leased machines or not. The proposed policy aims to help the lessors to effectively maximize leasing profit, avoid lessee's shutdown, and improve lessor's service. The remainder of this paper is organized as follows: Section 2 gives the problem statement of leased systems under the product-service paradigm. Section 3 presents mathematical formulations in the lease-oriented opportunistic maintenance methodology and the decision-making process of LPO programing. Section 4 investigates case studies of the proposed methodology to demonstrate its effectiveness for multi-unit leased systems. The simulation results can effectively prove the effectiveness of this lease-oriented maintenance methodology. Finally, Sec. 5 provides some concluding remarks and future works.

2 Problem Statement

This paper proposes a lease-oriented opportunistic maintenance methodology specifically designed for product-service settings, where original equipment manufacturers (lessor) lease multi-unit manufacturing systems to their client companies (lessee). Due to their comprehensive knowledge of the system's design, OEMs typically offer the best maintenance practices. Classical

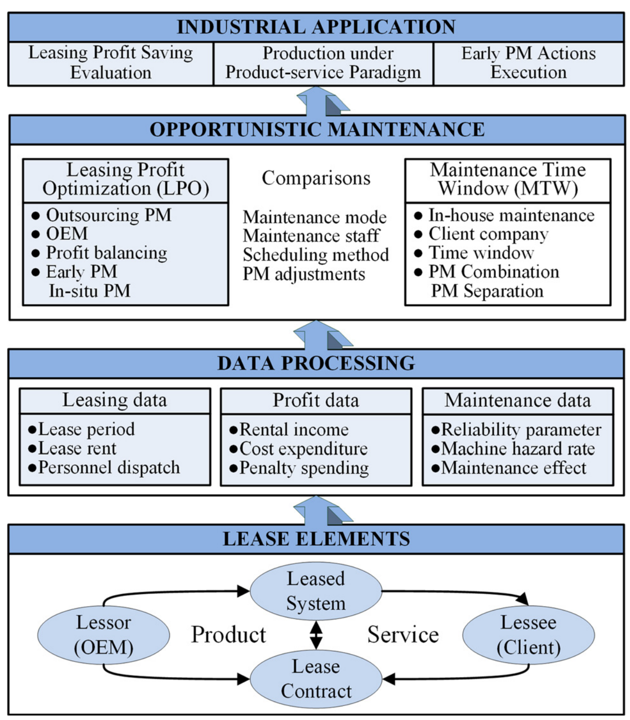

Fig. 1 Illustration of lease-oriented opportunistic maintenance

opportunistic maintenance policies exploit a PM event for one machine as an opportunity to maintain other machines if economically feasible. Our framework extends opportunistic maintenance to settings lease-oriented applications by considering the effects of maintenance on leasing profits. And the unique interactions between the lessor and the lessee are also taken into account. This is accomplished by developing a real-time leasing profit optimization policy that aims at adaptively computing optimal PMs based on leasing profit savings. Unlike classic opportunistic maintenance policies, such as the maintenance time window policy [26], lease-oriented opportunistic maintenance is unique in that it utilizes LPO to increase lease profit for the lessor while reducing maintenance costs for the lessee. The proposed policy dynamically computes the leasing profits resulting from advancing the maintenance of other machines in an opportunistic manner. In other words, it calculates the cost savings that would be realized by expediting future PMs of others to the current PM epoch. It adaptively calculates the benefits of advancing the PM action of each machine and how many PMs should be advanced. The design of our lease-oriented maintenance framework is illustrated in Fig. 1.

In this study, we consider a setting where multi-unit systems that consist of multiple machines are being leased. Machines are assumed to have different degradation rates, and therefore, exhibit different hazard rates and PM intervals. Preventive maintenance is assumed to bring back a machine to a better state, but not as good as new. In the event of an unexpected failure, minimal repair is performed to bring back the failed machine to its operational state. However, minimal repair does not improve its hazard rate. We assume that PMs are scheduled adaptively per machine. However, additional machines can be maintained in an opportunistic sense if it proves economical. A lease contract governs the dynamics between the lessor and the lessee and is considered binding. It spells out the rights and obligations of both parties, e.g., lease period, machine rent, maintenance costs, cost of dispatching maintenance personnel, cost of unexpected failures, rates of depreciation of each machine, PM intervals, etc. Without loss of generality, we consider a series system, i.e., a system where all the machines are critical and are arranged in series. Thus, the failure of one machine implies shutting down of the entire system.

3 Mathematical Formulation

In the lease-oriented opportunistic maintenance methodology, the lessor dynamically schedules PM actions and minimal repairs to provide service during the lease period. For individual machines, sequential PM intervals are scheduled according to diverse deteriorations by integrating internal factors (lessor's maintenance effect) and external factors (lessee's environmental condition). By pulling original PM intervals, LPO policy dynamically optimizes real-time PM actions in the system level by achieving leasing profit savings at every opportunity. And LPO decisions will be fed back to the machine-level PM scheduling. This opportunistic maintenance methodology considers system structure interactivities, advanced maintenance opportunities, and leasing profit savings to achieve the profit maximization.

