CHAPTER 9

MODELLING

CONTENTS

1 INTRODUCTION

1.1 General

1.1.1 The aim of this chapter is to provide an understanding of the concepts and processes involved in modelling. Modelling is used to provide "evidence-based decision making" in many fields including R&M. The same issues must be considered and many of the same problems are encountered in every application of modelling.

1.1.2 This chapter provides general information, applicable to all modelling techniques. More specific information on individual R&M modelling techniques is contained in the relevant chapters in Part C of this manual.

1.1.3 This chapter does not attempt to provide lists of known or "approved" models or even modelling tools. Such a list could never be complete and would become immediately out of date once printed. Instead, it describes the fundamental stages of a modelling study and problems often encountered, because these issues affect the success of any modelling exercise.

1.2 Definition and Purpose

1.2.1 A **model** can be defined as:

"A simplified representation of a complex system or process"

OR

"An external and explicit representation of part of reality, as seen by people wishing to understand it" [after Prof. Michael Pidd (1996) – Tools for Thinking].

1.2.2 The understanding given by use of the model, may support decision making to change, manage or control that part of reality represented by the model. Modelling should not be done for its own sake, but to provide a useful input into the process of evidence-based decision making.

1.2.3 The prime purpose of any model is to provide a relatively cheap method of understanding and predicting the behaviour of a system or process without the need either to build the system or to conduct extensive testing.

1.2.4 As for scientific theories, it is not right to speak about a model being "correct": the model is not reality. It is important that the model should represent reality sufficiently well to support the decision making for which it was intended.

"Things should be as simple as possible, but no simpler" – Albert Einstein.

1.2.5 A model is always an approximate representation of reality, but there must be a balance between its authenticity and manageability. The model must be detailed and elaborate enough to show the essentials, but coarse enough to be tractable.

1.3 Terminology

1.3.1 The following terms and meanings are used in this chapter:

Term	Meaning	Example(s)
Model class	The type of relationship between the model and the system or process which it represents (see Section 3).	**Physical** models (e.g. a 1/10 scale wind tunnel model). **Virtual** models (e.g. a Virtual Reality representation of a building). **Logic** models (e.g. Fault Trees). **Diagrammatic** models, which are either: **Schematic** (e.g. Flow Charts, Entity Relationship Diagrams, Functional Block Diagrams, Company Organisation Charts). or **Scale** (e.g. Maps and Engineering Drawings). **Abstract** models, i.e. ones without a graphical or physical depiction of reality (e.g. Newton's Laws of motion).
Modelling technique	One of a number of standard ways commonly used to represent systems or processes (cf. R&M Techniques in Part C of this manual).	Reliability Block Diagram modelling used to represent the dependency of a function or system on the component parts.
Modelling evaluation method	The means by which the model produces its outputs from the given inputs (see Section 3).	**Analytical** methods (e.g. standard equations used to calculate the trajectory of a projectile). **Simulation** methods – which may be deterministic or stochastic and may be continuous or discrete.
Modelling tool	The particular means (often a software package) used to implement the model.	**RAM4** software package used to build and simulate Reliability Block Diagram models.
Model	The specific representation of a system or process.	The Reliability Block Diagram model of the Concept Stage Submarine Propulsion System for the function "able to achieve and sustain 12 knots forward speed".

Table 1: Terminology used in this chapter

2 THE MODELLING PROCESS

2.1 Stages in a Modelling Study

2.1.1 A modelling study will usually have five stages, although there may be overlap between them and iterations within the study. The stages are as follows:

- System analysis;
- Model design and development;
- Model validation;
- Model use and interpretation of results;
- Feedback into decision making.

2.1.2 There may also be a requirement to support the model so that it can be re-used, with or without alterations.

2.1.3 Each of these stages is discussed in the following sub-sections.

2.2 System Analysis

"The key to solving a problem is recognising the right question to ask."

2.2.1 The most important parts of the system analysis stage are to identify the output required from the model and the input data to be used. These will determine the system boundary for the model and the lowest level of detail at which it is feasible to model. Of course, it is not always appropriate to model at a fine level of detail, if a coarse but quick assessment would give results which are good enough.

