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Simulation of Industrial Support Systems in the Context of Functional Products

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Abstract

Functional Products, consisting of hardware and service support systems owned by the supplier, are sold to customers with a guaranteed availability of the function. The availability achieved is dependent on the reliability of both hardware and the service support system. The reliability of the latter can be defined as its ability to provide the required maintenance services in a timely manner. This paper reports simulation of a service support system from an industrial case study in order to predict its reliability. To identify and develop a suitable case together with an industrial partner company, a number of phone meetings were held in order to explain the research question, interview knowledgeable people and plan on-site visits and interviews. A number of interviews face to face were carried out with the industrial partners, where the goal was to obtain enough information to be able to model the support system correctly. The research involved both qualitative information gathering and applied computer aided simulation. An improved model for simulating a service support system is developed that considers the context in which the maintenance procedures are performed within a Functional Product. A software implementation of the model, developed by the authors, is applied to simulate the case study service support system in various scenarios such as different personnel availability and number of systems supported. The results show how the modeling can be used to improve and predict the reliability of the service support system.

1. Introduction

A Functional Product is an integrated offering consisting of hardware and support services. The supplier, who retains ownership of the hardware, sells the function of the product and guarantees a specified availability. This reduces risk for the customer, encourages close cooperation between the two parties and avoids an unevenly balanced cost cycle. In Alonso-Rasgado et al (2004) a review of the development process is presented.

The service support system includes the provision of maintenance, amongst other services, and is therefore crucial in providing the promised availability for the Functional Product to the customer. Availability is a function of mean time to failure and mean time to repair as defined by Thompson (1999). Both

these factors are of course affected by the support system since an effective support system can decrease the repair time and increase the time to failure through preventive maintenance. It is therefore of great interest to obtain a working computer model capable of predicting the performance of a service support system.

Support systems are complex to model since the availability is dependent on several factors such as installation, personnel availability, qualification, operational condition, design, monitoring, record keeping and analysis. As some of these parameters are challenging to quantify, correct data gathering is required in order for the result to be meaningful. This is probably one reason why little work has been done in the area of support system simulation in the context of Functional Products as compared to hardware products.

Hardware reliability has been studied extensively and methods are presented by Andrews and Moss (2002) and Gnedenko and Ushakov (1995). The vast majority of models found in the literature assume either a distribution or fixed time for the time to complete a maintenance procedure such as a repair. This approach is widely used due to its simplicity but is not viable if the completion time distribution is not known but the structure of the maintenance procedure and task completion time distributions are known. Even if the completion time distribution is known, several weaknesses remain with that approach, such as not allowing:

- Detailed analysis of the maintenance procedure, such as finding critical tasks or optimising the task sequence - primary aims for the Functional Product model.
- Variation in completion time due to limited resources and concurrent performance of maintenance procedures – a realistic situation for real world implementations of Functional Products.
- Additional maintenance (rework or corrective) caused by maintenance task failures.
- Variations in maintenance task sequence or sub-procedures due to outcomes from hardware inspections during the procedure.

These arguments render the analytical approach unsuitable for use in a Functional Product model.

Li and Thompson (2009) used a simulation approach to address some of the problems and study service reliability in the context of Functional Products. They modelled a service as a set of tasks arranged in a structure representing the sequential and parallel sequence in which they are performed. The structure also allowed unreliable tasks to be represented, with failure leading to the repetition of tasks. They included the possibility of varying the number of people utilised for each task with the completion time found as the sum of a fixed component and a component inversely proportional to the number of people utilised. However, there was no constraint on resources and the number of people assigned to each task was assumed to always be immediately available.

O'Connor (2002) split the time spent performing maintenance into three areas:

1. Preparation time.
2. Logistical time.
3. Active time.

The approach by Li and Thompson only considers the active time spent performing the job and not the preparation or logistical times which are both related to time spent awaiting and obtaining the necessary resources for the tasks. The method therefore models a service support system with a performance that is independent of the resource availability. However, the resource availability within a Functional Product, and hence also the performance of maintenance procedures, is very much dependant on the hardware, maintenance strategy and logistics either directly or indirectly. Some of the interactions within a Functional Product are shown in figure 1.