3.1 Sequential Preventive Maintenance Scheduling for Each Leased Machine. We consider a multi-unit leased system consisting of different machines. Each machine M_j, $j \in \{1, 2, \ldots, j\}$, is assumed to be operating except when there is a scheduled PM or an unscheduled breakdown. M_J has its individual degradation, and therefore, its own hazard rate $\lambda_{ij}(t)$ defined for the ith PM cycle for $j \in \{1, 2, \ldots, I\}$. A PM interval is defined as the duration between two successive PM actions. If a leased machine fails during a PM interval, it undergoes a minimal repair to bring it back to an operational state without altering its hazard rate. Thus, the relationship between hazard rates before and after the ith PM is defined by

$$\lambda_{(i+1)j}(t) = \varepsilon_{ij}\lambda_{ij}\left(t + a_{ij}T'_{ij}\right), \quad t \in \left(0, T_{(i+1)j}\right) \tag{1}$$

where T'_{ij} is the last PM interval feedback from system-level LPO optimization. The machine-level PM interval output T^*_{ij} may be shortened to perform early PM in the system level. Thus, for the new cycle $i+1$, the actual PM interval T'_{ij} should be used to reflect the failure rate after last imperfect PM. a_{ij} is the age reduction factor for imperfect maintenance, where $0 < a_{ij} < 1$ reflects the internal maintenance capability of the leased machine. The age reduction factor can be fixed (stable maintenance capability) or variable (changeable maintenance capability), and $\lambda_{ij}\left(a_{ij}T'_{ij}\right)$ is the failure rate after imperfect PM [12,13]. ε_{ij} is a parameter that captures the effect of the lessee's environment on a machine's hazard rate, and $\varepsilon_{ij} > 1$ indicates that the environment leads to machine accelerated degradations. The environment factor can be estimated from historical degradation data [30–32].

Based on the hazard rate, we develop a cost rate model that calculates sequential PM intervals for each individual machine. The objective of this cost rate model is to minimize the maintenance cost per unit time of the ith PM cycle for M_j

$$C_{ij} = \left[C^{\mathrm{P}}_{ij} + C^{\mathrm{R}}_{ij}\int_0^{T_{ij}}\lambda_{ij}(t)\mathrm{d}t\right] \Big/ \left[T_{ij} + \left(T^{\mathrm{P}}_{ij} + T^{\mathrm{R}}_{ij}\int_0^{T_{ij}}\lambda_{ij}(t)\mathrm{d}t\right)\right] \tag{2}$$

where $\int_0^{T_{ij}}\lambda_{ij}(t)\mathrm{d}t$ is the expected failure frequency, $C^{\mathrm{P}}_{ij} + C^{\mathrm{R}}_{ij}\int_0^{T_{ij}}\lambda_{ij}(t)\mathrm{d}t$ is the total maintenance cost, and $T_{ij} + \left(T^{\mathrm{P}}_{ij} + T^{\mathrm{R}}_{ij}\int_0^{T_{ij}}\lambda_{ij}(t)\mathrm{d}t\right)$ is the total duration of the PM interval. By balancing the PM cost and CM cost, a unique machine-level PM interval T^*_{ij} for M_j at cycle i can be obtained by solving the following derivative function, $\mathrm{d}C_{ij}/\mathrm{d}T_{ij} = 0$:

$$\lambda_{ij}(T_{ij})\left(C^{\mathrm{R}}_{ij}\cdot T_{ij} + C^{\mathrm{R}}_{ij}\cdot T^{\mathrm{P}}_{ij} - C^{\mathrm{P}}_{ij}\cdot T^{\mathrm{R}}_{ij}\right) - C^{\mathrm{R}}_{ij}\int_0^{T_{ij}}\lambda_{ij}(t)\mathrm{d}t - C^{\mathrm{P}}_{ij} = 0 \tag{3}$$

When the new machine-level PM interval T^*_{ij} is calculated, we identify the cumulative PM interval to judge that whether $T^*_{ij} + \sum_{k<i}T'_{ij} < T_L$. By pulling these inputs T^*_{ij} from the machine-level PM scheduling of each leased machine, the system-level LPO optimization can adjust PM interval as T'_{ij} for the entire system by dynamically calculating leasing profit savings at every maintenance opportunity. The system-level LPO output T'_{ij} can be used to schedule the subsequent PM cycle by integrating $\lambda_{(i+1)j}(t)$ in Eq. (1).

3.2 Opportunistic Preventive Maintenance Adjustment for the Leased System. For a given PM event, the goal of our maintenance policy is to opportunistically advance future scheduled PM of other machines by optimizing leasing costs. Our policy is designed to dynamically analyze leasing profit savings to decide between advancing a PM or performing it on schedule (early PM or in situ PM) for every machine while maximizing leasing profits. By opportunistically advancing PM actions, repeated dispatching of maintenance personnel can be minimized. Unlike an unscheduled minimal repair, scheduled PM actions can provide the lessor with the necessary lead time to arrange maintenance engineers and prepare maintenance resources. Thus, the opportunistic maintenance policy is calculated when a PM action is scheduled to be performed on one machine.

The proposed leasing profit optimization policy is processed with the following mechanism: For a J-unit leased manufacturing line, pull real-time PM intervals T^*_{ij} from the machine level for each unit and choose the unit to be performed PM first. Define its PM time point t_{ij} as an LPO decision-making moment t_u for the whole system. For all the other units, the lessor has to decide whether to advance their original PM actions or not. Thus, LPO policy will calculate leasing profit savings of each machine. If early PM can lead to larger leasing profit additions than leasing profit reductions, it will be performed in current group PM set GP_u at t_u. Processing this optimization cycle by cycle during the lease period T_L, the proposed policy can ensure the maximization of leasing profit and the reduction of lessee's shutdown.

3.2.1 Leasing Profit Additions of Preventive Maintenance Advancement. On the one hand, according to the series structure and lease contract of the leased system, leasing profit additions of early PM (the machine M_j is performed PM in advance at time t_u) consist of three profit saving sources, which can be evaluated by

$$\mathrm{LPA}_{ju} = \mathrm{LPA}_{ju}^{\mathrm{R}} + \mathrm{LPA}_{ju}^{\mathrm{D}} + \mathrm{LPA}_{ju}^{\mathrm{M}} \tag{4}$$

where $\mathrm{LPA}_{ju}^{\mathrm{R}}$ is the machine rent saving, $\mathrm{LPA}_{ju}^{\mathrm{D}}$ is the personnel dispatch saving, while $\mathrm{LPA}_{ju}^{\mathrm{M}}$ is the unexpected failure saving of early PM.

