The Impact of System Redundancies in the Optimization of the Support Solution

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SUMMARY & CONCLUSIONS

It is vital for the mission success of a technical system to have the combination of good reliability and an optimal support system. A very reliable system can still experience a low availability with a poor support system and vice versa. All decisions made in the design of the technical system and the support system design influences the cost effectiveness of the system. By combining optimization and simulation techniques in a model that can take the complex nature of both aspects into consideration, cost effective decisions can be made throughout the life cycle of the system.

1 INTRODUCTION

At the heart of the performance of a technical system lies the inherent capability of the technical system itself. The reliability of the components within the system and their impact on the overall system state is of course imperative to how well the system can fulfill its mission requirements. But, in addition to these factors the impact of a failure or need for maintenance is also crucial in determining mission fulfillment or how well a system will perform a requested task. This means that a state-of-the-art system operating with a high reliability and a high degree of redundancy can still experience a low mission success rate or availability due to a suboptimal support system. To understand these dependencies and to be able to evaluate them is important when creating the optimal technical system. In particular, for the most important stakeholder the end user, who will either be able to operate the system or not.

Typically, methods for evaluation of the performance have been skewed to focus on either the reliability or the supportability analysis and hence not been sufficient for analyzing the correlating factors. There have been historical reasons for this and it is primarily explained by the division of the tasks of reliability engineering and supportability engineering. In addition, the technical difficulties of performing the complex analysis have also been limiting.

In this study the focus lies on evaluating the capability of a technical system to perform its prescribed missions by the combination of the design of the support solution and the design of the primary system itself. This is made possible through combining a complex reliability model using reliability block diagrams (RBDs) with a time varying operational profile and a complex support system. The study has been performed using simulation and optimization techniques implemented in the Opus Suite® software by Systecon®.

The study shows the importance of evaluating both the reliability and the supportability aspects of the technical system and its support system in order to achieve an effective technical solution.

2 THE BIG PICTURE

The scenario covered in this study is that of a generic technical system used to perform a task of some kind. This setting is very general and could apply to many situations. The factors determining how well the system will perform its tasks can be broken down into three distinct parts:

- The technical system design
- The support system design
- The operational concept

2.1 The technical system design

The systems considered are typically complex with a large number of subcomponents. The failure of a system will usually be caused by the failures of some components which will then render the entire system inoperable. Naturally, the design of the technical system has a major impact on the reliability of the system, i.e., choosing subcomponents with higher reliability will; in general, result in a system with a higher reliability. The reliability of the system can also be enhanced by the introduction of redundancies which reduces the criticality of individual component failures. Even if the reliability is very high all systems will, in practice, suffer failures. When this happens it is up to the support organization to get the system back into an operational state.

2.2 The support system design

The support system (or support organization) is the term used for the organization carrying out the support. This organization includes resources, such as technicians and tools, but also a spares strategy, i.e., the number and location of spares etc. The ability to respond to maintenance needs on the system determines how well a system is able to perform. In situations with long resupply times, poorly dimensioned stock levels and lacking resources, each failure on the system will result in a longer than necessary down time for the system.

2.3 The operational concept

The operational concept for a technical system can have different characteristics. For instance, the utilization can be high or low, evenly distributed or it might have peaks of different magnitude. There can also be different modes of operations, different configuration requirements and different environments that the technical system is intended to operate in. All of these aspects will influence the reliability of the system and the load on the support system.

The operational concept will be the driving force in the generation of demands that the support system has to handle.

3 THE AVAILABILITY OF A SYSTEM

The steady state availability for a technical system is given by the classical formula,

$$A = \frac{MTTF}{MTTF+MDT} \quad (1)$$

where MTTF is the mean time to failure and MDT is the mean down time. It is easy to see that there are two ways to increase the availability:

- Increase MTTF, e.g. by the use of redundancies in the system.
- Decrease MDT, e.g. by increasing the maintainability and shorten the repair time or by reducing the logistic delay time by speeding up the supply of spares.

