European Journal of Operational Research 247 (2015) 310–320

Contents lists available at ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Innovative Applications of O.R.

Defining line replaceable units

J. E. Parada Puig[a,b,*], R. J. I. Basten[c]

[a] Faculty of Engineering Technology, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands
[b] Departamento de Tecnología y Diseño, Facultad de Ingeniería, Universidad de los Andes, Mérida, 5101, Venezuela
[c] School of Industrial Engineering, Eindhoven University of Technology, P.O. Box 513, 5600 MB, Eindhoven, The Netherlands

ARTICLE INFO

Article history:
Received 28 August 2014
Accepted 22 May 2015
Available online 3 June 2015

Keywords:
Maintenance
Replacement
Integer programming
Line replaceable unit definition

ABSTRACT

Defective capital assets may be quickly restored to their operational condition by replacing the item that has failed. The item that is replaced is called the Line Replaceable Unit (LRU), and the so-called LRU definition problem is the problem of deciding on which item to replace upon each type of failure: when a replacement action is required in the field, service engineers can either replace the failed item itself or replace a parent assembly that holds the failed item. One option may be fast but expensive, while the other may take longer but against lower cost. We consider a maintenance organization that services a fleet of assets, so that unavailability due to maintenance downtime may be compensated by acquiring additional standby assets. The objective of the LRU-definition problem is to minimize the total cost of item replacement and the investment in additional assets, given a constraint on the availability of the fleet of assets. We link this problem to the literature. We also present two cases to show how the problem is treated in practice. We next model the problem as a mixed integer linear programming formulation, and we use a numerical experiment to illustrate the model, and the potential cost reductions that using such a model may lead to.

1. Introduction

To maintain capital assets, a typical maintenance organization repairs them by replacing failed items (repair-by-replacement). A physical item that is replaced is called a *line replaceable unit* (LRU; see, e.g., DoD, 1996). The LRU definition problem is a maintenance policy decision that should be considered as a part of strategic or tactical maintenance planning: the exchange of LRUs produces downtime, and therefore the selection of items that should be defined as LRUs is a critical decision. Downtime can be compensated for with spare assets, and this means that the LRU decision should be considered from the outset of a capital asset acquisition program.

Traditionally, non-economic criteria are used to define LRUs. For example: Is it possible to know (test) that the item requires maintenance? Can the failed item be disassembled, and a spare reassembled to the asset without destruction or damage to other parts? Are there special adjustment and calibration needs? These technical criteria help engineers fit the LRU definition to existing practices and available resources of the maintenance organization. While these non-economic criteria are of key importance, inclusion of economic criteria can lead to a more cost effective LRU definition. The aim of this paper is to take a step in that direction.

We first link the problem to the scientific literature. Three relevant literature streams are reviewed: (i) maintenance task analysis, (ii) maintenance optimization, and (iii) level of repair analysis. The setup of this review is based on the Logistics Support Analysis framework (see, e.g., Jones, 2006). We find that the LRU decision is implicit in existing models for maintenance planning, and thus has not received the attention that it requires.

We next show how the problem is treated in practice by gathering insights from two organizations: a system developer, Thales Nederland BV, and a maintenance service provider, NedTrain BV. We show how LRU decisions are made at these organizations, giving insights about when they make the decision, who makes the decision, and what criteria are used. Also here, we find that the LRU definition decision is often made implicitly.

We propose to model the LRU definition problem explicitly. Using insights from the literature and from practice we come up with a *mixed integer linear programming* (MILP) formulation to find the optimal LRU definition. We perform a numerical experiment using typical problem sizes and parameters as they appear at NedTrain. Our theoretical contribution is as follows:

1. We link the problem to multi-component maintenance optimization and frame it in the literature as a decision that should be made after maintenance task analysis, and before level of repair;

* Corresponding author. Tel.: +3153 489 2520; fax: +3153 4893631.
E-mail address: j.e.paradapuig@utwente.nl, jorgep@ula.ve (J.E. Parada Puig).

http://dx.doi.org/10.1016/j.ejor.2015.05.065
0377-2217/

2. We improve the LRU definition decision that is traditionally technical, by explicitly modeling the trade-off between downtime and cost, including replacement lead time, spare assets and the cost of replacement;
3. In multi-component maintenance optimization, the interactions between components are modeled. We explicitly incorporate one type of interaction called structural dependence, in which defining *what* to replace depends on the assembly structure of the capital asset.

From a practical point of view, we contribute by examining the cost savings that could be achieved compared to ad-hoc decisions made by experts. We do this in an extensive numerical experiment. We thus show that it is important to make the LRU definition decision explicitly in practice, and we give a model that can be used to do this.

The remainder of this paper is structured as follows. Section 2 presents the relevant literature and frames the LRU definition problem in the literature. Section 3 then shows two example cases from practice. Section 4 presents the LRU model notation, assumptions, and the mathematical formulation. Appendix B shows that the resulting LRU definition problem is NP-hard. Section 5 presents the numerical experiment. Finally, Section 6 discusses the conclusions and perspectives for future research.