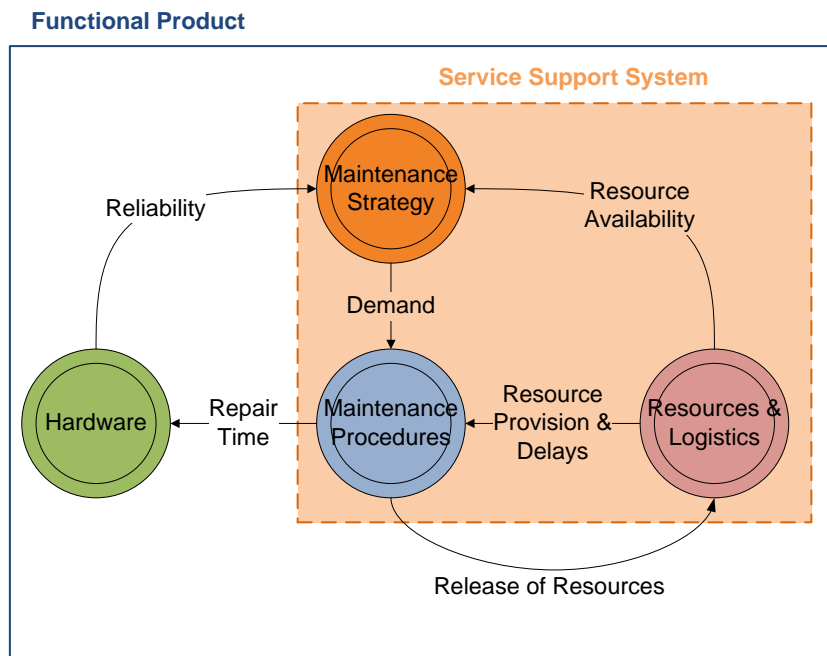


Figure 1 – Interactions between hardware, maintenance procedures, maintenance strategy and resources within a Functional Product.

2. Model development

As part of a framework for the optimisation of Functional Product designs (Löfstrand et al 2010), a method for modelling a Functional Product that includes both the hardware and service support system aspects has been developed and implemented as a software tool by the authors. Only the modelling of maintenance procedures, which forms one part of the service support system model, is described in this paper.

In this work an improved model for simulating a service support system is developed that considers the context in which the maintenance procedures are performed within a Functional Product. The modelling of limited resources and modelling of hardware inspections that take place during a maintenance procedure are two of the major enhancements. Compared to the service

support system model by Li and Thompson (2009), the model used in this work has several benefits, such as:

- Allowing the modelling of maintenance procedures with more complex task sequences than the sequential and parallel structures.
- Modelling the competition for limited resources and allowing tasks to consume, utilise or produce resources.
- Expanding the resources modelled from only people to all types of resource such as tools and facilities (for example, ability to model limited number of repair bays).
- Adding the possibility for modelling the influence of hardware states on the task sequence followed.

The model will be used to investigate the reliability of a maintenance procedure from a real world service support system under a variety of scenarios. The reliability of the maintenance procedure in each scenario will be compared using three of the five practical metrics for service reliability in the context of a Functional Product that were given by Li and Thompson (2007). The metrics that will be used are:

1. Mean service time
2. Maximum service time
3. Probability of successful service within a given time

2.1 Model Description

The implementation of the modelling is based upon discrete event simulation (Banks 1998) which involves the generation of events that occur at discrete points in time according to the random properties of the real or conceptual system being simulated. Each simulation trial generates a single artificial history for the system being simulated and, by executing a large number of trials, the behaviour, characteristics and performance of that system can be inferred. Simulation was chosen, rather than an analytical approach, because the model must deal with a wide variety of complex processes that have many interactions and dependencies between them. The use of simulation has also enabled an implementation that can produce detailed output data for many statistics. For the availability of the modelled functional product hardware, for example, the expected value, confidence and prediction interval estimates for the expected value, variance value and distribution plot can all be produced.

A maintenance procedure consists of a set of tasks that have randomly distributed completion times and are performed in a defined sequence. The tasks can consume, utilise or produce resources and may have one or more failure modes. For input into the model, they are represented through a structure known as an MP Graph (Reed et al 2010). The graph consists of a source, a terminal node and intermediate nodes representing tasks and decisions. Each task node, represented by a rectangle, is labelled with its resource requirements and completion time distribution. Edges connect intermediate nodes to the nodes that begin on their completion; complex sequences such as parallel structures are not considered in this paper. Task nodes representing unreliable tasks, those that have one or more failure modes, have multiple output edges that each represents a possible outcome

and is labelled with its probability of occurrence (such that the sum of the output edge probabilities from a node is 1). Decision nodes, represented by diamonds, are labelled with a test statement and have multiple output edges that are each labelled with a possible outcome for that test. The edge with the outcome matching the outcome for the test is the one that is followed. The test statement may, for example, be the state of a hardware component.