2.2.2 System Analysis or Requirements Capture will define what question(s) the model is required to answer. The answers expected may be:

- **Qualitative** (e.g. whether or not there are any single-point failures);
- **Semi-quantitative** (e.g. a ranked list of relative performance for various options);
- **Quantitative** (e.g. numerical estimates of real world performance).

2.2.3 When considering the question which the model is to answer, the modeller must decide the form in which the results will be required. For example, what measure or measures are of interest for the system and must these be output in a particular style ? Will a visual representation of the actual system or process be required, or are tables of numerical results adequate ?

2.2.4 The specification for model outputs may also have to consider any additional information required for the model debugging process at the development and validation stages. These outputs required specifically for testing the model are analogous to diagnostics built into equipment or software.

2.2.5 At this early stage it will be necessary to determine the availability of data which will be used as input to the model. If such information is not available, then a data gathering exercise may be required to support the modelling.

2.2.6 The relevance and accuracy of the input data for the model will determine the credibility of the results produced. This is why every modelling study must provide traceability for the input data used and also indicate the range of uncertainty for the results.

2.2.7 The modelling method chosen determines the data requirements, but the availability of data also constrains the methods that are available.

2.2.8 System Analysis will also define the case studies which are to be modelled. Depending on the purpose of the modelling, these could include several competing design options or various approaches to system operation or support.

2.2.9 The System Analysis stage will form the foundation of the complete modelling study. It will include the selection of an appropriate method (see Section 3 below) and tools.

2.2.10 The findings of the System Analysis should be documented to provide traceability. A **Model Requirements Specification** document or **Master Data and Assumptions List** (MDAL) is often used to record the basis of a modelling study. It should ensure a common understanding between the modellers and their customers, as well as ensuring that the model is readily understood and supportable in the future.

2.2.11 An important attribute of most successful models is flexibility. This may be achieved in part by ensuring that the System Analysis stage considers possible future uses, and the model is not over constrained to particular situations.

2.3 Model Design and Development

2.3.1 Once the modelling approach and specification have been defined, the actual model can be designed. The design and development process is analogous to that for software. Equivalent processes of design, implementation, debugging, integration and system testing are required.

2.3.2 As for software development, good configuration management is vital when building models. Records of the model and sub-model version and testing status are crucial, especially when there are several parties involved in the development. The model design and development must consider future maintainability of the model so that documentation within the modelling tool or supporting the model (e.g. the MDAL) is kept up to date.

2.3.3 Model development is often a two part process of creating a representation of the system or process (e.g. a logical representation) and then populating it with the necessary input data.

2.3.4 If the System Analysis has identified that the input data required for the model is not currently available, then there will have to be a data collection exercise before or during the model development stage. This can dramatically increase the cost and duration of the modelling study and must be carefully considered before committing to it. For example, the data required may be the output from another model or automatic process and be relatively cheap to capture. However, manual accumulation of appropriate data from non-automatic sources such as hand written records, or specific trials for data collection will be time consuming and manpower intensive.

2.4 Model Validation

2.4.1 Validation should be carried out as part of the development process. Again, the activities are similar to those for software development where testing is used to ensure that the model correctly implements the requirements defined during System Analysis.

2.4.2 Validation is often an iterative process, including the checking of separate parts of the model as they are developed and final checking in its complete state. It may be desirable to check separately the logic or arrangement of the model and then one that is populated with data.

2.4.3 The user will have to check all versions of the models, including those used for what-if and sensitivity runs. However, if case study models are minor adaptations from a base case model, this will require little additional effort.

2.4.4 The validation process must confirm that the final model or models satisfy the requirements set. Where a standard modelling package is used to implement the model, then the pedigree and appropriateness of that tool must be considered. Even some widely-accepted modelling tools have been known to contain bugs. A good modelling tool can also be used to build a bad model if the System Analysis or development are poor of if it is applied to the wrong sort of problem.

2.4.5 Validation is an important aspect of modelling acceptance, which is the subject of Annex B to this chapter.

2.5 Model Use and Interpretation of Results

2.5.1 Once a validated model exists, it can be applied and conclusions drawn about the real world system or process which it represents. Any conclusions drawn from the modelling should be accompanied by an assessment of the **uncertainty**. A review of the major uncertainties may be necessary for input to the decision making process, so that the most robust solutions can be identified.