First, if a machine's PM action can be advanced to a group PM set GP_u, its extra PM breakdown (time duration of PM action) can be avoided, which means the rent saving for the lessor. According to the PM duration T_{ij}^{P} and the leasing rent K_j, the machine rent saving for M_j is represented as

$$\mathrm{LPA}_{ju}^{\mathrm{R}} = T_{ij}^{\mathrm{P}} \cdot K_j \tag{5}$$

Second, cost of personnel dispatches for sending maintenance engineers for a single machine each time is wasteful. If a machine' PM action can be advanced to be performed together, the lessor can save corresponding cost of personnel dispatch. Thus, the personnel dispatch saving equals to the cost of personnel dispatch for M_j

$$\mathrm{LPA}_{ju}^{\mathrm{D}} = C_{ij}^{\mathrm{D}} \tag{6}$$

Third, a lessee pays its attention to the availability of the leased system under the product-service paradigm. The shorter PM interval $T_{ij}^{*} - (t_{ij} - t_u)$ can reduce the cumulative failure risk, which means unnecessary cost of minimal repairs for unexpected failures can be saved. The unexpected failure saving for M_j can be evaluated as

$$\mathrm{LPA}_{ju}^{\mathrm{M}} = \left[\int_0^{T_{ij}^{*}} \lambda_{ij}(t)dt - \int_0^{T_{ij}^{*}-(t_{ij}-t_u)} \lambda_{ij}(t)dt\right] C_{ij}^{\mathrm{R}} \tag{7}$$

3.2.2 Leasing Profit Reductions of Preventive Maintenance Advancement. On the other hand, it should be noticed that if the lessor decides to advance a PM for M_j, it will also lead to some kinds of leasing profit reductions, which include two main profit reductions

$$\mathrm{LPR}_{ju} = \mathrm{LPR}_{ju}^{\mathrm{P}} + \mathrm{LPR}_{ju}^{\mathrm{D}} \tag{8}$$

where $\mathrm{LPR}_{ju}^{\mathrm{P}}$ is the extra PM spending, while $\mathrm{LPR}_{ju}^{\mathrm{D}}$ is the machine depreciation spending of early PM in cycle u.

First, if a machine's PM action is advanced, its current PM interval will be shortened to $T_{ij}^{*} - (t_{ij} - t_u)$. This will cause the fact that during the lease period, more PM actions will be needed and the lessor has to spend more cost of PM actions. According to the ratio of PM interval change and the actual PM interval, the extra PM spending for M_j can be defined as

$$\mathrm{LPR}_{ju}^{\mathrm{P}} = \frac{t_{ij} - t_u}{T_{ij}^{*} - (t_{ij} - t_u)} C_{ij}^{\mathrm{P}} \tag{9}$$

Second, more PM actions will cause accelerating depreciation in the view of machine's value [33]. Based on the ratio of PM interval change and the lease period, the machine's value attenuation $\left(V_j^{\mathrm{S}} - V_j^{\mathrm{E}}\right)$, and the machine depreciation rate δ_j, the machine depreciation spending of early PM in cycle u can be represented as

$$\mathrm{LPR}_{ju}^{\mathrm{D}} = \delta_j \frac{t_{ij} - t_u}{T_L} \left(V_j^{\mathrm{S}} - V_j^{\mathrm{E}}\right) \tag{10}$$

3.2.3 Leasing Profit Saving of Preventive Maintenance Advancement. Based on the above real-time calculations of leasing profit additions and leasing profit reductions, the lessor can dynamically make LPO optimizations $\Omega(j, t_u)$ for M_j ($j = 1, 2, 3, \ldots, J$) at each maintenance opportunity t_u to obtain the leasing profit saving of PM adjustments (early PM)

$$\begin{aligned}\mathrm{LPS}_{ju} &= \mathrm{LPA}_{ju} - \mathrm{LPR}_{ju} \\ &= \mathrm{LPA}_{ju}^{\mathrm{R}} + \mathrm{LPA}_{ju}^{\mathrm{D}} + \mathrm{LPA}_{ju}^{\mathrm{M}} - \mathrm{LPR}_{ju}^{\mathrm{P}} - \mathrm{LPR}_{ju}^{\mathrm{D}}\end{aligned} \tag{11}$$

If the lessor finds that $\mathrm{LPS}_{ju} = \mathrm{LPA}_{ju} - \mathrm{LPR}_{ju} > 0$, which means that leasing profit additions are larger than leasing profit reductions, early PM (M_j is performed PM in advance at time t_u) will be taken. Otherwise, in situ PM (no early PM on M_j) will be the choice. In sum, the proposed policy dynamically makes the real-time optimization by maximizing the leasing profit saving of every leased machine at every maintenance opportunity. The PM adjustment decision for M_j at t_u is represented as

$$\Omega(j, t_u) = \begin{cases} 1 & \mathrm{LPS}_{ju} > 0 \quad \text{(Early PM)} \\ 0 & \mathrm{LPS}_{ju} \le 0 \quad \text{(In situ PM)} \end{cases} \tag{12}$$

3.3 Decision-Making Process of Leasing Profit Optimization. In Sec. 3.2, LPO programing for one leased machine at one maintenance opportunity has been introduced. Here, the cyclic decision-making process for achieving leasing profit maximization cycle by cycle during the lease period is presented.

Step 1 (*Sequential PM pulling*): During the lease period, start the maintenance scheduling from the first cycle $i = 1$. Pull the original PM intervals T_{ij}^{*} from the machine-level PM scheduling for each leased machine.