Even though both MTTF and MDT can be used to increase availability there is a fundamental difference in what the impact of an increase or decrease, respectively, has for the operation of the system. To clarify, consider for example a train which has just come out of service. The purpose of the train is to transport passengers according to a time table. If the train has a sufficiently large mean time to failure the train will probably be able to run the entire day. If, however, the train suffers a failure and the mean down time is long it will typically not be able to run the next day. Thus, in some sense, MTTF determines how well a system will be able to complete a started "mission", while MDT determines how well the system will be able to start the "next mission". In the extreme case where the mean time to failure is infinite no mission will be aborted due to failure. On the other hand, if MDT is zero the system will always be ready for the next mission.

4 THE TOTAL COST FOR THE SYSTEM

In order to influence the total cost of ownership of a technical system it is important to be able to as early as possible understand the implications of the design decisions that are made. A method that enables this is Life Cycle Cost analysis or LCC. LCC can be used at any stage in the life cycle of a technical system from concept to termination and will provide valuable input to the design phases of the technical system, the support system and the operations.

LCC is a tool for estimating the total cost of ownership for a system by addressing the main components of the cost, e.g. design, manufacturing, operations, support and termination. LCC is not primarily a budgetary tool but rather a decision support tool that should highlight the differences in cost between different options and help to focus the analysis options on the cost drivers. In early stages the LCC will be based on rough estimates and in later stages on the actual costs derived from the operations.

The LCC for a technical system must be used together with a specified measure of effectiveness for the system or fleet of systems in order to be useful when comparing alternatives. This measure of effectiveness can be very different depending on the type of system, business or environment under which the system operates. The measure can range from production in a wind farm, the number of person-miles of a mass transport system to the availability of a naval ship and beyond.

5 THE COST EFFECTIVENESS OF A SYSTEM

For the end user the system efficiency is represented by the how well the system performs during its operation in relation to the total cost of ownership. In order to make the best decisions throughout the life cycle this can be estimated through a cost effectiveness model that can evaluate the measure of effectiveness and the Life Cycle Cost. By using this model the decisions that will give the effectiveness required at the lowest Life Cycle Cost can be identified

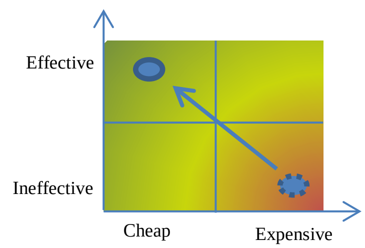

Figure 1. Cost effectiveness is achieved when an effective system has a low total cost of ownership. The aim is to make decisions that produce solutions with a high cost effectiveness. i.e. as close as possible to the top left corner of the figure above.

5.1 Evaluating the cost effectiveness

The complex relationship between the technical system, the support system and the operations makes it a daunting task to make the right decisions and understand their impact in regards to the overall cost effectiveness of the program. Because of this it is important to have a model that can take into consideration these different aspects at a detailed level while still being able to keep it simple enough to interpret the results. In this study the Opus Suite® software by Systecon® has been used for the analysis.

6 ANALYZING THE SCENARIO

6.1 Analyzing the effectiveness

When analyzing logistics scenarios of the type considered in this paper the simulation tool SIMLOX® in the Opus Suite® is ideal for evaluating measures of effectiveness. Once the model, complete with technical system, support system and operational concept has been created Monte Carlo simulation is used to capture the system states, mission success and different events that can occur during the operations, such as failures, preventive maintenance, fleet build up etc. The technical system can be modeled in detail in SIMLOX® through a multi indenture structure and it is also possible to model redundancies in different configurations by using Reliability Block Diagrams (RBD). This powerful capability makes it possible to model a scenario where not all component failures are critical in terms of system functionality for a given mission type. The spares requirement, maintenance concept and resources can be optimized using OPUS10® in the Opus Site®. The optimization is based on the same model as the one used in SIMLOX®.