2.5.2 The interpretation of model results should always include a **Sensitivity Analysis**. This varies the assumptions, including the data used, and explores the sensitivity of the conclusions to them. Any key assumptions or data items having a significant influence on the model outputs must be identified (often termed the **drivers**). The drivers should be reviewed and verified through extending the System Analysis or data research in these critical areas.

2.5.3 For certain types of model, such as Project Programmes or Cost Forecasts, a **Risk Analysis** will be required. This will examine the impact of combinations of two or more future events and how the adverse outcomes could be constrained.

2.6 Feedback into Decision Making

2.6.1 The results of the model are of little value until conclusions have been drawn and these are fed back into the decision making process. The decisions to be taken depend on the purpose of the model, but this will have been taken into account at the System Analysis stage.

2.6.2 Examples of decisions taken using evidence provided by models include the following:

- The current design of the system will satisfy the performance requirements and should be implemented;
- Option C is forecast to have the best balance of cost and performance and should be chosen;
- The project should be cancelled because the costs significantly outweigh the benefits;
- The annual insurance premium should be set at 15% of the sum assured to give acceptable Risks to the insurer.

2.6.3 Modelling can provide some or all of the "evidence" for evidence-based decision making. It is very important that there is an audit trail to show that the decisions made are well founded. Thus both the model documentation, such as the MDAL, and the models themselves must be stored or archived in an appropriate way.

3 MODELLING METHODS

3.1 Classes of Model

3.1.1 There are many classes of model available for different applications. Unfortunately the terms are not consistently used in the same way, possibly because there are so many different fields of modelling.

3.1.2 The modelling methods encountered include the following, but the boundaries between them are not always clear-cut:

- **Physical models** such as scale models and full-scale mock-ups;
- **Virtual models** such as Virtual Reality representations used to examine a new building or system before it is built;
- **Logic models** such as Fault Trees and Reliability Block Diagrams;
- **Diagrammatic models**, which are either:
  - ♦ **Schematic** such as Flow Charts and Functional Block Diagrams;

  or

  - ♦ **Scale** such as Maps and Engineering Drawings.
- **Abstract** models (i.e. ones without a graphical or physical depiction of reality) such as Newton's Laws of motion.

3.1.3 Models may be applied to both **static** and **dynamic** problems.

3.1.4 Evaluation Methods

3.1.5 The outputs provided by models are usually produced in one of two ways:

- **Analytical** – where the solutions are produced by direct calculation using given equations or relationships;
- **Simulation** – where the solutions are produced by imitating the real world behaviour through determining the implications of all the relationships defined for the variables in the model.

Often, to arrive at a solution by analytical means, it is necessary to drastically simplify the problem.

3.1.6 An analytical solution can generally be obtained rapidly but often requires restrictive assumptions to make the problem tractable.

3.1.7 Simulations may be either **deterministic** or **stochastic**. A model or process is deterministic if "*the results are always exactly the same, given the same starting conditions*." A stochastic or probabilistic process is not deterministic, and so has an element of chance which affects the results.

3.1.8 Stochastic models will use either a **Continuous** or a **Discrete Event** approach. Continuous models are best suited to situations where the variables change continuously rather than in finite increments. A discrete event simulation progresses by looking for the next significant occurrence (e.g. a system failure, arrival of a message) and working out the status of all entities at that time. If there are very many discrete events in the real world process being modelled, then it may be appropriate to aggregate them together and treat them as a continuous flow.

3.1.9 System simulation begins at a specified starting state and then replicates a possible history of events through time according to the rules built into the model. Almost always the simulation will provide **time compression**, so that many years of operation can be replicated in a few minutes of model running time. There are also situations where the objective of the simulation is to expand the time scale in the model, for example if investigating rapid chemical reactions or the Big Bang.

3.1.10 If a process is stochastic then it can follow many different histories from the same starting conditions. **Monte Carlo** simulations (see PtDCh4 of this manual) involve repeated runs to estimate the range and variability of the results of interest. Monte Carlo simulations almost always require a computer, but their increasing power has meant that excessive simulation times are not often a problem.

3.1.11 It is important that users of models of stochastic processes do not confuse the variations due to chance events with the uncertainty of input data.

4 COMMON PROBLEMS

4.1 General

4.1.1 Regardless of the field of modelling, many of the same difficulties can arise which compromise or ruin the exercise. If this happens to models used to provide "evidence-based decision making", the wrong evidence may well be presented and incorrect decisions taken.