Step 2 (*Time point assignment*): Assign PM intervals in sequential PM scheduling T_{ij}^{*} of each unit to PM time points in LPO programing t_{ij} in the system level

$$t_{ij} = T_{ij}^{*} \quad (j = 1, 2, \ldots, J) \tag{13}$$

Step 3 (*Maintenance opportunity choice*): For a leased manufacturing line, PM of one machine creates opportunities for all the other units. From the first cycle $u = 1$ in LPO optimizations, choose the PM execution point t_u in LPO programing by

$$t_u = \min(t_{ij}), \; 0 < j \le J \tag{14}$$

Step 4 (*Real-time saving calculation*): At this LPO decision-making moment t_u for the whole system, calculate leasing profit savings of all the other leased machines by comparing leasing profit additions and leasing profit reductions

$$\begin{aligned}\mathrm{LPS}_{ju} &= \mathrm{LPA}_{ju} - \mathrm{LPR}_{ju} \\ &= T_{ij}^{\mathrm{P}} \cdot K_j + C_{ij}^{\mathrm{D}} + \left[\int_0^{T_{ij}^{*}} \lambda_{ij}(t)dt - \int_0^{T_{ij}^{*}-(t_{ij}-t_u)} \lambda_{ij}(t)dt\right] \\ &\quad \times C_{ij}^{\mathrm{R}} - \frac{t_{ij} - t_u}{T_{ij}^{*} - (t_{ij} - t_u)} C_{ij}^{\mathrm{P}} - \delta_j \frac{t_{ij} - t_u}{T_L} \left(V_j^{\mathrm{S}} - V_j^{\mathrm{E}}\right)\end{aligned} \tag{15}$$

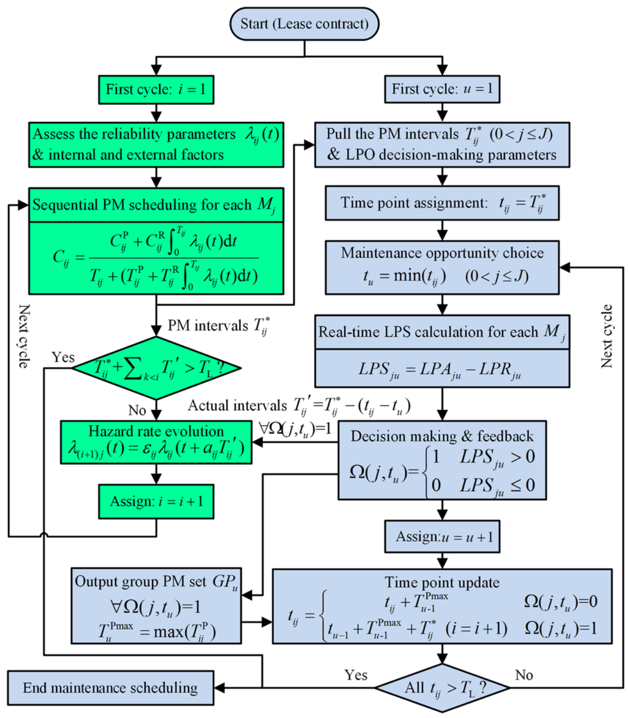

Fig. 2 Flowchart of opportunistic maintenance based on LPO

Step 5 (*Decision-making and feedback*): Output LPO decisions of each leased machine in the current cycle. If $\text{LPS}_{ju} = \text{LPA}_{ju} - \text{LPR}_{ju} > 0$, PM action of M_j will be performed in advance at t_u. Besides, feedback the system-level PM intervals of LPO decisions ($\Omega(j, t_u) = 1$) to the next machine-level PM scheduling

$$T'_{ij} = T^*_{ij} - (t_{ij} - t_u), \quad \forall \Omega(j, t_u) = 1 \tag{16}$$

Step 6 (*Group PM arrangement*): $\text{LPS}_{ju} > 0$ means early PM will be taken. Otherwise, in situ PM (the machine M_j is not performed PM in advance) will be the choice. Arrange the leased machines all $\Omega(j, t_u) = 1$ in the current group PM set GP_u. The lessor can perform PM actions on these machines at time t_u together. Maintenance engineers are sent to handle these PM actions simultaneously to reduce the system downtime. The duration of GP_u is the maximum duration for PM actions combined at t_u

$$T_u^{\text{Pmax}} = \max\left(T_{ij}^{\text{P}}\right), \quad \forall \Omega(j, t_u) = 1 \tag{17}$$

Step 7 (*Time point update*): For the next cycle for LPO programing, assign $u = u + 1$. Then update the new PM time points t_{ij} for M_j $(j = 1, 2, ..., J)$ based on the sequential PM scheduling for each leased machine and the last LPO feedback

$$t_{ij} = \begin{cases} t_{ij} + T_{u-1}^{\text{Pmax}} & \Omega(j, t_u) = 0 \\ t_{u-1} + T_{u-1}^{\text{Pmax}} + T^*_{ij}(i = i + 1) & \Omega(j, t_u) = 1 \end{cases} \tag{18}$$

It should be noticed that if an unscheduled failure happens on one machine M_j, a minimal repair will be performed to bring back this failed machine to its operational state. Since the machines are connected in series, the whole system will experience a downtime (time duration of this minimal repair). Thus, all the new PM time points t_{ij} for M_j will be added the time duration C_{ij}^{R} if M_j has an unscheduled failure.

Step 8 (*Lease period check*): Identify whether these new PM time points in LPO optimizations t_{ij} are out of lease period range T_L. If the answer is YES, end LPO optimizations. Otherwise, turn back to step 3 to find the next maintenance opportunity and continue LPO programing for the next cycle. This cyclic lease-oriented opportunistic maintenance is shown in Fig. 2.

