Multi System Mission Analysis and Cost/Performance Optimization in a Constrained Environment

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SUMMARY & CONCLUSIONS

The traditional Level of Repair Analysis (LORA) concept was developed to provide decision support when choosing where, in a support organization structure, to perform repairs. The analysis determines at what level in a hierarchical support organization it will be most cost effective to repair each component in a technical system, considering the investment in maintenance resources, such as personnel and test equipment. The traditional LORA, however, does not consider the large impact the repair level decision has on the spares investment nor the strong dependency between different items for the system effectiveness. Furthermore, it cannot handle asymmetric organizations. Since both technical systems and their support solutions are becoming more and more complex the requirements for decision support in this field has changed, and traditional LORA has become obsolete.

In this paper a new approach to LORA and Maintenance Concept Optimization is presented. This approach is more relevant and up to date with current requirements and it is also much more powerful than the traditional item-by-item approach for LORA. The new approach offers a simultaneous optimization of maintenance locations, maintenance resources, spare parts and repair/discard decisions. The approach offers a fast and effective methodology for reaching cost-effective logistic support solutions with the objective of achieving high system effectiveness.

1 INTRODUCTION

Before addressing the issue of Level of Repair Analysis (LORA) we need to establish the problem setting in which this analysis exists. First, you must understand this setting contains a *technical system* and a *support system*. The objective of the technical system is to perform some type of operation and the objective of the support system is to maintain the technical system when it needs maintenance. Of course, you want the system to be down for maintenance as seldom as possible and you want a short down time when it is maintained. This means that you want to design a reliable system with a low need for maintenance and have a support system that can quickly restore the system to an operational state. Further, it also means that, given a technical system, it is possible to influence the operational effectiveness by altering the support system. Naturally, this alteration might lead to costs and it will then be important to put this cost in relation to the effectiveness that is gained.

The traditional LORA methodology is used to determine where in a hierarchical support organization a failed component should be repaired or if it should be discarded. This choice depends on the cost for each component to be repaired versus the unit cost of the component. Typically, an intermediate level repair, which is more distributed, will result in a higher cost for resources but a lower need for spares then a centralized repair. Traditional LORA will provide an answer for the cost and repair alternative for each component so that it is possible to choose the one with the lowest cost.

However, there are several major drawbacks with the traditional LORA. The two main issues are a failure to consider the large impact the repair level decision has on the optimal spare parts package and the strong dependency between components for the system effectiveness. Another restriction is difficulty or inability to handle asymmetric organizations.

Due to the increasing complexity of technical systems the utilization of the support, solutions have become more complex. Thus, the need for decision support in this field has increased and, therefore the traditional LORA has become inept for the task.

This paper presents Maintenance Concept Optimization (MCO) as a new approach to achieving the objectives of LORA which gives an optimal, cost effective solution and is more up to date with current requirements. The new approach uses simultaneous optimization of maintenance locations, maintenance resources, spare parts and repair/discard decisions making. It is a fast and effective methodology for reaching cost-effective logistic support solutions with the objective of achieving high system readiness.

2 THE PROBLEM SETTING

The setting analyzed in this paper is that of a complex technical system, for example an aircraft, which is being used for operation, like cargo transport. Typically, there are a lot of different aircraft deployed at several operational sites, see O1 and O2 in *Figure 1* for an example.

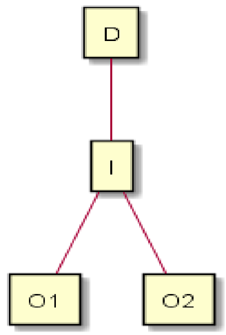

Figure 1 - An example of a support organization.