An example of a MP Graph representation of a maintenance procedure is shown in figure 2, where task details are omitted and only the task numbers are shown. In this maintenance procedure, task 1 is performed first followed by task 2 if completed successfully (with a probability of 0.8) or by task 3 if it fails (with a probability of 0.2). On completion of task 2 or task 3, an inspection occurs and the procedure ends if component A is not failed otherwise task 4 is initiated and the procedure ends on its completion.

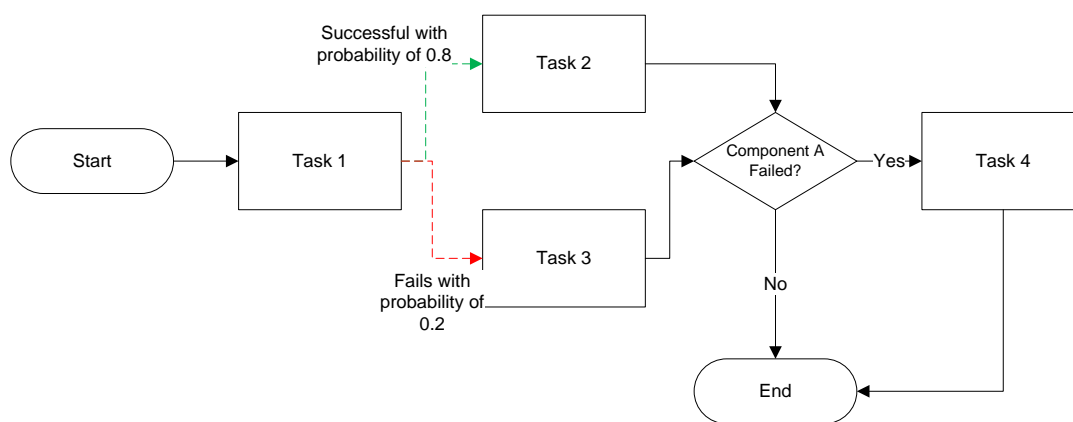


Figure 2 - An example of a MP Graph representation of a maintenance procedure.

In order to perform the simulations the MP Graphs are converted into their Petri net representations prior to analysis. This is a deterministic procedure and is performed automatically by the software implementation. Petri nets are one of the most versatile ways of modelling dynamic and concurrent systems. They can be represented graphically and are simple to understand but also have an underlying formal mathematical definition. Many different specifications for Petri nets have been developed, such as the powerful coloured Petri net specification developed by Jensen et al (Jensen, 2007). The specification used in the models described here follows the far simpler specification used by Schneeweiss (Schneeweiss 1999) with the addition of some colour features that allow complex behaviour to be represented with fewer nodes. However, the real novelty is the application of the Petri net modelling rather than the specification used.

Figure 3 shows the MP graph for a simple maintenance procedure consisting of one task that must be repeated if it fails. Figure 4 shows the Petri net representation of the task from the MP graph from figure 3.

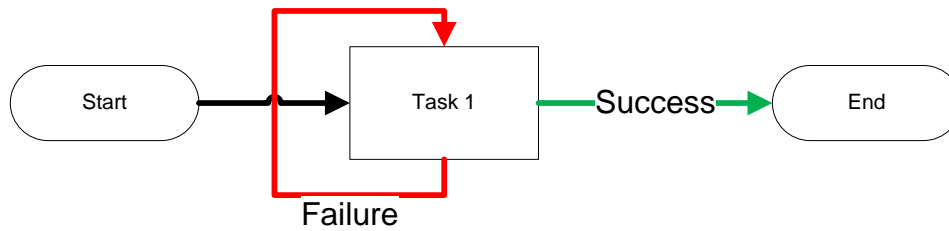


Figure 3 - MP graph for simple maintenance procedure.

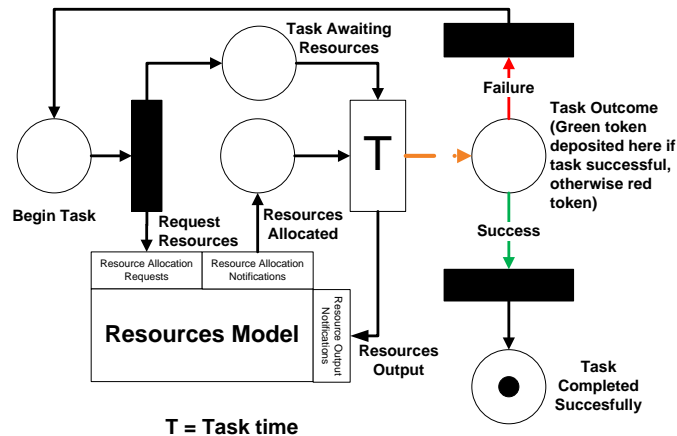


Figure 4 – Petri net representation of MP graph shown in Figure 3.