4.1.2 The modelling study should be kept on track through good communication between the users of the output and the model developers. This is necessary from the point of formulating the problem and specifying the outputs required, through to the interpretation of the results.

4.1.3 During the modelling process, there is a need for flexible thinking, good configuration management and healthy scepticism about the limitations of the model.

> *"Theoretical estimation is as accurate as our oversimplified estimation models backed by obsolete historical data. The real thing is a somewhat more reliable indicator"* – Tom Gilb

> *"Structural engineering is the art of forming materials we do not wholly understand, into shapes we cannot precisely analyse, so as to withstand forces we cannot properly assess, in such a way that the public at large has no reason to suspect the extent of our ignorance."* – Chairman of Scottish Branch of the Institution of Structural Engineers 1946.

4.1.4 The users of the model results must also be open minded about what the evidence is telling them. There is little value in a modelling study, if the customer knows at the start the only answer that they will accept.

4.1.5 The following points summarise many of the common pitfalls in modelling studies in different disciplines. The intention is develop each point further with examples from the field of R&M modelling.

4.2 What Goes Wrong

4.2.1 Mistakes frequently made in modelling studies include the following:

- Modelling as a standalone activity, no input to decision making;
- Poor definition of actual requirement by the customer;
- Model developed to support a view already fixed;
- Model developed in ignorance of the big picture;
- Inadequate System Analysis;
- Wrong system/model boundary;
- Wrong level of detail;
- Inappropriate modelling tool;
- No sensitivity analysis;
- Poor data quality;
- Model used with out of date or inappropriate data;

- Unjustified assumptions;
- Implicit assumptions;
- Inflexible model;
- Unjustified conclusions drawn;
- Poor configuration management of model or its constituent parts.

5 USE OF MODELLING IN R&M

5.1 General

5.1.1 Modelling is used in the discipline of R&M Engineering for the following main purposes:

- To understand why parts of a system fail (be they hardware, software or human);
- To estimate when parts of a system are likely to fail;
- To estimate the system's A, R or M Performance;
- To identify R&M weaknesses in the system.

5.1.2 The individual R&M Techniques which serve these purposes are listed below and described in detail in the Chapter of the Manual referenced. Each Chapter also describes where computer tools exist to support the R&M Modelling Technique and refers to the supporting theory in Part D of the manual.

5.1.3 When using any R&M Modelling technique, the general guidelines and warnings presented in this Chapter should be taken into account.

5.2 Understanding Component Failure Processes and Estimating Failure Times

5.2.1 The R&M Techniques used for this purpose include:

- Weibull models (see PtCCh *);
- Physics of Failure models (see PtCCh 24);
- Stress/Strength interference (see PtCCh*);
- Empirical Reliability Estimation Models (such as Mil Hdbk 217F) (see PtCCh*);
- Software Reliability Estimation Models (see PtCCh52);
- Human Reliability Assessment (see PtCCh32).

5.3 Estimating System A, R or M Performance and Identifying Problems

5.3.1 The R&M Techniques used for this purpose include:

- Reliability Block Diagrams (see PtCCh30);
- Fault/Success Trees (see PtCCh29);
- Markov models/chains (see PtCCh38);

- Maintainability models (see PtCCh37);
- Event Trees (see PtCCh34);
- Growth models (see PtCCh15).

FLUOR GLOBAL SERVICES

MODELLING OF COMMUNICATIONS NETWORKS

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ANNEX A

MODELLING OF COMMUNICATIONS NETWORKS

CONTENTS

ABBREVIATIONS

AoS	Availability of Service
ARM	Availability Reliability Maintainability
ATM	Asynchronous Transfer Mode
CMF	Common Mode Failures
COTS	Commercial Off The Shelf
CTS	Communication Transfer System
FDDI	Fibre Distributed Data Interface
FGS	Fluor Global Services
FMS	Facility Management System
FPMH	Failures Per Million Hours
GoS	Grade of Service
HF	High Frequency
LAN	Local Area Network
LF	Low Frequency
Mps	Messages per second
MTBF	Mean Time Between Failures
MTFF	Mean Time To First Failure
MTTR	Mean Time To Repair
PABX	Private Automatic Branch Exchange
PSU	Power Supply Unit
QoS	Quality of Service
RAM4	Reliability Analysis Program RAM4
RBD	Reliability Block Diagram

