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A Dynamic IoT-Based Maintenance Model For Agricultural High-Tech Equipment

Ipek Kivanç, Claudia Fecarotti, Néomie Raassens, Geert-Jan van Houtum

Eindhoven University of Technology, Eindhoven, the Netherlands

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The advancement of the Internet-of-Things (IoT) and sensor technology has revolutionized the approach to maintenance across various industries, including the agricultural sector. The monitoring of the current conditions of physical systems and its constituent components, and the prediction of degradation paths and failures, allow to perform the appropriate maintenance intervention in a timely manner. Conventional maintenance strategies, often based on corrective or purely time-based approaches, frequently lead to unexpected breakdowns, waste of remaining useful life and inefficient utilization of maintenance engineer potential, thus resulting in excessive costs, downtime, and the unavailability of maintenance engineers. This challenge is particularly pronounced in industries like the agricultural sector, where service locations are dispersed across different geographical regions and systems consist of multiple heterogeneous components, thereby amplifying the complexity of maintenance tasks.

In this study, we consider a complex autonomous machine used in the agricultural sector and propose a dynamic maintenance policy that leverages the potential of IoT technologies for continuous monitoring of components conditions, thus moving beyond traditional approaches. We consider maintenance visits which occur during business hours, being this scheduled or unscheduled, as opportunities to replace additional components as needed. This approach not only enables setup costs to be shared across multiple components, but also the alignment and adaptation of maintenance activities with the real-time needs of the system. Scheduled preventive replacements are triggered once a given degradation level close to failure is reached. Consequently, our adaptive strategy ensures targeted and just in time replacements, thus significantly decreasing maintenance costs and system downtime. Additionally, we distinguish between maintenance visits occurring inside and outside business hours and restrict scheduled maintenance to standard working hours. By doing this, we emphasize the availability of maintenance engineers and the importance of employee satisfaction and work efficiency, thus prioritizing also human factors.

The system under consideration consists of multiple heterogeneous components connected in series, such that the failure of any component causes the system to stop. Some components are continuously monitored and subject to Condition-based maintenance (CBM), while others are subject to Failure-based maintenance (FBM) and are simply replaced upon failure. The condition of CBM components, represented by $X(t)$, is constantly monitored over time t, $[0, t)$. If $X(t)$ reaches a predetermined failure threshold H, immediate maintenance is required to restore the component's functionality. Any failure of CBM or FBM components leads to unscheduled downtimes (USDs). The system's lifespan T is segmented into discrete time intervals of one week. A week starts at time $t-1$ and ends at time t, with $0 \leq t \leq T$.

The primary maintenance policy is defined as semi-urgent preventive maintenance, conducted during specifically allocated semi-urgent downs. At the beginning of each week, unless maintenance has already been scheduled, a decision is made for each functioning component to either 'do nothing' or perform a 'semi-urgent replacement.' If conditions meet the semi-urgent preventive threshold, a 'semi-urgent visit' is arranged within the next few days. If a 'semi-urgent' replacement occurs at time t, the component is promptly restored to as good as new conditions within the same week. If a component fails before its scheduled maintenance, it undergoes immediate unscheduled corrective replacement. Unscheduled downtimes which occur within business hours due to corrective replacement of components within the system are taken as an opportunity to preventively replace other CBM components if an opportunistic threshold is exceeded. Similarly, opportunistic maintenance can be triggered by exogenous failures (failures of other machines). Outside business hours, only the failed component is replaced. We optimize the semi-urgent and opportunistic thresholds per component which minimize system costs and downtime.

The cost implications of these maintenance actions are as follows: an unscheduled visit within business hours incurs costs $c^{usd} + \sum_{i \in K_t} c_i^{rep}$, while a semi-urgent visit costs $c^{ssd} + \sum_{i \in K_t} c_i^{rep}$, where c^{usd} and c^{ssd} are the setup costs for an unscheduled and a semi-urgent visit, respectively, c_i^{rep} is the replacement cost of component i, and K_t is the set of components to be replaced at time t. If a corrective replacement is needed outside business hours, then the incurred cost is simply $c^{usd} + c_i^{rep}$. Unscheduled visits result in the longest downtimes due to the immediate nature of the response, therefore we assume that $c^{ssd} < c^{usd}$. Table 1 summarizes the maintenance actions and related triggers and decisions, differentiating between events occurring inside or outside business hours.

Table 1. Maintenance action types.

Actions	**Moments**	**Decision Moment**	**Business Hours**	**Triggers for Maintenance**
Semi-urgent preventive replacement	Semi-urgent Downs	Every week	Inside	Semi-urgent preventive threshold
Corrective replacement	Unscheduled Downs	Depends on failure	Inside	Failure
			Outside	Failure
Opportunistic replacement	Unscheduled Downs	Depends on other components' failure or exogenous failures	Inside	Opportunistic threshold

The literature on dynamic maintenance scheduling has significantly advanced with contributions from several researchers. Notable works include Van Horenbeek et al. (2013), who introduced algorithms for dynamic maintenance scheduling, and Wu et al. (2020), who integrated economic dependence into maintenance strategies. Wildeman, Dekker, and Smit (1997) advocated for a rolling-horizon approach for adaptive decision-making. Bouvard et al. (2011) emphasized dynamic grouping in CBM, and Vu et al. (2014) proposed a dynamic maintenance grouping strategy using heuristic optimization and genetic algorithms. These studies provide a foundation for understanding and further developing sophisticated maintenance strategies.

By integrating IoT and advanced sensor technology, our proposed dynamic maintenance policy aims to transform maintenance practices in the agricultural sector. By focusing on real-time condition monitoring, opportunistic maintenance, and strategic scheduling, we anticipate a significant reduction in maintenance costs and downtime. The alignment of maintenance activities with actual system needs and consideration of human factors further enhance the strategy's effectiveness and applicability. This research contributes to work on advanced maintenance strategies, offering a practical solution to the unique challenges faced in high-tech industries.

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