When a token is deposited in the “Begin Task” place in figure 4, the “Request Resources” transition fires instantaneously. This sends a request for the allocation of the resources required to complete the task to the Resources Model, and deposits a token in the “Awaiting Resources” place. Once the Resources Model has allocated the required resources and deposits a token in the “Resources Allocated” place, the final transition fires after delay T . T represents the completion time for the task and is sampled from a probability distribution. This transition notifies the resources model that the task has completed and deposits a green or red token in the “Task Outcome” place if the task was completed with success or failure respectively. Whether the task completes successfully or not is chosen randomly based on the reliability of the task. If a green token was deposited in the “Task Outcome” place then the “Task Success” transition fires instantaneously and a token is deposited in the “Task Completed Successfully” place, whereas if a red token is deposited then the “Task Failure” transition fires instantaneously and a token is deposited in the “Begin Task” place and the process repeats. The total time taken to complete the task is the time taken from the moment that a token is deposited in the “Begin Task” place to the moment a token is deposited in the “Task Completed Successfully” place.

More complex maintenance procedures can be modelled in the same way. As seen in the above example, the Petri net for a maintenance procedure task notifies the resource model that it requires the allocation of resources once it

is ready to start. The resources and logistics models then processes this request and once it can allocate the appropriate resources, which will depend on the resources available and demand for resources from other tasks, deposits a token in the “Resource allocation” place of the maintenance procedure task Petri net. A simple resource model will be used in this paper, where a limited number of maintenance personnel are available initially and become unavailable whilst occupied performing maintenance.

2.2 Industrial case study

The method has been applied to model part of a service support system from a product manufactured by an industrial partner. A number of phone meetings were held in order to explain the research question to the industrial partner, find knowledgeable people to interview and plan the interview. The interviews were semi-structured in order to give the interviewee room to spell out their own point of view and allow the conversation to focus on their field of expertise, this with the interview methods from (Yin 2006) and (Kvale 1996) in mind. The information gained from these interviews was then used pick out a suitable case from a service support system on which to test the model and demonstrate its potential.

The chosen case that is to be modelled is a procedure for the repair of an unspecified subsystem failure that causes the system to be unavailable. For the case study, it is assumed that there are specialist maintenance personnel dedicated to performing this procedure alone who are always available and who support a number of hardware systems.

The maintenance procedure contains two sub procedures that are only performed if certain components, named components B and C and that have unrevealed failure modes, are in the failed state at their respective inspection points during the repair. The repair procedure, maintenance procedure A, is shown in figure 5. The sub-procedures, maintenance procedures B and C, that are referenced in maintenance procedure A and return components B and C to the working state on completion respectively, are shown in figure 6 and figure 7 respectively. Uniform distributions were used for all task times such that the probability of any time within the specified ranges is equally likely.

The modelling of the hardware, with the exception of components B and C, is not considered in this case study and therefore the demand for maintenance procedure A must be generated in a simplified manner. It is set at a constant rate of 0.0014 times per hour for each hardware system supported, resulting in a mean interval between executions of the repair procedure of approximately 1 month. The failure rates for components B and C are 0.00038 and 0.0014 respectively.

The main reasons for selecting this support system were:

- The relatively high frequency of occurrence with which it is performed improves the quality of the data available.

- The system is unavailable whilst the repair is performed and its timely completion is therefore critical to the availability.

Maintenance procedure A, see figure 5: This is the main procedure which starts each time a maintenance demand is generated. Activities 1 to 9 always have to be performed. The diamond shaped nodes are decision gates. At these nodes a test is performed, as labelled on the node, and the outcome determines whether the performance of maintenance procedures B and C are required. Activities 7 to 9 do not affect the time to repair since the repair is complete by this point and their only affect is to occupy resources.

Maintenance procedure B, see figure 6, is performed when component B is failed at the point of inspection in maintenance procedure A. This procedure consists of a long chain of serial activities. The only oddity is activity 17, which if it fails, results in an additional 6 hours of repair time.