REL	Reliability
SFR	System Failure Rate
SHF	Super High Frequency
STGR&M	Sea Technology Group R&M
UHF	Ultra High Frequency
VHF	Very High Frequency

1 INTRODUCTION

1.1 The use of a Network based architecture to implement Data Communications both within, and between, Systems is now commonplace, due to the advantages that it provides i.e. multiple routes, dynamic re-routing, dynamic bandwidth management. However, the very nature of the architecture presents several difficulties in the creation of models for both the setting of requirements (for the tender/design phase) and for monitoring achievement (for acceptance or in-service phases).

1.2 A fundamental problem is the translation of User expectations into the Technical performance delivered by the Network, which can then be specified by meaningful parameters. While some of these will be addressed by simple functional considerations (e.g. distortion, signal to noise ratio), the only accurate way to measure user service levels is to measure service availability and response time from the end user's perspective. Unfortunately, while Availability and response time are the most important parameters, they are difficult, if not impossible, to measure directly.

1.3 On behalf of STGR&M, FGS have conducted several modelling exercises on Network Communications Systems for the purposes of Tender Assessment and Requirements definition. This paper, drawing on FGS experience with STGR&M and other projects, presents the approach adopted, the lessons learnt from the modelling, and issues to be considered for network modelling in the future.

2 MODELLING APPROACH

2.1 General

2.1.1 Due to the multiplicity of services implemented on a Communications Network and the large User population that it services, a single model of the entire system is inappropriate for the objective of assessing its performance from the User perspective. The approach adopted was therefore to model the provision of individual services to Users, termed a Functional Thread. For each Functional Thread, R&M and Performance models were developed.

2.1.2 For the purposes of this paper, only the models for a single Functional Thread are presented.

2.2 System Definitions

2.2.1 **Boundary**: The set of interfaces between the Network and other systems, defining the limits/scope of responsibility of the Network for service provision.

2.2.2 **Functional Thread**: The set of items (hardware and software) which deliver a service through the Network.

2.2.3 **Availability of Service, AoS.** This parameter is used to determine the proportion of a mission that the service will be available for use. It is a straightforward calculation of system availability as determined by hardware configuration and maintenance policy, incorporating redundancy, system repair/restore times and spares. It should be noted that this method does not include an allowance for permitted delays incurred when setting up secondary, or activating redundant paths, for transmission, etc. Therefore the AoS is a parameter determined by the failure rate and configuration of the items in a static system.

2.2.4 Grade of Service, GoS. The GoS is the level of service required based upon priority and security rating assigned to the message. GoS could be a measure of the probability of completing a transaction. Constraints on the speed of transmission and the specific equipment types required would limit the degree of redundancy available to each specific type of message, i.e. grade of service required. As the calculation must account for time delays as well as redundancy this analysis will be modelled using a process type of simulation analysis which incorporates such dynamic factors as loading, input message rate, etc.

2.2.5 Quality of Service, QoS. QoS are failure definitions for a type of service specified at the equipment level, irrespective of how the service level is achieved, e.g. the GoS is that a warning must be audible on the upper deck of a ship and the QoS is that the Klaxon output level must be +120dBa.

2.3 R&M Modelling (AoS)

2.3.1 The Functional Thread was modelled using the RAM4 Analysis Program, version 3.2.2d. RAM4 is a digital simulation program for the assessment of R&M parameters of complex repairable and non-repairable systems when operated for a defined period of time (termed a mission). The system is represented as a Reliability Block Diagram (RBD) whose blocks are characterised by reliability and repair-time parameters. A more detailed description of the program and its application will be found in the RAM4 User's Manual.

2.3.2 Software was treated as a single additional element in series with its associated hardware platform. The software element also includes an allocation for Common Mode Failures (CMF) where items are in a redundant configuration.

2.4 Performance Modelling (GoS)

2.4.1 The Functional Thread was modelled using the Extend Analysis Program, version 3.2.3. Extend is a dynamic, iconic simulation modelling tool, enabling the simulation of discrete event, continuous and combined discrete event/continuous process systems. The models produced are highly graphical with the option of producing a number of graphs from any one simulation to represent any chosen parameter. The model is built from components (called 'blocks'), usually with connections between the blocks. Each block contains procedural information as well as data.

