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Condition based renewal and maintenance integrated planning

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ABSTRACT

From the perspective of facility life cycle management, timely renewal and appropriate maintenance are important to minimizing life cycle cost and environmental loads. To determine whether a system should be renewed or the components replaced or repaired, we need to assess the condition and residual life of the items. This paper proposes a method for selecting the optimal treatment from among the following options: doing nothing, component replacement, and system renewal. This method takes into consideration the facility conditions and operation status identified through monitoring data, as well as the operation and maintenance history. The method was verified by application to the multi-split-type air-conditioning system of a commercial building.

1. Introduction

People are able to perform daily tasks using various products and facilities, such as household appliances, cars, manufacturing facilities, and infrastructure. We have accumulated such artifacts in our society to the extent that maintenance and renewal of existing artifacts require more financial resources than creating new ones. Exhausting the potential lives of artifacts through appropriate maintenance and renewal planning has become essential to reducing environmental loads and resource consumption [1]. We urgently need to improve the effectiveness and efficiency of maintenance and renewal management.

Renewal is usually differentiated from maintenance. Replacing whole systems is regarded as renewal, whereas replacing a part of a system is regarded as maintenance. However, when we consider a hierarchical system, renewal and maintenance cannot be clearly differentiated [2]. Consider, for example, a building air-conditioning system: the system must be replaced several times during the life of the building, which is usually much longer than the life of the air-conditioning system. In this case, replacement of the air-conditioning system is regarded as part of the building maintenance, whereas it is regarded as renewal from the standpoint of the air-conditioning system. Furthermore, because the building air-conditioning system usually has a hierarchical structure, the above-mentioned relations between maintenance and renewal are iteratively applied to the higher and lower levels of the hierarchical system. Therefore, renewal planning and maintenance planning should not be discussed separately. They should be planned in an integrated way, especially when considering a hierarchical system.

In facility management, we must reconcile two requirements: exhausting the potential life of the facilities and reducing the risk of stoppage due to failures. To address this issue, we need to predict the residual life and failure probability and estimate the effects of failures. The residual life and failure probability depend on the current condition of the facility, which in turn depends on the operation and maintenance history, and on future operation and maintenance conditions.

In this paper, we discuss a method for determining appropriate treatments, whether they are renewal (complete replacement), maintenance (partial replacement), or doing nothing, based on the current and future condition of the facility and the relations among items (systems, facilities, units, parts, etc.) in the facility hierarchical structure.

The remainder of this paper is organized as follows. Section 2 explains the concept of integrated planning of renewal and maintenance considering hierarchical structure of facilities. In Section 3, the detailed planning algorithm is described. The proposed method is applied to the air-conditioning system of a commercial building in Section 4. Section 5 concludes the paper.

2. Concept of integrated planning of renewal and maintenance

We consider situations in which appropriate treatments must be determined, such as when a periodic inspection is executed, when the recommended time for replacement is reached, when a failure occurs, or when a failure symptom is detected. In such situations, we need to select an appropriate treatment from among several options, such as whole replacement, partial repair, or doing nothing. Such a decision can be made based on various factors, such as the maintenance cost, failure probability, and effects of stoppage of the facilities, each of which should be evaluated for each treatment option considered.

In the case of a hierarchical system, we need to consider the inclusive and complemental relations among items in evaluating these factors. For example, consider a compressor with a standard lifetime of eight years that is part of an air-conditioning system

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with a standard lifetime of 15 years. Suppose the compressor fails and is replaced when the accumulated operation time of the system reaches 13 years. If the whole system will be renewed after 15 years of operation—in other words, two years after the replacement of the compressor—most of the life of the compressor goes to waste. On the other hand, if the renewal time of the system is delayed for a certain number of years, the risk of system failure will increase because of the increase in the failure probability of other parts of the system.

When there are complementary relations between items at the same hierarchical level, the effects of failure should be evaluated with the condition of other items taken into consideration. For example, consider the case in which one of two outdoor units of an air-conditioning system fails, but the other unit can cover the required load. The appropriate decision would be to do nothing as long as the other unit is running. When both units are broken, however, at least one of the units should be repaired immediately.

The selection of the proper treatment based on the future results of the decision has been studied using various methods, such as Markovian prediction modeling, dynamic programming, and the real option approach [3–5]. However, most previous studies on this subject have assumed a single failure mode for a non-hierarchical system. There are few studies in which inclusive and complementary relationships among items in hierarchical systems have been taken into account, because of the complexity of the problem.