Maintenance procedure C, see figure 7, is performed when component C is failed at the point of inspection in maintenance procedure A. The time required to pass through this procedure is greatly dependant on the nature of the failure. 90 per cent of the time a minor failure is the case, 9.9 per cent it is a major failure and 0.1 per cent of the time it is the most severe failure.

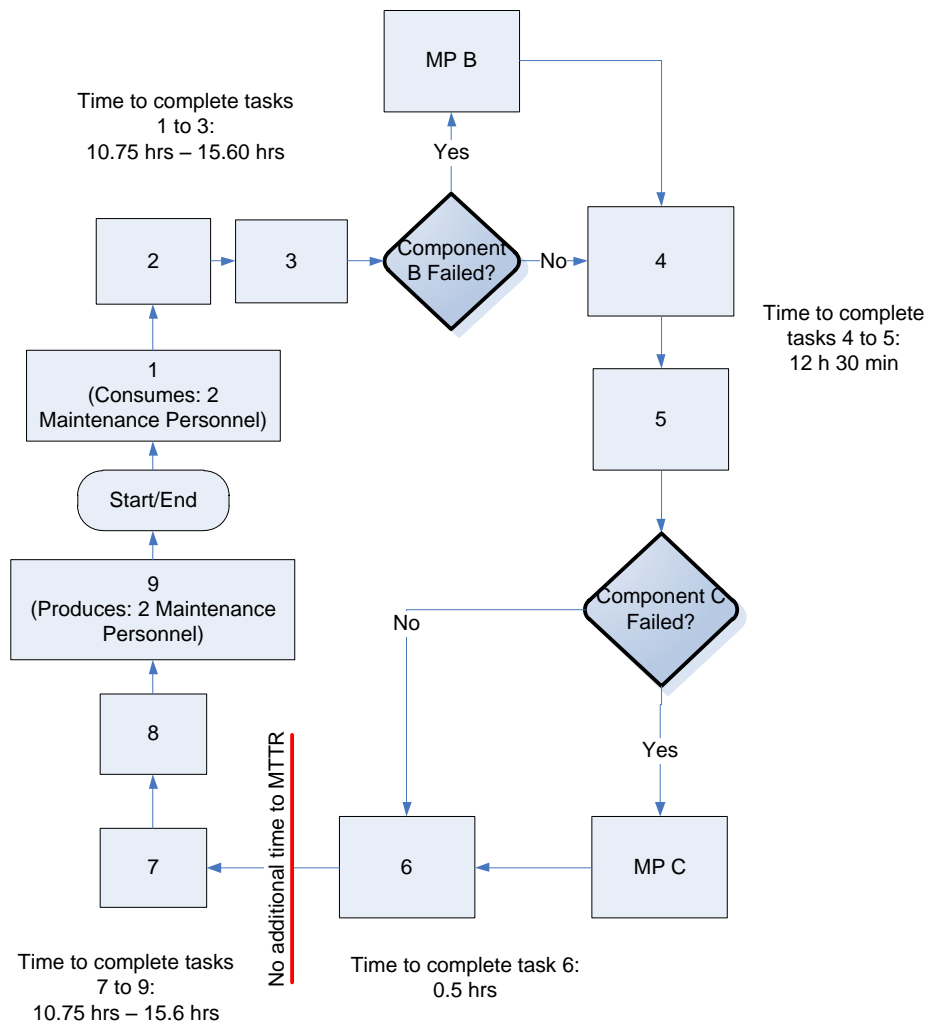


Figure 5 - Maintenance procedure A.