3 SYSTEM DESCRIPTION

3.1 Network Description

3.1.1 The typical Network Communication System being analysed is based on that pictured in Figure 1. The specific Functional Thread modelled in this paper is for the drafting and authorisation of a message for transmission over a radio system and consists of User (Subscriber) Workstations, the Communications Transfer System (CTS), the Facility Management System (FMS) and a Radio System.

3.1.2 The message flow is from Subscriber workstations to the Radio System where the system is also handling other traffic which may/may not delay the transmission of the message. The CTS processes data from the Workstations and forwards it to the destination. It is assumed the CTS either forwards all messages without incurring a delay (i.e. the CTS has excess capacity) or processes the messages in a queue as determined by the message priority. The FMS manages the circuit allocation, e.g. allocates the necessary radio systems, and supplies message management information to the CTS.

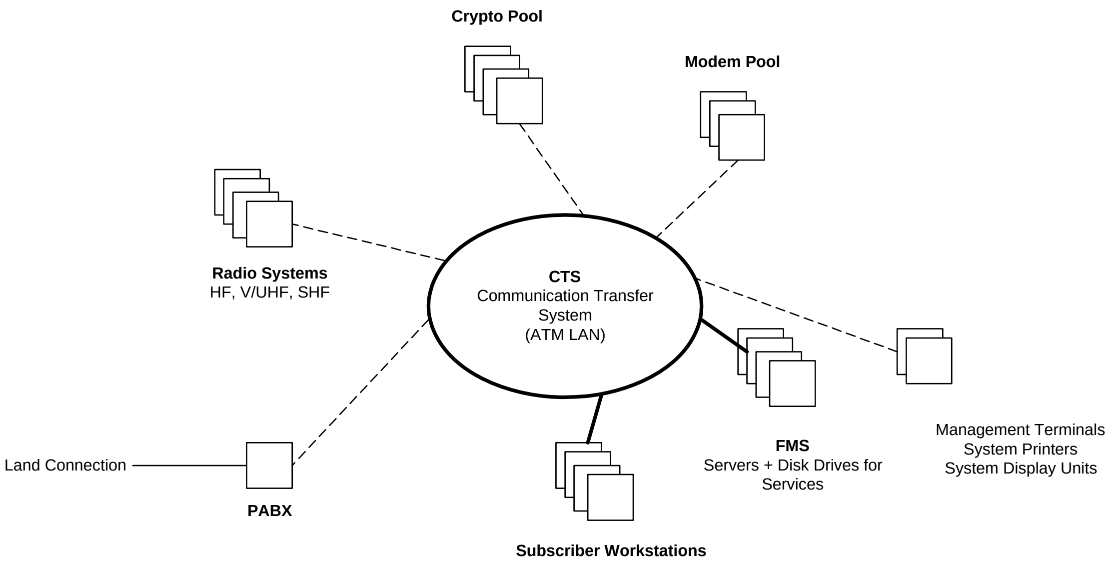

Figure 1 A Typical Communications System Architecture

3.2 Functional Thread Description

3.2.1 The following paragraphs provide details of the different equipment contained in the Functional Thread model. The Failure and Repair data presented in the equipment descriptions are summaries of that used in the Reliability modelling and are the values that would be expected from standard COTS equipment, maintained on a first line repair by replacement basis.

3.2.2 Workstation

Function: Workstations to provide the User interface to the Network.

Comprises: COTS type terminal consisting of single board processor, interface card, display module and keypad, speaker and headset.

		Failure Rate (FPMH)	**MTBF (hours)**
Workstation	Terminal + speaker	20	50,000
Headset	-	5	200,000
Terminal software	-	100	10,000

3.2.3 CTS

Function: Supports the distribution of messages (voice, data, video etc) from internal or external addresses to and between Network Subscribers.

Comprises: Hubs and Routers; 6 hubs, each with 2 routers.

		Failure Rate (FPMH)	**MTBF (hours)**
Hubs	Backplane + PSU	16	60,000
Hub software	-	100	10,000
Router	Router	5	200,000

3.2.4 FMS

Function: Covers management of the CTS, security and system configuration.