The goal is to have as many of the aircraft available for cargo transport as possible since this will increase our revenue. However, as all technical systems, the aircraft will need maintenance which will keep it on the ground. The reason for the maintenance on the aircraft is usually that some subcomponent, from here on called *item,* has failed. As an example, assume that the engine has failed. Now, using the support organization shown in *Figure 1*, the following actions happen after the engine has failed. First, it is removed from the aircraft, at O1 or O2 depending on where the aircraft is deployed. The failed engine is then shipped to I and then to D where the engine is repaired. If we do not have a spare engine we get a *backorder* and the aircraft will be on the ground until the repair has been completed and the engine is shipped back to the operating site where it is put back in the aircraft. If the repair time is long it might be beneficial to keep an engine in stock at a location, for example, at I. In this case the aircraft is only grounded for the time it takes to ship the engine to the operational site. This decreased down time, however, comes at a cost; the cost of buying an engine and keeping it in stock. The question is then; is it worth it? Does the increase in system availability justify the cost of keeping the part in stock? This problem of determining what to buy and where to keep it is the classical spare parts optimization problem, see reference [1] and the references therein for more details. In principle, it comes down to balancing the cost versus the operational performance of the technical systems which means that we want to solve the following multi-objective optimization problem (in some decision variable x)

$$\min_{x\in X} \begin{bmatrix} C(x) \\ -E(x) \end{bmatrix}, \qquad (1)$$

where $C(\cdot)$ denotes the cost and $E(\cdot)$ denotes the “effectiveness”, for example the average number of operational aircraft. Note that maximizing the effectiveness is equivalent to minimizing the “negative effectiveness”.

The most common definition of optimality with respect to a multi-objective optimization problem such as (1) is that a feasible solution is optimal if there exists no other feasible solution that is at least as good in both objectives, and strictly better in one objective. Solutions that satisfy this non-dominance criterion are called Pareto optimal, or *efficient*, and these are the points that are of interest. An example of this is shown in *Figure 2* where cost is on the x-axis and effectiveness is on the y-axis. It is clear that increasing the cost can give an increase in the effectiveness and it is also clear that the efficient points are the desired points to choose from.

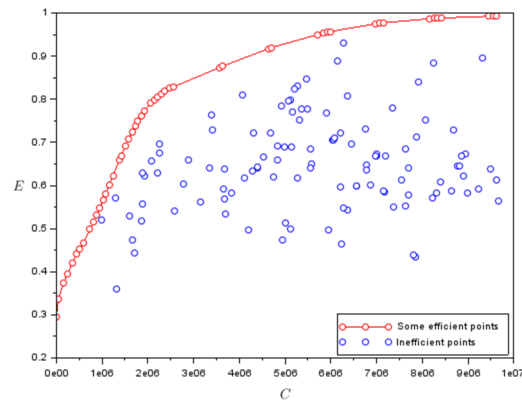

Figure 2 - An illustration of efficient and inefficient points.

An important thing to remember is that the optimal spares assortment depends on the way the technical system is designed, the way it is used and the way the technical system is supported, i.e. the support system design. The formulation (1) is very general where x includes all of these parts, and therefore the problem, as it is stated, is basically not solvable in practice. This obstacle can, however, be overcome if the decision variable x is split into parts.

Let the operation of the system be fairly fixed since it is controlled by some “external demand”. In the aircraft example the operation is given by the cargo that should be shipped and there is no real point of choosing not to ship if it is possible to do so. Thus, the operation of the technical system will, for the remainder of the paper, be treated as given. Also, unless we have the power to influence the design before buying or renting it, the technical system can be given as well. Note that even though the technical system and operation is considered fixed the methodology described in this paper can still be used to compare different technical systems and different types of operation to decide which is preferred. When we state that it is given we simply mean that those decisions are removed from the optimization problem given in (1).

The operational requirements and repair requirements of the technical system are still complicated constrains to fulfill. To clearly design a support system to achieve this, we need to review the following.

1. Determine what maintenance capability for the different locations in the support organization, e.g. whether an item should be repaired or discarded and where this should happen. This could also involve

having different maintenance alternatives for the same maintenance action.

2. Determine where maintenance resources should be located.
3. Determine the number of spare parts and where they should be placed. This choice is dependent on the decision in 1 as we will see later.
4. Determine the transportation times through the designed support structure.

