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Reduction rules-based search algorithm for opportunistic replacement strategy of multiple life-limited parts

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Abstract The opportunistic replacement of multiple Life-Limited Parts (LLPs) is a problem widely existing in industry. The replacement strategy of LLPs has a great impact on the total maintenance cost to a lot of equipment. This article focuses on finding a quick and effective algorithm for this problem. To improve the algorithm efficiency, six reduction rules are suggested from the perspectives of solution feasibility, determination of the replacement of LLPs, determination of the maintenance occasion and solution optimality. Based on these six reduction rules, a search algorithm is proposed. This search algorithm can identify one or several optimal solutions. A numerical experiment shows that these six reduction rules are effective, and the time consumed by the algorithm is less than 38 s if the total life of equipment is shorter than 55000 and the number of LLPs is less than 11. A specific case shows that the algorithm can obtain optimal solutions which are much better than the result of the traditional method in 10 s, and it can provide support for determining to-be-replaced LLPs when determining the maintenance workscope of an aircraft engine. Therefore, the algorithm is applicable to engineering applications concerning opportunistic replacement of multiple LLPs in aircraft engines.

1. Introduction

Much equipment must be continuously maintained under certain maintenance policies to ensure the safety and reliability. This especially applies to aircraft engines, nuclear power plants and other complex equipment whose failure may result in disastrous consequences. Every year, equipment operators invest many human resources and materials in equipment maintenance. For example, Air China spends over 300 million USD ($) on aircraft engine maintenance every year. Therefore,

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equipment maintenance has attracted the attention of both the industrial circle and the academic circle.

Many equipment maintenance problems can be abstractly deemed as optimization problems, and one of the important problems is Opportunistic Maintenance (OM).[1–4] Preventive Maintenance (PM) and Corrective Maintenance (CM) are two widely used maintenance policies. PM is regularly performed on equipment to lessen its likelihood of failing. CM is performed after failure occurrence. OM means the combination of PM and CM. Every equipment halt for failure occurrence or other reasons is deemed as an 'opportunity', and even if there is no PM activity planned to be carried out at this time, some PM activities may be shifted to this earlier moment. OM can effectively reduce the number of maintenance occasions, thus reducing the cost for disassembling and assembling equipment.[5] Many results from the study of OM have been achieved in multiple aspects such as modelling, algorithms and engineering applications.[6–11]

As a variant of the OM problem, the opportunistic replacement of multiple Life-Limited Parts (LLPs) is a problem widely existing in industry. LLPs are components with mandatory replacement limits, which are also called 'life limits'. The life limits are often specified in the maintenance manual by equipment manufacturers, and equipment operators must abide by the life limits. When the operation time reaches its life limit, an LLP must be replaced no matter what its true technical status is; if not, the equipment will not be allowed to operate according to relevant regulations. In order to ensure that the LLP life does not exceed its life limit, equipment operators must accurately record all the LLP data. To a piece of equipment with multiple LLPs, if LLPs are replaced in advance, life wastage of LLPs will be caused; if all LLPs are not replaced until their life limits are reached, the number of maintenance occasions will be significantly increased.[12] How to balance the number of maintenance occasions and the wastage of LLPs is the goal of the opportunistic replacement of multiple LLPs.

George et al. were the first to come up with the opportunistic replacement of multiple LLPs.[13,14] They studied the opportunistic replacement of two LLPs at first. When an LLP needs to be replaced, it is checked whether the residual life of the other LLP is lower than a certain threshold. If yes, the other LLP also needs to be replaced; if not, the other LLP will not be replaced. The solution to this threshold is given. The strategy for the opportunistic replacement of two LLPs also applies to the opportunistic replacement of multiple LLPs. The same threshold is used for all LLPs. This replacement strategy cannot guarantee to identify the optimal solution for the opportunistic replacement of multiple LLPs. Epstein and Wilamowsky further proposed the solution to the optimal replacement strategy involving the least calculation for the opportunistic replacement of two LLPs.[15] Dickman et al. studied the opportunistic replacement of multiple LLPs through the nonlinear 0–1 integer programming model and the linear mixed integer programming model,[16] pointed out that the solving difficulty under the finite time horizon is higher than that under the infinite time horizon, and studied the integer programming model of the opportunistic replacement of two LLPs under the finite time horizon.[17] Andréasson expanded the model, studied the opportunistic replacement of multiple LLPs under the finite time horizon, builded the dynamic programming model and the linear integer programming model, studied the convex hull of the feasible solution under the linear integer programming model, and pointed out that the convex hull is generally full-dimensional.[18] Almgren et al. further theoretically proved that the opportunistic replacement of multiple LLPs is an NP-hard problem and proposed an acquisition method of a new class of facets.[19] For cost monotones with time, another constraint is added: the equipment is maintained only when the replacement of at least one LLP is necessary. This constraint can reduce the time consumed to obtain the optimal solution. When maintenance occasions are fixed, the problem is solved through a greedy algorithm.

The study in this article is based on problems encountered in aircraft engine maintenance. LLP cost is an important part of aircraft engine maintenance cost. Both maintenance occasions in the whole life cycle and LLPs replaced in each maintenance affect the total LLP cost in the whole life cycle of aircraft engines. How to find the optimal replacement strategy is a difficulty in aircraft engine maintenance. Obviously, this is a problem about the opportunistic replacement of multiple LLPs. According to the literature review, no quick and effective method has been applied to such engineering applications so far.

This article starts from the problem solution space, analyzes the conditions of the feasible solution and optimal solution, suggests the reduction rules for the problem solution space, and proposes a quick search algorithm for the opportunistic replacement strategy of multiple LLPs. This search algorithm can identify one or several optimal solutions.

The remaining part of this article is organized as follows: first, the opportunistic replacement of multiple LLPs is formally described, the solution space is analyzed, and the solution space reduction rules and the search algorithm process are proposed; then, a numerical experiment of the algorithm is carried out using randomly generated problems; finally, a practical application case is given.

2. Problem description

Consideration is given to the opportunistic replacement problem with the equipment total life T_t and n ($n \geqslant 2$) LLPs. The disassembling and assembling cost involved in the replacement of LLPs is c_b, which is independent of the number of replaced LLPs. Each LLP is denoted as A_i ($i = 1, 2, \ldots, n$), its life limit is denoted as $t_{i,\lim}$, and its cost is denoted as c_i. The equipment operation time is denoted as T, and the operation time of A_i is denoted as t_i. With the increase in T, t_i increases accordingly. When $t_i = t_{i,\lim}$, A_i must be replaced, and the incurred cost is $c_b + c_i$. After the replacement of A_i, t_i returns to zero and begins to accumulate again. To reduce the number of maintenance occasions in the whole life cycle, certain LLPs may be replaced in advance when others are replaced, i.e., there exists an 'opportunity', so that the disassembling and assembling cost is reduced but some lives of LLPs are wasted. The number of maintenance occasions in T_t is denoted as m, and each maintenance occasion is denoted as T_j ($j = 1, 2, \ldots, m$). m, T_j and the LLPs replaced in each maintenance all influence the total LLP cost C in the whole life cycle. The aim of this article is to determine the optimal opportunistic replacement strategy of LLPs, i.e., determine m, T_1, T_2, …, T_m and the LLPs replaced in each maintenance, so that C is the lowest.

The opportunistic replacement of multiple LLPs can be expressed as