4 Illustrative Example and Discussion

In this section, the lease-oriented opportunistic maintenance methodology is illustrated through some numerical examples. When the lessee (a small automotive company) prefers leasing instead of buying equipment to avoid a large amount of investment, the product-service paradigm is the best choice to expand capacity and raise productivity. In this situation, the lessor can

Table 1 Maintenance parameters of various leased machines

j	m_j	η_j	a_{ij}	ε_{ij}	T_{ij}^{P} (h)	T_{ij}^{R} (h)	C_{ij}^{P} ($)	C_{ij}^{R} ($)
1	3.1	7000	0.025	1.035	20	66	6500	18,000
2	1.8	6400	0.016	1.042	25	74	8000	30,000
3	2.1	8200	0.023	1.054	10	38	3400	8800
4	1.9	9500	0.038	1.032	12	68	9600	28,000
5	2.5	7900	0.018	1.044	14	48	6000	17,000
6	3.3	9900	0.015	1.039	15	30	7000	20,000
7	1.7	8500	0.036	1.052	10	22	8800	26,000
8	2.3	7500	0.048	1.041	8	18	4000	6800

Table 2 Lease parameters of individual leased machines

j	V_j^{S} ($) (kW)	V_j^{E} ($)	K_j ($/h)	δ_j	C_{ij}^{D} ($)
1	700,000	660,000	12	0.11	1200
2	960,000	860,000	16	0.15	1440
3	400,000	350,000	8	0.12	800
4	860,000	700,000	18	0.22	1600
5	520,000	400,000	14	0.13	1000
6	600,000	550,000	10	0.14	1350
7	750,000	600,000	20	0.28	1500
8	330,000	250,000	16	0.16	900

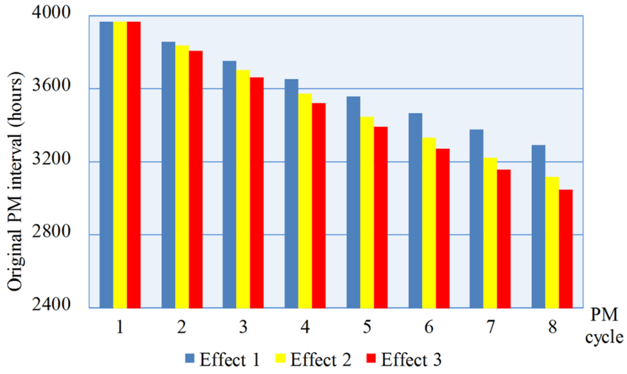

Fig. 3 PM intervals with different lessor's maintenance effects

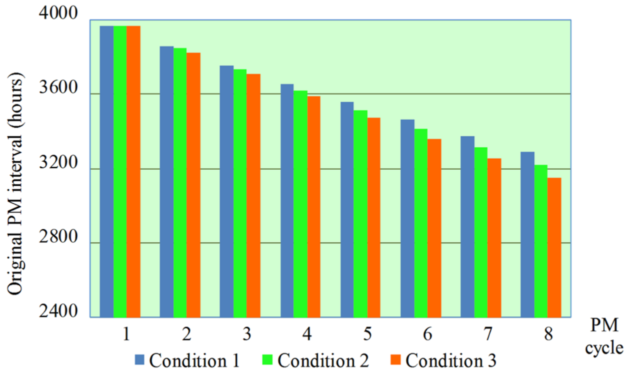

Fig. 4 PM intervals with different lessee's environmental conditions

provide a leased system (the product) bundled with maintenance (the service) specified in a lease contract.

The reliability information of a leased manufacturing system is collected with the cooperative enterprise to validate the lease-oriented maintenance methodology. Consider an eight-unit leased automotive manufacturing line as the illustrative example. The system consists of different leased machines, such as marking machine, CNC center, lathe machine, drilling machine, milling machine, grinding machine, balance machine, and washing machine. This simulation study can test every aspect of the proposed methodology in detail. Suppose that the lifetime distribution of each leased machine follows a Weibull distribution:

$$\lambda_j(t) = \left(m_j/\eta_j\right)\left(t/\eta_j\right)^{m_j-1} \tag{19}$$

The Weibull distribution is widely used to fit repairable machines in mechanical engineering. Under the product-service paradigm, maintenance is no longer a responsibility for the lessee (in-house maintenance), but for the lessor (outsourcing maintenance). For applying the lease-oriented opportunistic maintenance, the maintenance parameters (hazard rate, maintenance duration, and maintenance cost) of various leased machines are estimated by reliability engineers of the original equipment manufacturer and provided in Table 1.

To demonstrate that the proposed policy can effectively achieve leasing profit savings for the lessor, some in-depth investigations on sequential PM scheduling and real-time saving calculation during the lease period $T_L = 24,000$ h (1000 days, three shifts during the 24-h period) have been made in this section. Table 2 provides the lease parameters (machine value, lease rent, depreciation rate, and dispatching cost) of individual machines according to the lease contract.

4.1 Sensitivity Study on Internal and External Factors. First, we evaluate the outputs of sequential PM scheduling for each leased machine, where both internal factors (lessor's maintenance effect) and external factors (lessee's environmental condition) are considered to characterize imperfect PM action. M1 is taken as an example for the sensitivity study on the internal and external factors. These outputs from the machine-level PM scheduling would be pulled to support LPO programing in the system level.