2.1 Traditional LORA example and drawbacks

To illustrate the deficiencies of using the traditional LORA approach we can turn to a well-known example described in reference [2]. In this example an LORA is performed on a computer system with 15 assemblies. Each assembly can be discarded or repaired either at an intermediate level (with 3 stations) or at the supplier level. The task is to evaluate the cost for each of these three alternatives for each assembly. A cost model is used that takes many aspects into account but we will focus on cost for resources and spares.

To be able to repair an assembly a *Test equipment* that costs $25,000 must be installed at the location where the assemblies are repaired. To take this into consideration in the approach of [2] an installation cost of $25,000 / 15 per assembly is assumed. When evaluating the cost for each assembly it will include $1,667 if the part is repaired at the supplier, $5,001 if repaired at the intermediate level and $0 if discarded.

The result from the analysis in [2] is that 6 assemblies should be repaired at the intermediate level, 4 at the supplier and 5 be discarded. This underestimates the cost for the *Test Equipment* since the installation cost at intermediate level (per assembly repaired there) should be 3*$25,000/6 = $12,500 and $25,000/4 = $6,250 at the supplier. This increase in cost to bear for each alternative should of course also affect the LORA decision for each assembly, which can be seen by manually updating the costs.

A better way to do this cost analysis would be to try to minimize the total cost over all assemblies considering the cost of installing the test equipment once a maintenance capability had been established at a location which is what we suggest in this paper.

Another drawback of the method presented in [2] is that it does not properly account for the effect of spares. A simplified method is used and described as covering for "transportation time, the maintenance queue, TAT etc.".

However, by failing to properly integrate the spares decision with the maintenance decision and not taking into account the effect on the system effectiveness the resulting decision will not be the correct one from a cost-effectiveness perspective. The spares decisions for the assemblies are also strongly dependent from a systems perspective which adds further complexity to the problem.

Overall this example shows that from a maintenance resource and spares perspective the item by item approach used in traditional LORA will give results that are not cost effective.

2.2 System vs item-by-item approach

In this example there are two operational sites and one regional depot, see *Figure 3*.

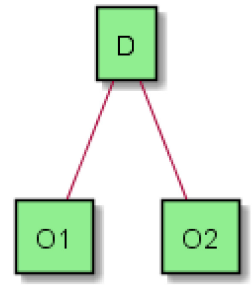

Figure 3 – The support organization for the second example.

The example considers one type of technical system which consists of ten items with data given in *Table 1*. Each technical system will, on average, be used 12 hours a day and there are five technical systems deployed at O1 and two at O2.

Table 1 - The data used in the item-by-item example.

Entity	*Value [failures per 1 000 operating hours]*	*Price [USD]*	*Repair time [hours*
ITEM1	4.170	4 039	1,200
ITEM2	0.487	3 223	1,200
ITEM3	3.688	20 814	1,200
ITEM4	1.323	5 665	1,200
ITEM5	2.720	4 514	1,200
ITEM6	0.472	28 178	1,200
ITEM7	3.148	2 053	1,200
ITEM8	0.236	9 872	1,200
ITEM9	1.293	12 700	1,200
ITEM10	2.464	8 942	1,200

When it comes to repairs, there are four different strategies for each item; either repair locally (at O1 and O2), or repair centrally (at D) or a mixed strategy (at O1 and D or at O2 and D). The item-by-item approach used here sets a fixed risk of shortage for the parts instead of looking at the whole system availability.

Two different methods have been used for calculating the spares assortment. In the first case a model combining spares optimization and Maintenance Concept Optimization has been used. In the second example a maximal risk of shortage per part has been set to 10%. It is clear that using the item by item method we get a less cost effective solution even in this relatively small example.

These two examples clearly demonstrate the drawbacks of using the item by item approach as opposed to a system centered method. For the same investment in spares it would have been possible to have a 95% availability or make a significantly lower investment.

Figure 4 – The results for the item-by-item example compared to total system optimization(MCO).

3 THE NEW APPROACH TO LORA

The examples in the previous section showed some major drawbacks with the traditional LORA approach. The increasing complexity of technical systems and, consequently, their support solutions is creating a need to solve problems for which traditional LORA simply cannot provide cost-effective solutions. As already discussed, the primary reason is the high correlation between the choice of maintenance locations, the need for maintenance resources and the spares assortment.