Once a simulation is completed SIMLOX® will have generated a results cube through replications of the scenario, and by varying the model the effect of changes to the technical system and/or support organization can easily be analyzed. A (small) selection of important results obtained by SIMLOX® is:

- *Mission start fraction*

This shows how many of the requested missions that are able to start. If there are not enough systems available at the launch of the mission then the mission will fail to start.

- *Mission success fraction*

This shows how many of the requested missions that are able to finish. If failures occur during the mission the system might have to abort and then the mission will not succeed.

- *System availability*

This is the amount of time that the technical system is in a state where it either is on mission or is available for missions.

6.2 Analyzing the cost

When analyzing the cost of the system, especially when comparing alternatives, the LCC approach is good. LCC can be studied using the CATLOC® in the Opus Suite. In this study a simple cost model has been implemented that takes the results from the simulation as input and calculates a total LCC.

The LCC consists of three different parts, LCCA, the cost of acquisition, LOC, the cost of operations, and LSC, the cost of support. In the model an initial acquisition cost for systems and parts as well as costs for repair and storage of parts has been included. The cost of operating the system is also included.

$$LCC = LCCA + LOC + LSC \qquad (2)$$

7 CASE STUDIES

This section covers some examples intended to illustrate the impact of the technical system design and the support system design on the performance of a system. We will begin with a small example demonstrating the concept and continue with a larger example that also includes the Life Cycle Cost of the system.

7.1 A simplistic case

The first example is a simple model with a very basic system consisting of just one component type. The system is operating from a single location and this location has both repair and spare parts storage capabilities. The task to perform is a 12 hour mission every day.

To demonstrate the effect of redundancies the model has been run on three different technical systems; one with a single component, one with a 1-out-of-2 passive redundancy and one with a 1-out-of-3 passive redundancy. The nominal number of spares has been varied between 0 and 3.

This case has only been evaluated from an effectiveness perspective.

7.2 The initial mission success

When starting from a pristine condition where all the components are working, the positive effect of the redundancy can easily be seen in *Table 1*. In this case all missions can be started but due to the risk of failures during the mission one redundant component will greatly enhance the probability of being able to finish the mission without critical failures. Adding a second redundant component will further increase the probability of finishing the mission successfully.

Table 1 The mission success rate in a pristine situation.

Redundancy	*Mission Success fraction*	*Mission Start fraction*
None	88.20%	100%
1/2	99.10%	100%
1/3	99.99%	100%

7.3 The steady state success

In this section we study the situation when we have reached a steady state. This occurs once the initial transient state is over. In the steady state some of the components have failed and the average number of spares on the shelf is less than the nominal level. It can be seen that the performance of the system is greatly influenced by the support system (in this case reduced to a varying number of spares), see Figure 2 and Table 2) We can see that the redundancies in the system will enhance the capability to perform missions, but when the stock level is low it is not close to achieving the high availability suggested by the pristine case. This is of course due to the long waiting times that will be experienced once a critical failure occurs.

With a stock size greater than zero the effect of the redundancies are also beneficial but it can be seen that if the stock size is not set up to match the operational requirements the logistic downtime due to lack of spares will limit the mission success rate. It can also be seen that from a mission success rate perspective a higher level of redundancy or higher stock level might give a similar result as both will increase the mission success fraction.

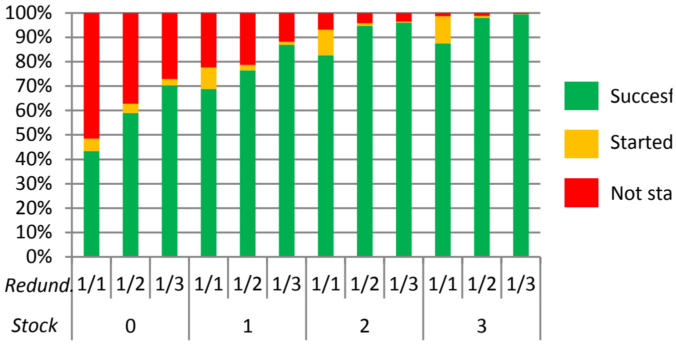

Figure 2. the steady state mission success fraction. The figure shows the average number of missions that where requested but not started (red), started but not finished (yellow) and successful (green) when using different combinations of redundancy and stock sizes.