Table 3 LPO programing at first system-optimization cycle

j	t_{ij}	t_1	T^*_{ij}	T'_{ij}	LPA_{j1}	LPR_{j1}	LPS_{j1}	$\Omega(j, t_1)$	T_1^{Pmax}
1	3969		3969	3470	2496	1026	1470	1	
2	3470	3470	3470	3470	—	—	—	1	25
3	4987		4987	3470	2531	1886	665	1	
4	5729		5729	3470	8396	9563	−1167	0	
5	4431		4431	3470	3028	2287	741	1	
6	5594		5594	3470	3912	4904	−992	0	
7	5540		5540	3470	8589	8872	−283	0	
8	5315		5315	3470	2953	3111	−158	0	

Table 4 Saving calculations at the first system-optimization cycle

	LPA ($)				LPR ($)			
j	$\text{LPA}^{\text{R}}_{j1}$	$\text{LPA}^{\text{D}}_{j1}$	$\text{LPA}^{\text{M}}_{j1}$	LPA_{j1}	$\text{LPR}^{\text{P}}_{j1}$	$\text{LPR}^{\text{D}}_{j1}$	LPR_{j1}	LPS_{j1} ($)
1	240	1200	1056	2496	935	91	1026	1470
2	—	—	—	—	—	—	—	—
3	80	800	1651	2531	1487	379	1886	665
4	216	1600	6580	8396	6250	3313	9563	−1167
5	196	1000	1832	3028	1662	625	2287	741
6	150	1350	2412	3912	4285	619	4904	−992
7	200	1500	6889	8589	5250	3622	8872	−283
8	128	900	1925	2953	2127	984	3111	−158

Table 5 Saving results of sequential system-optimization cycles

LPS_{ju} (\$) j	t_1 3470	t_2 5340	t_3 7380	t_4 10,476	t_5 13,581	t_6 15,399	t_7 17,191	t_8 20,035	t_9 22,798
1	1470	−3243	PM	1304	1397	−2558	PM	1295	1288
2	PM	878	1873	2078	PM	1744	1871	PM	PM
3	665	−2635	953	551	680	−1913	1001	660	—
4	−1167	1884	−10,985	1901	−16,400	1918	−12,410	1915	—
5	741	−4894	1169	444	627	−4037	1197	483	489
6	−992	1523	−8591	1508	−1782	1481	−10,312	1393	—
7	−283	1789	−8259	1805	−297	1819	−8785	1874	—
8	−158	PM	−3993	PM	−250	PM	−4352	1036	—

On the one side, three cases with different maintenance effects for M1 are compared to investigate how maintenance effects affect the original PM intervals. Effect 1: $a_{ij} = 0.025$, the age reduction factor is constant and small, as listed in Table 1; effect 2: $a_{ij} = i/(25i+5)$, which means decreasing maintenance ability trend; and effect 3: $a_{ij} = 0.045$, which implies the lessor with lowest maintenance ability. Figure 3 provides the original PM intervals T^*_{ij} for M1 with above three maintenance effects.

On the other side, three cases with different environmental conditions are also compared to analyze how environmental conditions influence the PM intervals. Condition 1: $\varepsilon_{ij} = 1.035$, the environmental factor is small, as listed in Table 1; condition 2: $\varepsilon_{ij} = (23i+1)/(22i+1)$, which means worsening environmental condition trend; and condition 3: $\varepsilon_{ij} = 1.055$, which implies that M1 working with worst environmental condition. Correspondingly, the original PM intervals T^*_{ij} for M1 with different environmental conditions are shown in Fig. 4.

The outputs from sequential PM scheduling in Figs. 3 and 4 reveal the following conclusions:

(1) Original PM intervals for individual leased machines decrease as PM cycle i increases. This reflects the fact that for a machine under degradation, its hazard rate trend becomes more and more steep. Therefore, more frequent maintenance will be required with the leased system ages.
(2) For the internal factor, it can been found that the original PM intervals for M1 tend to decrease more rapidly as the age reduction factor a_{ij} increases, since a larger a_{ij} means that imperfect PM recovers the machine's failure rate to a higher $\lambda_{ij}\left(a_{ij}T'_{ij}\right)$. Thus, the lessor should improve the maintenance ability to extend PM intervals.
(3) For the external factor, it is clear that the original PM intervals also decrease more rapidly under a larger environmental factor ε_{ij}. This proves that the lessee with a worse environmental condition needs more PM actions. It is necessary for the lessor to evaluate the working conditions and assess corresponding lease rents.

4.2 Analysis of Leasing Profit Optimization Decision-Making Based on Saving Calculation. This study focuses on the effectiveness of the proposed policy for multi-unit leased systems under the product-service paradigm. By pulling original PM intervals, LPO policy dynamically optimizes real-time PM actions for the whole automotive line at every maintenance opportunity. When one machine is to be stopped for PM (as an LPO decision-making moment t_u), the system-level programing analyzes the leasing profit saving LPS_{ju} to choose the best decision $\Omega(j, t_u)$ (early PM or in situ PM) for each machine. Table 3 illustrates the decision-making at first PM cycle in LPO optimizations ($u = 1$).

According to the outputs from sequential PM scheduling, M2 is scheduled to be performed PM action first. Define its PM time point $t_{ij} = 3470$ as the LPO decision-making moment t_1 for the whole system. In this group maintenance opportunity, PM actions of M1, M3, and M5 are advanced to the current group PM set GP_1 at $t_1 = 3470$ with their $LPS_{j1} > 0$. Detailed leasing profit additions and leasing profit reductions for each leased machine are listed in Table 4.

It can be seen in Table 4 that three profit saving sources and two profit reductions are investigated. For example, M5's machine rent saving $LPA^R_{51} = 196$ and personnel dispatch saving $LPA^D_{51} = 1000$ are achieved, since its PM advancement avoids extra PM breakdown and personnel dispatch. And the shorter PM interval leads to unexpected failure saving $LPA^M_{51} = 1832$. However, this PM advancement of M5 also causes the extra PM spending $LPR^P_{51} = 1662$ and the machine depreciation spending $LPR^D_{51} = 625$. In sum, $LPS_{51} = 741$ means that PM advancement of M5 at first system-optimization cycle can lead to more leasing profit savings. Based on Tables 3 and 4, LPO decision-makings for all the leased machines at first system-optimization cycles are obtained, and the same LPO programing has been performed at each PM execution points t_u ($u = 1, 2, ..., 8, 9$) for the whole leased manufacturing line.