This section describes a new approach to LORA that aims to fill the gaps in the traditional methodology. We will begin by describing how the decision variable in (1) is split into parts.

3.1 Splitting the decision variable

The variable x in (1) covered essentially "everything" causing the problem to be insolvable in practice mainly because there are too many degrees of freedom in the model. By fixing some elements of the model (the operation and the technical system) and splitting the decision into interconnected parts we will demonstrate that powerful decision helping results can be obtained. In *Section 2* four design decisions were listed and how they will be used as design variables is covered in the following sections.

3.2 The maintenance capability

A defective item will always be handled in *some* way to ensure that the system gets up and running again. Basically, there are two ways to restore functionality for a failed item, either repair it or discard it and buy a new one. The repair decision might involve equipment that is not needed if we simply discard the item. Thus, it becomes a tradeoff between the cost and time of repair versus the cost and time for reorder. As the small example illustrated this tradeoff is hard to do manually and therefore it is a great advantage that this decision can be obtained using the optimization algorithms implemented in the Opus Suite® software.

Included in this definition of maintenance capability is also the afore mentioned possibility to have different maintenance alternatives at the same location. One possibility could be to compare a fast, but expensive, solution to a slow cheap one.

3.3 Spare parts allocation

Solving the spare parts allocation problem heavily relies on the calculation of the efficiency measure, see references [3] and [4]. Since, as the small example demonstrated, the optimal spare parts allocation will depend on the repair/discard decision it is very powerful to be able to include the maintenance capability considerations described in *Section 3.2* when calculating the efficiency measure and solving the optimization problem. The new approach to LORA described in this paper includes this feature and therefore the optimal stock allocation will also come with a (possible) reorder policy.

3.4 Maintenance resources

In order to perform maintenance, it might be necessary to allocate resources of some kind, maintenance personnel or test equipment for example. The allocation of resources could be associated with costs and these costs could be different by location. Thus, in order to find cost efficient solutions the allocation of resources needs to be included in the optimization model. The solution to the optimization problem will answer both where to put *enabling* resources, i.e. resources that enable maintenance actions at the location, and the number of other resources to allocate to the different locations.

3.5 Transportation times

Just as having different maintenance alternatives at the same location it is reasonable to allow different choices when it comes to the transportation alternatives. In this case the comparison could be between shipping by lorry versus air transport. In that case the latter is fast, but expensive, while the former is fairly cheap but the transport takes longer. This decision is currently not in the optimization model in the Opus Suite® software by Systecon®.

The capability of the new approach to LORA is demonstrated using the example in the next section.

4 A LARGE SCALE MCO EXAMPLE

This example considers the engine system in an aircraft that is going to be operated for 30 years. A total of 1730 aircraft are deployed at 9 different locations worldwide. The support organization is shown in *Figure 5* where the sites starting with "O" are the operational sites. The number of deployed aircraft at each site is given in *Table 2.*

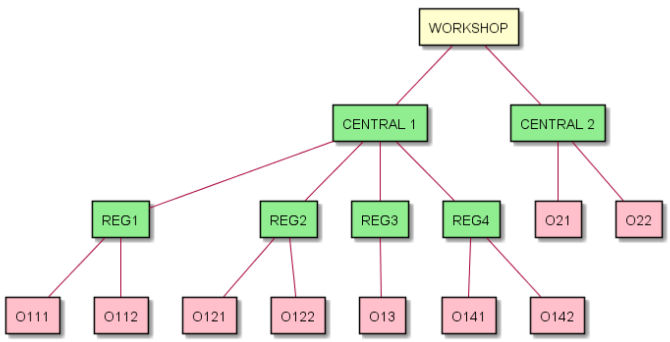

Figure 5 - Support organization for the large-scale example.

Table 2 - The number of deployed aircraft in the large example.

Operating site	*#A/C*
O111	120
O112	240
O121	200
O123	90
O13	300
O141	360
O142	240
O21	60
O22	120

All locations starting with "C" and "REG" have the possibility to store items.