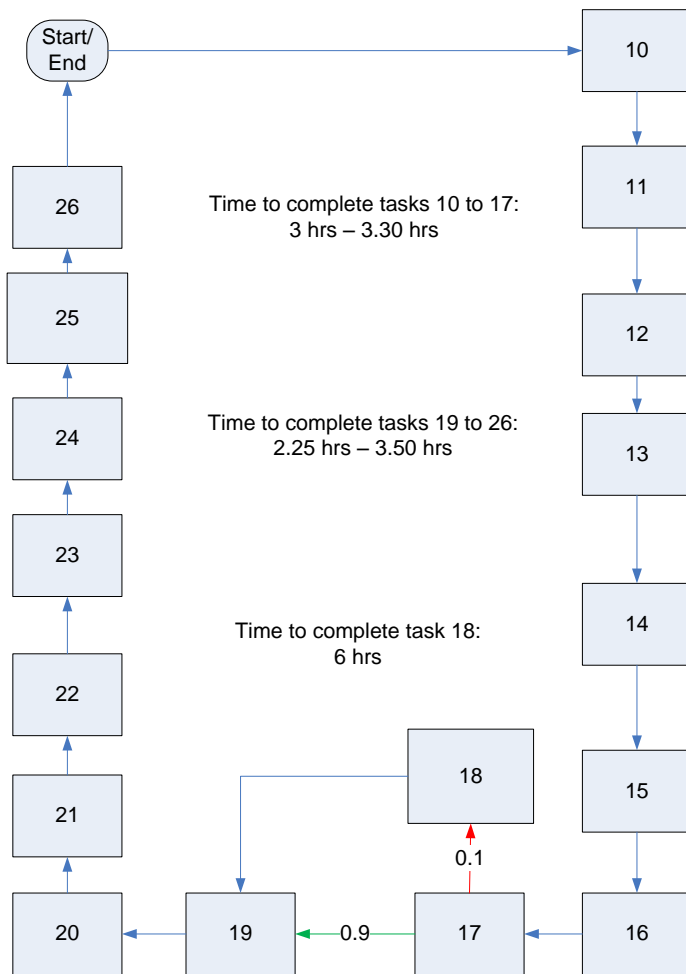


Figure 6 - Maintenance procedure B

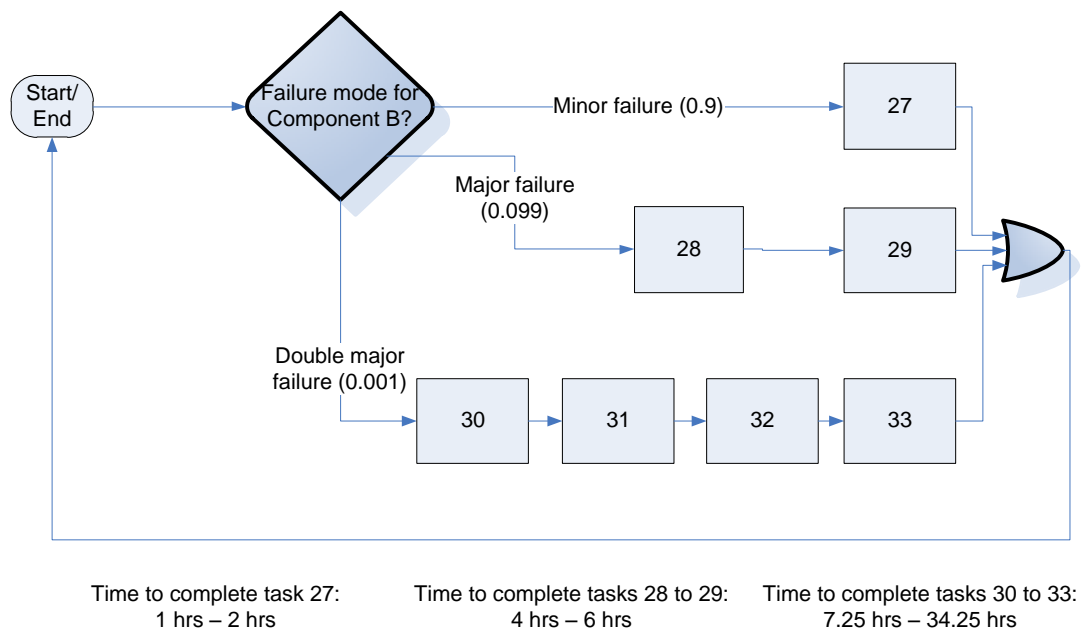


Figure 7 - Maintenance procedure C.

The scenarios simulated for the service support system are shown in Table 1, where the base failure rates for components B and C are as described earlier. In each scenario the service support system was simulated for a period of 2 years. Base failure rate indicates that the failure rate from interviews is used without modification.

Scenario	Number of maintenance personnel	Failure rates for components B and C	Number of systems supported
A	2	Base	5
B	2	50% of base	5
C	2	Base	10
D	2	50% of base	10
E	4	Base	10

Table 1 – Scenarios simulated for the service support system case study.

3. Results

The results for the mean time to repair (MTTR), mean minimum repair time and mean maximum repair times from the simulations of each scenario are shown in Table 1.

Scenario	MTTR	Mean minimum repair Time	Mean maximum repair time
A	35.10	23.80	97.52
B	33.91	23.80	94.71
C	49.64	23.81	170.02
D	46.81	23.77	161.48
E	30.81	23.75	71.62

Table 2 – Results of simulations for scenarios A - E.