Table 2, The steady state mission success fraction as a function of redundancies and number of spares.

Redundancy	Stock Size 0	1	2	3
No redundancy	43.4%	68.8%	82.6%	87.5%
1/2 Passive	59.1%	76.5%	94.6%	98.0%
1/3 Passive	70.3%	86.9%	96.0%	99.4%

7.4 A realistic case

For the second example a more complex scenario has been set up. The system consists of 20 different components with varying failure rates. Two different reliability configurations have been used and compared. In the first example a serial structure has been used and in the second a complex RBD (see Figure 3) has been created with nested parallel structures, a tree structure and a bridge. Some of the items also remain in series. The system operates from four different locations (bases) and missions are requested every second day.

The support system consists of a stock at each of the bases. At the bases components can be removed and replaced, but not repaired. Two regional stock points support two bases each and the regional stores are supported by a central depot where components are repaired and also stocked.

In the examples the stock size has been varied from a situation without any spares, a suboptimal spares assortment, and a situation with a high budget optimal spares assortment and a low budget optimal spares assortment, both calculated using Opus10®.

In this case the cost element has also been added with a varying price per part of purchase, store and repairs but also costs for the acquisition of the complete systems, additional investment for building the redundancies into the system and the operation of the system. The cost model has been simplified to suit this paper.

The case has then been evaluated from a cost and effectiveness perspective.

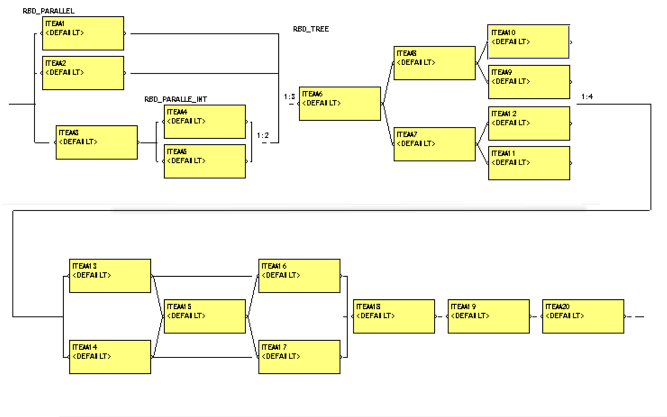

Figure 3 The RBD for the more complex model.

7.5 The mission success

Also for the more complex model we are interested in the effect on the mission success rate for different spares assortment when either having a large and complex degree of redundancy or a series structure.

After running the simulation it can be seen that by combining a complex reliability block diagram with an optimal spares assortment a very high level of mission success can be achieved, see 4. It can also be seen that the effect of the redundancy on the mission success rate is not realized unless a good support system is in place. In fact, even a series structure can give a better mission success rate with an optimal set of spares than a highly redundant system with a suboptimal spares assortment.

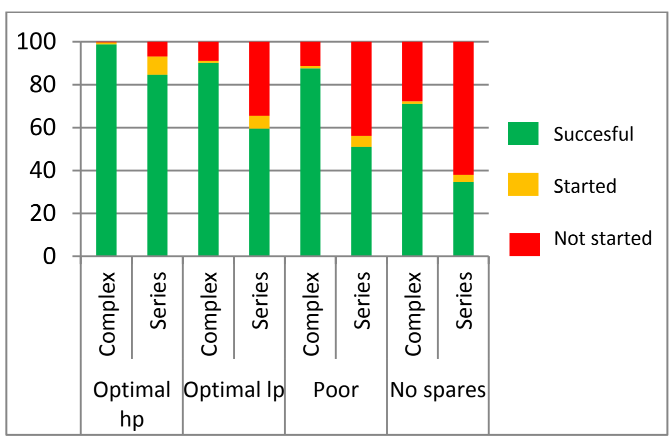

Figure 4, the mission success rate for the more complex scenario.