In this case we are focusing on the engine subsystem which consists of 22 items. The maintenance is split into three different groups depending on the item property. The engine belongs to one group and the fuel control to another. All other primary items are put in the third group.

The primary items have many different alternative strategies. They can be either repaired at one of the Central Locations or at the Workshop. At the workshop they can be repaired in two different ways (one fast and expensive and one cheap and slow). This gives a total of seven different policies to evaluate (see *Table 3*).

Similarly, the engine components and the fuel control components can be repaired at Workshop in two different ways. Further, the removal of subcomponents from the engine and the fuel control is performed at the two Central locations. Also in this case there are two different ways of performing the removal. In total there are $7 \cdot 2 \cdot 2 \cdot 2 \cdot 2 = 112$ different maintenance alternatives and 6 different stock locations. Using the item-by-item will be quite cumbersome and since the Opus Suite® software solves the problem on a standard laptop in just over one second we will only present those results, see *Figure 6*.

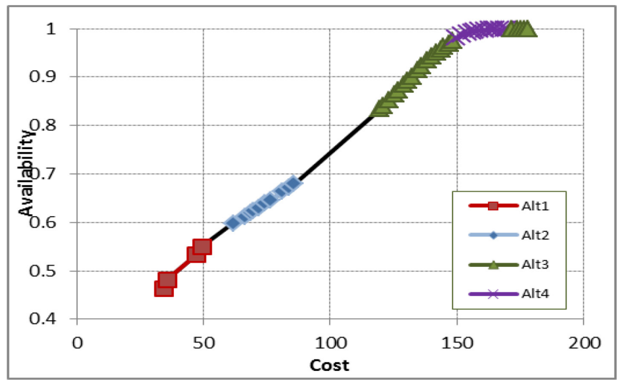

Figure 6 - The results for the big example using the Opus® Suite software by Systecon®.

It turns out that there are only four maintenance alternatives that are optimal and they are listed in *Table 3.* Which one that should be chosen depends on the budget and availability requirements. Note that each point also corresponds to a different stock allocation.

Table 3 – The optimal maintenance alternatives for the large scale example

Alternative	*Primary items*	*Fuel ctrl*	*Engine*
1	Repair WS (Slow)	Repair (Slow)	Repair (Slow)
		Removal(Slow)	Removal(Slow)
2	Repair WS (Slow)	Repair (Slow)	Repair (Fast)
		Removal(Slow)	Removal(Slow)
3	Repair WS (Fast)	Repair (Slow)	Repair (Fast)
		Removal(Slow)	Removal(Slow)
4	Repair WS (Fast)	Repair (Slow)	Repair (Fast)
		Removal(Slow)	Removal(Fast)

It should be noted that the example is still fairly "small" since we are not looking at repair/discard decisions or including preventive maintenance. Further there are only three item groups. Since the number of alternatives grows exponentially in the number of item groups increasing this number will make it much harder, not to say impossible, with an item-by-item approach.

5 CONCLUSIONS

This paper demonstrates a new approach to LORA which takes the simultaneous optimization of stock, resources and maintenance capability into account. It is demonstrated that not treating these decision variables as dependent will render suboptimal support system designs and it is stressed that the interconnection between them should be considered when making decisions regarding the support system. The new approach to LORA is implemented in the Opus® Suite software by Systecon® and used to design the support system for a large realistic aircraft scenario with a lot of different possible maintenance alternatives.

REFERENCES

[1] P. Alfredsson, *On the optimization of support systems* (Doctoral dissertation), Royal Institute of Technology, Stockholm, Sweden, 1997.

[2] B. S. Blanchard, Logistics Engineering and Management, Prentice Hall, Upper Saddle River, New Jersey, 1998

[3] C. C. Sherbrooke, ”METRIC: A multi-echelon technique for recoverable item control”, *Operations Research*, vol. 16, pp. 122--141, 1968.

[4] C. C. Sherbrooke, ”VARI-METRIC: Improved approximations for multi-indenture, multi-echelon availability models”, *Operations Research*, vol. 34, pp. 311--319, 1986.