2. Literature background

We use the framework of *logistics support analysis* (LSA) to structure our review of the literature. The LSA framework is shown in Fig. 1. It structures the decisions needed to produce the maintenance program for an asset, including the required (amounts of) resources. This enables us to position the LRU definition problem in the literature.

We first explain the LSA framework in Section 2.1. We then focus on three topics in detail; on maintenance task analysis in Section 2.2, on maintenance optimization, which covers the LRU definition problem, in Section 2.3, and on level of repair analysis in Section 2.4.

2.1. Logistic support analysis

Jones (2006) and Blanchard and Fabrycky (2011) provide good overviews of the LSA framework. It begins with the analysis of possible failure events. *Reliability predictions* are made for the failure of asset components. Next, maintenance significant items (and their failure effects and criticalities) are identified with the help of *fault-tree analysis* (FTA) and *failure modes, effects and criticality analysis* (FMECA). The analysis results are combined in the *reliability centered maintenance analysis* (RCMA) to establish the set of feasible maintenance policies for the capital asset, e.g., time based maintenance or run-to-failure (see, e.g., Moubray, 1997; Tinga, 2010). At this point in the LSA framework, engineers have thus determined which items may fail, how often that is expected to happen, what effect and criticality such failure may have, and what preventive measures (if any) to take.

The next three analyses, *Maintenance task analysis* (MTA), *maintenance optimization* and *level of repair analysis* (LORA), are discussed in detail in the next three sections. MTA helps to identify and quantify the required maintenance resources, such as manpower or support equipment. Maintenance optimization models are mainly used to determine the optimal preventive maintenance intervals and task clustering. LORA supports repair or discard decisions, and determines where in the repair network to carry out these activities.

Sparing analysis, which follows after LORA, helps determine the spare parts package (see, e.g., Basten & van Houtum, 2014; Muckstadt, 2005; Sherbrooke, 2004, for an overview of the literature on spare parts inventory control models). *Life cycle cost* (LCC) is determined next. Finally, *value engineering* (VE) highlights asset functions that add cost but do not add significant value and feedback is given to design.

2.2. Maintenance task analysis

Maintenance task analysis is the detailed, step-by-step analysis of a maintenance task to determine how it should be performed, who will be required to perform it, and what physical resources are needed to complete it. Most maintenance tasks involve manual disassembly and (re)assembly operations. To find the best task procedure for maintenance, engineers use human factors analysis, path/motion planning and assembly/disassembly sequencing.

Human factors analysis helps to assess the effort to access the maintenance point and the risks involved, given a proceduralized task (see, e.g., Dhillon & Liu, 2006). Together with human factors, path and motion planning helps to reveal the best way for a service engineer to reach and route a part into or out of an assembly. Next, optimal sequencing helps to establish the optimal order of assembly and disassembly (see, e.g., Lambert, 2003).

Once the task procedure is established, maintainability analysis is used to estimate (or measure) the required time and resources. The literature on maintainability analysis has mostly concentrated on estimating the (mean) time to repair, using either statistical methods or expert-based assessment (see, e.g., Barabadi, Barabady, & Markeset, 2011; Moreu De Leon, González-Prida Díaz, Barberá Martínez, & Crespo Márquez, 2012). A quantification of both resource demand and task time are very useful for decision making. The data will be used as input of maintenance optimization models. We will need the results from MTA for solving LRU definition problem.

2.3. Multi-component maintenance optimization

Most literature on maintenance optimization focuses on defining the best policy for *when* to replace a particular item. However, for multi-component assets it is important to define not only when, but also *what* to replace. This derives from the fact that in capital assets with many items, interaction between items influences the maintenance action that should be chosen. Nicolai and Dekker (2008) review the literature on multi-component maintenance optimization

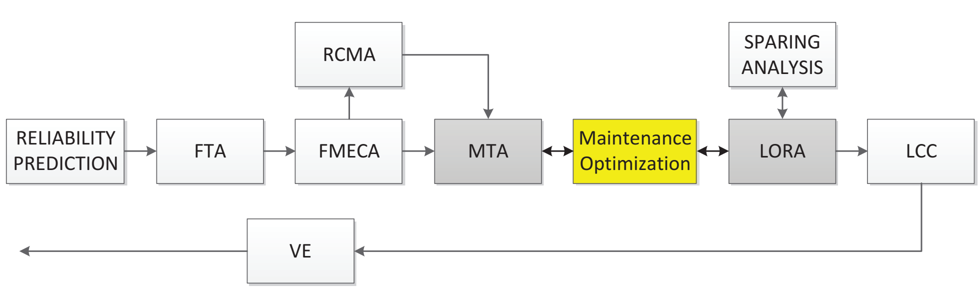

Fig. 1. The logistics support analysis framework (Adapted from Jones, 2006, page 11.23, Figure 11–16).