Comprises: Servers and disk drives; group of 5 redundant pairs of slave/master application servers with disk drives for address/directory database. Also includes Ethernet/ATM Switch and Network management terminal. Each server group also provides a specific function of the user applications to be supported by the Network e.g. Directory Service, Recording Service.

		Failure Rate (FPMH)	MTBF (hours)
Servers	Application server	3,333	300
Server software	-	100	10,000
Disk Drive	Disk drive + PSU	100	10,000
Front end processor	Drive pre-processing	33	30,000
Ethernet/ATM Switch	Acts as bridge between FDDI and ATM	100	10,000

3.2.5 Radio System

Function: The radio systems provide the communications coverage in the frequency bands LF - UHF, and SHF.

Comprises: Radio system, with modem and Interface Unit.

		Failure Rate (FPMH)	MTBF (hours)
LF – UHF Radio System	Transmitter, receiver, controller, antenna, antenna control unit	20	50,000
SHF System	Transmitter, receiver, controller, antenna, antenna control unit	2,000	500
Modem	-	10	100,000
Interface	-	10	100,000

3.2.6 Thread Message Parameters

The following values for processing delays at the Network elements and Message generation were assigned to the Performance model.

Network Element	Terminal 1 ⇒	Terminal 2 ⇒	CTS ⇒	FMS ⇒	Radio System
Introduced Delay	None	1.5 sec	varies	Varies	None
Function	User creation of messages each of various priorities, at Workstation 1	Fixed delay whilst User authorises the message, at Workstation 2	Processes messages by priority, identifies most suitable routing for message	Supply CTS with routing information, and forwards message to designated subscriber	Transmits message over Radio link.

Table 1 Message Flow Processing Delays

Priority	Percent of Messages
Flash	5%
High	20%
Medium	40%
Low	35%

Table 2 Message Priority Classification Percentages

Each node was assigned the capacity to hold up to 1,000 messages. When this limit is reached, the queue will not accept further messages for processing until the length of the queue has decreased to less than 1,000 messages. The effect of this ‘queue blocking’ would appear to a User as the inability to enter further data, with a message advising the likely length of the delay.

4 FUNCTIONAL THREAD MODELLING RESULTS

4.1 Availability of Service (AoS)

4.1.1 The Reliability Block diagram of the Functional Thread is shown in Figure 2. The detailed results obtained from the availability modelling using RAM4 are presented in Tables 3 and 4. The mission time used for the simulation modelling was 1080 hours (45 days).