A plot of the reliability, where reliability is defined as the probability that repairs can be completed within a given time, against completion time for scenarios A, B, C, D and E are shown in figure 8.

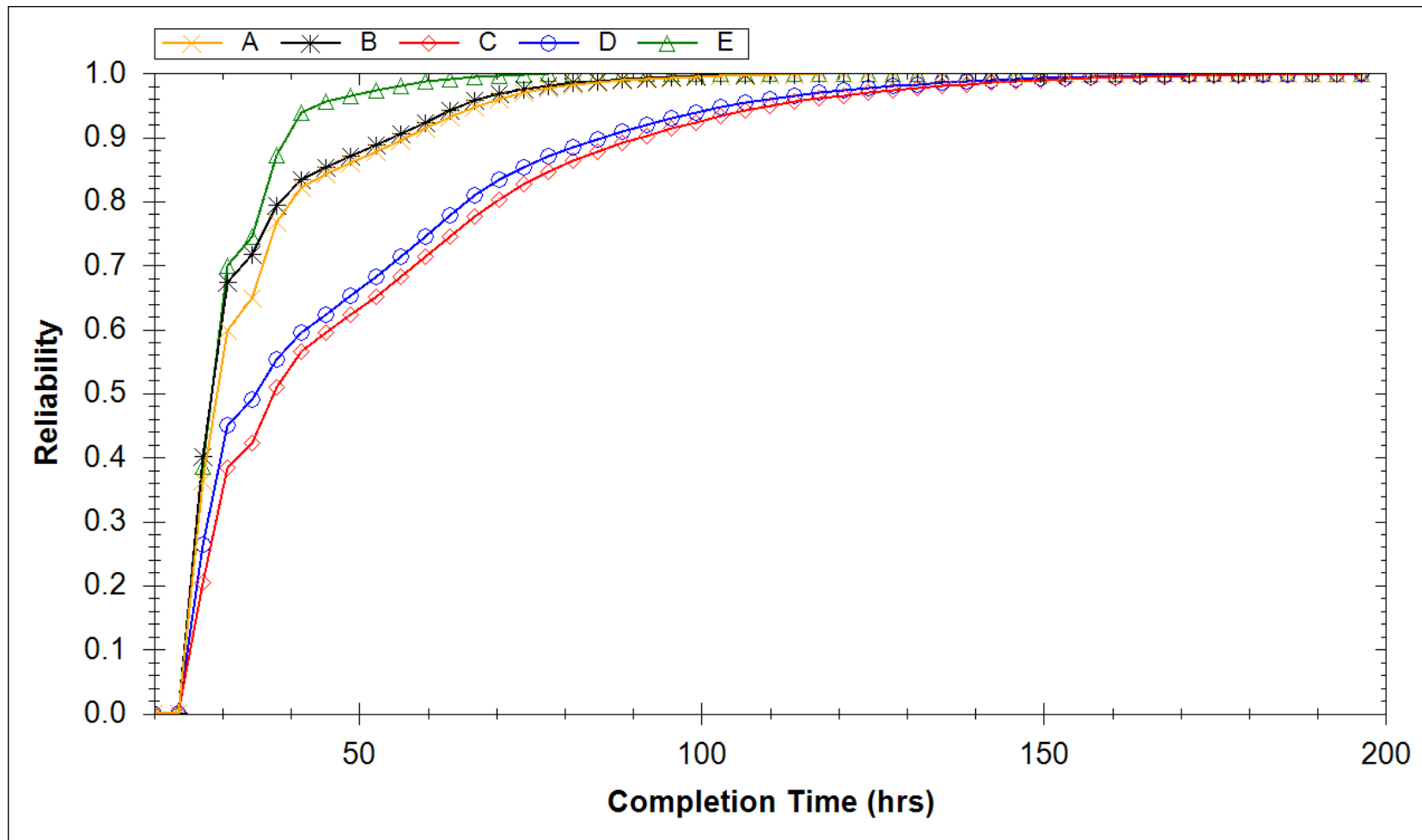


Figure 8 – Plot of reliability against completion time for scenarios A – E.

In scenario A, the mean completion time is 35.10 hours. The plot in figure 8 shows that the reliability rise rapidly as the completion time is increased from the minimum repair time, 23.80 hours, to 40 hours where the reliability reaches approximately 80%. Repairs that took longer than this time are almost exclusively where maintenance procedure B or C were performed due to failures of components B and C, and since the range of completion times for those procedures are large, the reliability rises slowly after this point.