7.6 The cost

When studying the cost of the different cases it can be seen that in this case the cost for the poor stock assortment is the highest due to excess number of expensive parts. From the cost data alone it is difficult to draw many conclusions other than the fact that there is a cost of using RBDs and there is a cost for improving the logistic support solution. One thing that is certain is that the cost for the poor spares assortment is high.

Table 3 , the cost results for the complex model in millions of the currency used. For the assortment the Optimal lp stands for an optimal stock at a low performance (low availability target), and Optimal hp corresponds to a high performance (high availability target.)

Assortment	*Redundancy model*	*LCCA Cost of acquisition*	*LOC Cost of operations*	*LSC Cost of support*	*LCC Life cycle cost*
None	Series	4	4.74	0.24	8.98
Poor	Series	4	4.74	3.50	12.24
Optimal lp	Series	4	4.74	0.74	9.47
Optimal hp	Series	4	4.74	2.50	11.23
None	Complex	5	4.74	0.24	9.97
Poor	Complex	5	4.74	3.55	13.28
Optimal lp	Complex	5	4.74	0.72	10.46
Optimal hp	Complex	5	4.74	2.61	12.34

7.7 The cost effectiveness

If we combine the results from the simulations and the costs we can create a graph that shows us the cost effectiveness for the different cases similar to *Figure 1*. We can then see that the cases with the complex redundancies is higher in effectiveness but that the extra cost of adding the redundancies to the system also has the effect that the same investment in spares gives a higher LCC for the RBD-case then for the series case. It is also clear that the solution with the poor spares assortment gives a very high cost but mission success rate which is comparable to the RBD-case with the optimal spares low budget. What decisions to be made for this case will of course be totally dependent on the actual requirements and what the LCC the project can accept.

As shown in Figure 5, if the maximum LCC acceptable is 10M the only acceptable solutions are the series structure with inexpensive stock. On the other hand if the requirement is a Mission success rate of more than 98% only the system with the complex RBD combined with an optimal high budget assortment is acceptable. If the requirement is the combination of at least 90% mission success rate at less than 10M in LCC then we do not have any solution that fulfills the requirements.

8 CONCLUSIONS

The performance of the system and the total cost of ownership are greatly influenced by the technical design and the support system design. These two design activities should not be treated independently and it is therefore important to be able to analyze the impact of design decisions of the two aspects together so the most cost effective solution can be reached. Which solution that is the most cost effective is dependent on the characteristics of the system, the environment under which the system operates, how much the system operates and the limitations placed on the support system. The most cost effective solution is also dependent on the requirements on the system and constraints on the budget. It is therefore difficult to make the right design decisions without a proper methodology and tools that can support the analysis.

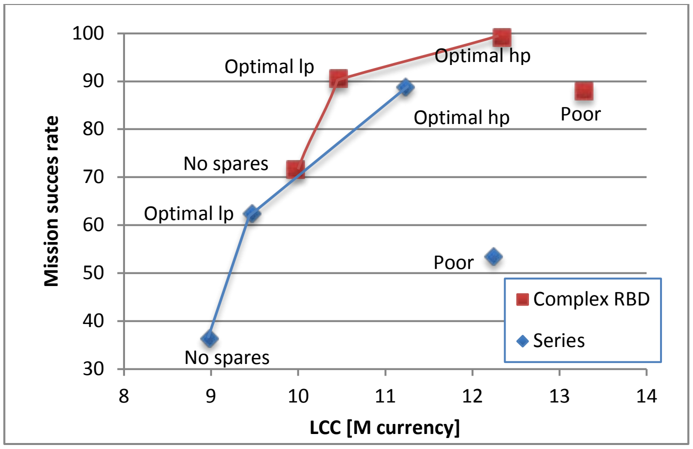

Figure 5, the cost effectiveness for the different RBD setups with different spares assortments. The selected assortment is shown in text adjacent to each point. For the assortment the Optimal lp stands for an optimal stock at a low performance (low availability target), and Optimal hp corresponds to a high performance (high availability target.)

BIOGRAPHIES

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