4.3 Output of Cyclic Group Preventive Maintenance Sets for Leased System. During the lease period T_L, LPO policy is designed to service the multi-unit leased system through a systematic perspective by utilizing every maintenance opportunity. The lessor can apply LPO programing to calculate real-time leasing profit savings of each leased machine cycle by cycle. LPO decisions T'_{ij} will be fed back to machine-level PM scheduling for next PM intervals. Like the examples at first system-optimization cycle, the proposed programing dynamically compares leasing profit savings to obtain the real-time optimizations. The analysis of sequential system-optimization cycles is shown in Table 5.

At each maintenance opportunity (PM execution point) t_u, LPS_{ju} values of all the machines are provided to make their LPO optimizations $\Omega(j, t_u)$. Machines with positive LPS_{ju} values will be performed early PM (M_j is performed PM in advance at t_u). Besides, the machine with "PM" at t_u means that it is scheduled to have PM first at this cycle and arises maintenance opportunities for others. For example, at first, fifth, eighth, and ninth system-optimization cycles, PM actions of M2 cause group maintenance opportunities. Furthermore, it can be seen that only M1, M2, and M5 have saving calculations at the last ninth cycle. Because those PM time points t_{ij} of M3, M4, M6, M7, and M8 have exceeded

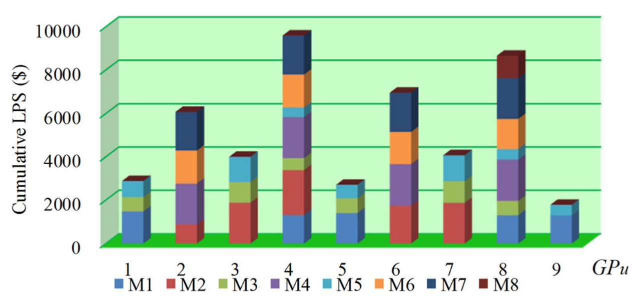

Fig. 5 Cumulative leasing profit savings of cyclic group PM sets

Table 6 Maintenance outputs of cyclic group PM sets for leased system

$\Omega(j, t_u)$ $j\backslash t_u$	GP_1 3470	GP_2 5340	GP_3 7380	GP_4 10,476	GP_5 13,581	GP_6 15,399	GP_7 17,191	GP_8 20,035	GP_9 22,798
1	1	0	PM	1	1	0	PM	1	1
2	PM	1	1	1	PM	1	1	PM	PM
3	1	0	1	1	1	0	1	1	—
4	0	1	0	1	0	1	0	1	—
5	1	0	1	1	1	0	1	1	1
6	0	1	0	1	0	1	0	1	—
7	0	1	0	1	0	1	0	1	—
8	0	PM	0	PM	0	PM	0	1	—

Table 7 AGM results of sequential group maintenance cycles

LPS_{ju} (\$) j	t_1 3470	t_2 6862	t_3 10,155	t_4 13,352	t_5 16,457	t_6 19,472	t_7 22,400
1	1470	1468	1466	1434	1461	1457	1452
2	PM	PM	PM	PM	PM	PM	PM
3	665	697	731	756	783	808	832
4	−1167	−1003	−851	−712	−582	−465	—
5	741	749	756	762	769	774	778
6	−992	−1063	−1133	−1205	−1277	−1353	—
7	−283	18	295	550	786	1000	1196
8	−158	−44	58	150	233	306	373

the lease period range $T_L = 24{,}000$ h, thus their LPO optimizations are ended. In sum, based on real-time saving results, the lessor can arrange the leased machines with PM and $\Omega(j, t_u) = 1$ in the corresponding group PM set GP_u ($u = 1, 2, ..., 8, 9$). Table 6 presents the maintenance outputs of cyclic group PM sets for the whole leased system.

4.4 Effectiveness of Lease-Oriented Opportunistic Maintenance. To demonstrate the effectiveness of this lease-oriented opportunistic maintenance methodology for multi-unit leased systems, the cumulative leasing profit savings of cyclic group PM sets are investigated and the mechanism of LPO policy for maximizing leasing profit is validated. In addition, we make a comparison of the proposed policy and two classical maintenance policies. It can clearly show the significant increase of total leasing profit under the product-service paradigm. According to the maintenance outputs of cyclic group PM sets, cumulative leasing profit savings of sequential system-optimization cycles are shown in Fig. 5.

In Fig. 5, we can see that if one machine is performed early PM, its leasing profit saving contributes to the cumulative LPS in this system-optimization cycles. For example, leasing profit savings by advancing the PM actions of M1, M3, and M5 constitute the cumulative LPS at first system-optimization cycle. During the lease period of the system, cumulative leasing profit savings of cyclic group PM sets will constitute the total leasing profit saving (TLPS). It is noteworthy that a lessor needs to service different lessees (client companies) of diverse leased manufacturing lines. Applying LPO policy on different multi-unit leased systems with various maintenance parameters and lease parameters would lead to various cumulative leasing profit savings. It is gratifying that the mechanism of LPO programing for calculating the leasing profit saving of each leased machine at every maintenance opportunity to make cyclic optimizations (early PM) could ensure the leasing profit rise for the whole system.