In scenario B, where the failure rate of components B and C is halved, the MTTR is 33.91 hours and mean maximum time is 94.70 hours, representing reductions of around 3% compared to scenario A in each case. This represents a mean reduction in maintenance time from this procedure, and hence also hardware downtime, of approximately 14hrs per year for each system. This could be used, for example, to justify investment in improving the reliability of components B and C.

The MTTR in scenario C, where the number of systems supported is doubled compared to scenario A, increases by 41% to 49.64 hours. The reason for this increase is that the two engineers are not always available when a system requires the repair due to being occupied maintaining another system. The logistical delay whilst a system that requires the maintenance awaits the availability of engineers is then compounded by the increased likelihood that components B or C have failed when it is finally performed, due to the increase in the interval since they were last in the 'as-new' state. The maximum repair time increases dramatically compared to scenario A, with a mean maximum repair time over the 2 year period simulated of 170.03 hours – an increase of 74%. Avoiding maximum repair times that are far higher than the mean is important for providers of Functional Products as customers become accustomed to the mean time and, as expressed by Thompson (2009), a service failure occurs when the service performance is worse than the customer expectation. Analysis such as this could be used to determine how many systems the manufacturer can support with acceptable service reliability and customer satisfaction given current resource levels.

In scenario D, where the failure rate of components B and C is halved compared to scenario C, the MTTR falls by almost 6%, whilst the mean maximum completion time falls by more than 5% from the values for scenario C. Comparing these reductions to those found between scenarios A and B shows that the benefits of improved reliability for components B and C increases when the number of systems supported is 10 rather than 5. This is due to the increased time between repair for components B and C in scenario D, due to the increased logistical delays caused by supporting a greater number of systems.

In the final scenario investigated, scenario E, the number of maintenance personnel is doubled compared to scenario C. This results in substantial reductions in both the MTTR and mean maximum repair times, with reductions of approximately 40% and 60% respectively. This type of analysis can be used to optimise the resources available in the service support system. Interestingly, the support system performs far better in this scenario than it

does in scenario A where the number of systems and maintenance personnel are halved. This type of analysis can be used to investigate how a manufacturer of a Functional Product might benefit from increasing the scale of their operations and optimising the number of resources available.

Very little variation in the mean minimum repair time was found between the five scenarios. The reason for this is that over a two year period there is a high probability that the repair procedure will be performed without logistical delay, without failure of either component B or C and with all tasks performed in a short time at least once for one of the systems supported, regardless of the scenario from the five simulated.

4. Conclusions

A method for simulating the reliability of a service support system in the context of Functional Products and its application to an industrial case study has been developed and presented. The development of the modelling and forming the description of the case study were quite time consuming due to the complexity of service support systems in general and of the specific system studied respectively.

Part of a service support system from an industrial partner was chosen as a case study and simulated using the modelling techniques presented in this paper. In collaboration with the industrial partner numerous failures and maintenance procedures were investigated. The criteria for choosing which systems to use were a combination of impact of failure, frequency and availability of data. A complex maintenance procedure, containing two sub-procedures, was chosen as good data for it was obtained from interviews and its timely performance is critical to the availability of the Functional Product.

A variety of different scenarios were simulated and the results generated to show the reliability of the service support system in terms of the time to complete the maintenance procedure. The results showed the effect on reliability of variations in service support system parameters, such as the number of systems supported, demonstrating the potential of the model as a service support system prediction and optimisation tool. For example, it showed that the reliability falls significantly if two engineers must support 10 instead of 5 systems. It also showed that the service support system reliability was far better when 4 maintenance personnel were supporting 10 systems than when 2 maintenance personnel had to support 5 systems.

The modelling tool is generic and it should be possible to apply the same technique to model service support systems from different industries. The most time consuming task is collecting data for the service support system to be modelled, although this is made easier by the software implementation which conceals the underlying complexity and power of the modelling, only requiring the input of the task details and maintenance procedure task sequence, in the form of an MP Graph, from the modeller.

The next step will be the addition of a costing model so that optimisation of the cost against reliability analysis can be performed. The analysis of the complete Functional Product from which the case study service support system was taken, including both the hardware and service support system components, is also an area for future work. The current developed modelling tool and ideas for future work have been favourably received by the related organisation. They are looking forward to contributing to the continuation of the development of the tool.

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