3. Planning algorithm

3.1. Decision tree

To select the proper treatment option, we need to estimate the effects of deterioration and failures that may occur in the future. This estimation should be carried out based on the current condition of the facility, determined from the operation and maintenance history, because the current condition of a facility depends on the operation mode and operation environment in the past. Furthermore, future occurrences of deterioration and failure depend not only on decisions made in the present but also on decisions made in the future. Therefore, in predicting the results of decision made now, we should take decisions made in the future and the uncertainty of future events, such as failure occurrences or detection of failure symptoms, into consideration.

We represent the future decisions and uncertain events by decision trees. Fig. 1 shows an example of a decision tree for a system consisting of a higher-level item and a lower-level item. The decision trees include the decision nodes, uncertainty nodes, and terminal nodes. We assume that the decisions are made at time t_k, which is the beginning of the kth term, based on the facility condition at t_k. The decision time is determined by the periodic inspection interval of the item. For the lower-level items, the treatment options, which are selected at the decision node, are doing nothing or replacement. For the higher-level items, they are doing nothing or renewal. When the item is renewed, the functional performance is improved.

The uncertainty node representing uncertain events is considered only for the lowest-level item because failures occur in the components, and their effects are transmitted to the higher-level items, causing their malfunction. We assume that the conditions and operating status of the items remain unchanged during the term and that uncertain events occur at the end of the term. Occurrences of uncertain events affect the item's condition and the operating status in the next term, depending on the decision made at the beginning of the next term. The terminal node represents the end of the service life of the facility.

3.2. Estimation of the expected effects based on consideration of the interactions between items

The effect of the current decision is calculated as the expected value in terms of the maintenance and renewal costs, operation cost, and stoppage effects that will be generated in the future. First, all possible uncertainty nodes, which represent the occurrences of all uncertain events, as well as all decision nodes and their options, are enumerated. The decision trees are separately generated for each item, to avoid excessive complexity. As explained later, the interactions among items are considered when the effects of stoppage are estimated.

The failure probabilities of the lowest-level items at each decision time are determined based on their cumulative operation times and the failure distribution function estimated from the operation and maintenance history of all items of the same type. If a failure symptom is detected in the previous term, the failure probability is estimated from the rate of correct predictions, which depends on the performance of the monitoring system.

Expected maintenance and renewal cost can be estimated from the treatments applied in the future. If the item is replaced with a residual life, the part of the item cost corresponding to the residual life goes to waste. This is reflected in the increase in the maintenance or renewal cost. The operation cost is calculated based on the operation time in the subsequent terms, which can be estimated from the operation history. In estimating the operation cost, we consider the decrease of the functional performance due to the deterioration of the item through the cumulative operation time. We also consider the performance increase due to the renewal, which causes decrease in the operation cost.

The effect of stoppage is evaluated in terms of the effect on the user of the facility caused by the stoppage or deterioration of the facility functions. Thus, it is estimated as the effect of the highest-level item, although the failures occur in the lowest-level items.

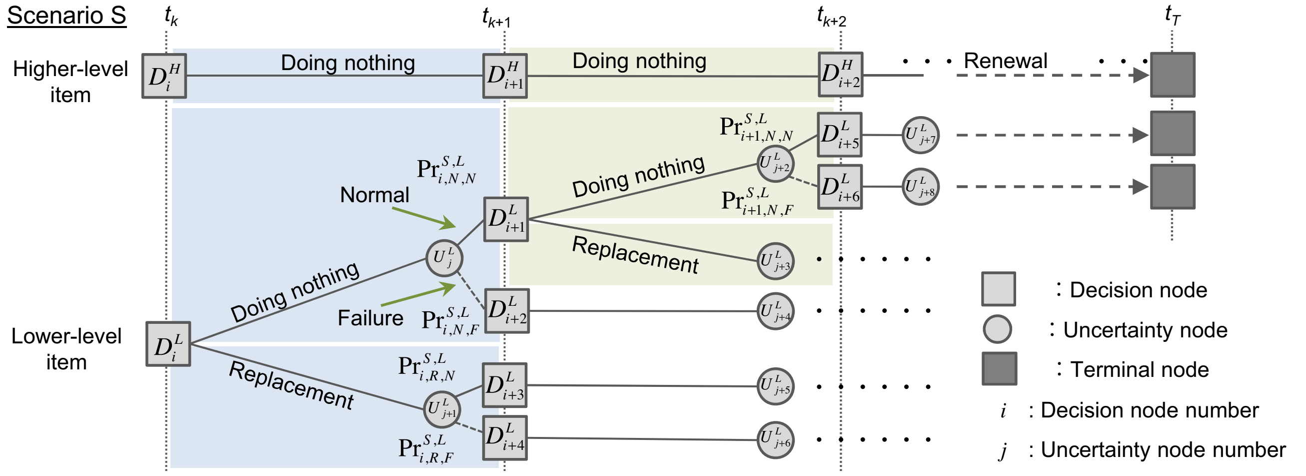

Fig. 1. Example of decision tree.

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