Besides, to validate that the proposed policy can achieved cost-effective maintenance schedules for multi-unit leased system during the lease period, two classical maintenance policies normally used in real industry are presented: (1) Individual preventive-maintenance (IPM) policy: PM actions are individually performed on leased machines according to their original PM intervals from the machine-level PM scheduling. IPM is applied based on machines' individual deteriorations without considering system structure interactivities, which is defined as the baseline of total leasing profit saving (TLPS), TLPS = \$0. (2) Advanced group maintenance (AGM) policy: Anytime one machine is scheduled to have a PM action, all the PM actions of the others are advanced to be performed together. AGM utilized advanced maintenance opportunities without analyzing leasing profit savings. AGM results of sequential group maintenance cycles are shown in Table 7.

Figure 6 shows the TLPS-value comparison of the above three maintenance policies. It can be seen that the total leasing profit saving (TLPS) of IPM policy is defined as the baseline (TLPS = \$0). By summarizing LPS_{ju} values in Table 7, we can obtain that AGM policy can achieve TLPS = \$13,486 in this case. In comparison, according to cumulative leasing profit savings of cyclic group PM sets in Fig. 5, LPO policy can achieve TLPS = \$46,704 by analyzing leasing profit additions and leasing profit reductions in depth to choose the best decisions. This TLPS-

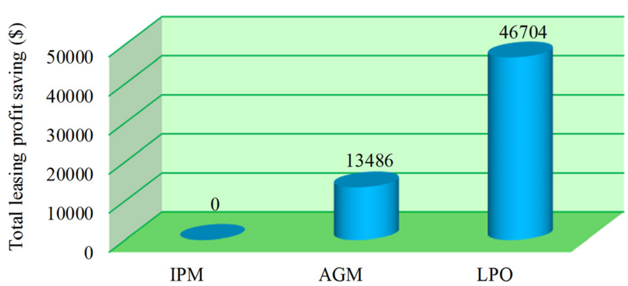

Fig. 6 Total leasing profit saving comparison of three policies

value comparison with classical maintenance policies can demonstrate the effectiveness of the proposed policy for multi-unit leased systems.

Furthermore, traditional opportunistic maintenance decision-making process calculates all the possible machine combinations and the corresponding cost savings at every time point of PM action. Thus, the maintenance scheduling complexity for a J-unit leased system will be $O(2^{(J-1)})$, which means the complexity grows exponentially with the machine number. This novel lease-oriented opportunistic maintenance methodology is designed to make real-time decision for each leased machine by calculating its leasing profit saving at every maintenance opportunity. Therefore, LPO policy can handle a larger manufacturing line, even its machine number J increases, to dynamically output maintenance schedules under the product-service paradigm.

5 Conclusion and Prospects

In this paper, we develop a lease-oriented opportunistic maintenance methodology for the lessor and the lessee to service multi-unit leased systems, other than a single leased machine. This profit-effective method not only considers individual machine degradations but also takes into account the product-service paradigm. For characterizing imperfect PM action, both internal factors (lessor's maintenance effect) and external factors (lessee's environmental condition) are integrated in the machine-level PM scheduling. By pulling original PM intervals, LPO policy is presented to obtain real-time PM optimizations for the whole system by considering system structure interactivities, advanced maintenance opportunities, and leasing profit savings.

Leasing profit savings achieved by applying LPO programing have been demonstrated in a leased automotive manufacturing line consisting of various machines. Results indicate that proposed policy can help the lessor to effectively achieve the larger total leasing profit saving by integrating lease elements of the product-service paradigm and opportunistic maintenance for a leased system. The mechanism of LPO programing can not only reduce the complexity of system scheduling but also ensure the maximization of leasing profit. It can be concluded that this lease-oriented opportunistic maintenance methodology is a viable and effective policy to help original equipment manufacturers to cope with global industrial competitions.

Further work is required for improving the industrial implementation of this newly proposed LPO policy worldwide. Although systematic lease-oriented maintenance schedules can help the original equipment manufacturer prepare maintenance activities in advance, how to introduce the limitation of maintenance resources will be investigated in future studies, especially for those leading manufacturers with a large number of international client companies.

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Nomenclature

a_{ij} = age reduction factor, $a_{ij} \in (0,1)$
C_{ij} = cost rate of the ith PM cycle
C_{ij}^{D} = cost of dispatching maintenance personnel for M_j at the ith PM cycle
C_{ij}^{P} = cost of a PM action for M_j at the ith PM cycle
C_{ij}^{R} = cost of a minimal repair for M_j at the ith PM cycle
GP_u = group PM set from LPO optimizations at t_u
i = index of machine-level PM cycles, $i \in \{1, 2, ..., I\}$
j = index of the leased machines, $j \in \{1, 2, ..., J\}$
K_j = rent of leased machine M_j
LPA_{ju} = leasing profit addition of PM advancement
LPR_{ju} = leasing profit reduction of PM advancement
LPS_{ju} = leasing profit saving for M_j at t_u, $\mathrm{LPS}_{ju} = \mathrm{LPA}_{ju} - \mathrm{LPR}_{ju}$
t_u = PM execution point in system-level LPO optimization
t_{ij} = PM time point from machine-level cost rate model
T_L = the lease period of the system
T_{ij}^{P} = time duration of a PM action for M_j at the ith PM cycle
T_{ij}^{R} = time duration of a minimal repair for M_j at the ith PM cycle
T_u^{Pmax} = maximum duration for PM actions combined at t_u
T_{ij}^{*} = PM interval schedule from machine-level cost rate model
T_{ij}' = PM interval feedback from system-level LPO optimization
u = index of system-level LPO cycles, $u \in \{1, 2, ..., U\}$
V_j^{E} = residual value of M_j at lease ending
V_j^{S} = original value of M_j at lease starting
δ_j = rate of machine depreciation
ε_{ij} = environmental factor
$\lambda_{ij}(t)$ = hazard rate function prior to the ith PM
$\Omega(j, t_u)$ = system-level maintenance decision for M_j at t_u

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