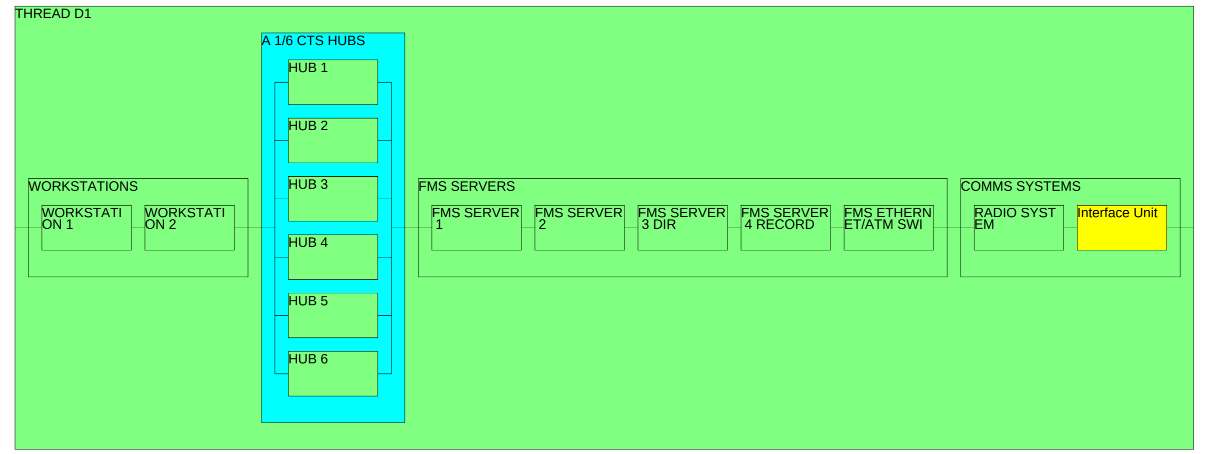

Figure 2RBD for Functional Thread

	Estimate	Lower 95% C.L.	Upper 95% C.L.
Missions Simulated	20373		
Mission Time Simulated	1080		
Failure Free Missions	4024		
Total System Failures Recorded	32768		
REL	0.197516	0.192107	0.20304
MTBF (Hrs)	671.045	666.43	675.661
MTTR (Hrs,Arith)	0.428332	0.423296	0.433368
MTTR (Hrs, Geom)	0.246163	0.243009	0.249359
MTFF (Hrs)	669.675	663.6	675.75
AVAILABILITY	99.9362	99.9352	99.9372
SFR (1/MTBF)	0.001490	0.001480	0.001501

Table 3 System R&M Model Results

Group Name	Total number of times failed	Total number of times repaired	Total Availability	Total Unavailability
THREAD D1	32768	32758	99.9	0.0637
WORKSTATION 1	3863	3861	100	0.0040
WORKSTATION 2	3900	3900	100	0.0040
CTS HUBS	101	101	100	7.34E-05
FMS SERVERS	21546	21539	100	0.0477
RADIO SYSTEM	3538	3537	100	0.0080

Table 4 Element Group contributions to System R&M

4.1.2 The results show that the overall availability of the Functional Thread to be greater than 99.9% with a corresponding MTBF of 671 hours. The simulation was terminated after 20,373 simulations as the RAM4 program will stop the simulation process when more than 32,767 failures have occurred.

4.1.3 The mission reliability of the Thread is predicted to be 0.197, based on the assumptions and model as described.

4.1.4 Using RAM4, a sensitivity analysis was performed to determine how sensitive the System Availability or MTBF is to a change in the MTBFs of the elements. With a sensitivity factor of 25%, the percentage change in System Availability was in the range of –0.0018% to +0.0045%, and that of the System MTBF +6.7% to +1.4% (716 to 661 hours). These results indicate the system R&M characteristics to be relatively insensitive to those of any individual element.

4.1.5 Examination of the results for Element Groups in the model, indicates that the major contributors to Thread unavailability are the Workstations, the Radio System (i.e. message ultimate origin and destination points) and the Network Servers, with the Routers (representing the multiple paths through the Network) having a negligible contribution.

4.2 Grade of Service (GoS)

4.2.1 The Process Schematic is shown in Figure 3. The simulation was run with a duration representing 7,200 seconds, i.e. two hours, with the message rate set at 5 mps.

4.2.2 The plot showing the mean time to process the different message priorities is given in Figure 4. The delay in seconds for the Flash and High priority messages are plotted against the left-hand (Y1) scale, whilst the Low and Medium priority message delays are plotted against the right-hand (Y2) scale.

4.2.3 The CTS throughput results are summarised in Table 5. The Average Message Delay is calculated only on those messages that are successfully forwarded to the Radio system during the simulation.

Message Priority Type	Total number of messages created by User at Terminal	Messages created at Terminal and accepted into System	Messages forwarded to Radio System (at end of simulation period)	Average Message Delay (seconds)	Messages created at Terminal but subject to Queue Blocking	Messages subject to Queue Blocking (%)
Flash	1801	1,801	1,800	2.0	0	0%
High	7201	6,751	6,749	2.1	450	6%
Medium	14401	6,924	6,922	52.3	7,477	52%
Low	12601	2,215	1,216	2289.5	10,386	82%
Total	36004	17,691	16,687	-	18,313	51%

Table 5 Performance Modelling Results for Functional Thread

4.2.4 delay being determined by the inherent CTS and FMS processing time delays. All attempts to send a Flash priority message are successful, but 1 in 16 requests to generate a High priority message is unsuccessful due to queue blocking, i.e. the queue, being full, declines to accept further input messages.

4.2.5 The Medium priority messages are subjected to a noticeable delay, nearly a minute in duration, and only 1 in 2 requests to send a Medium priority message are successful.

4.2.6 The Low priority messages are not processed until queue blocking occurs. At this point, the queue buffer will accept any message on a first come, first accepted basis. Thus, the probability of a message being processed will also be influenced by the quantity of messages generated, i.e. in accordance with the percentage of each message type. Eight out of ten requests to send a Low priority message are refused due to insufficient capacity, and those that are processed are delayed for 38 minutes.

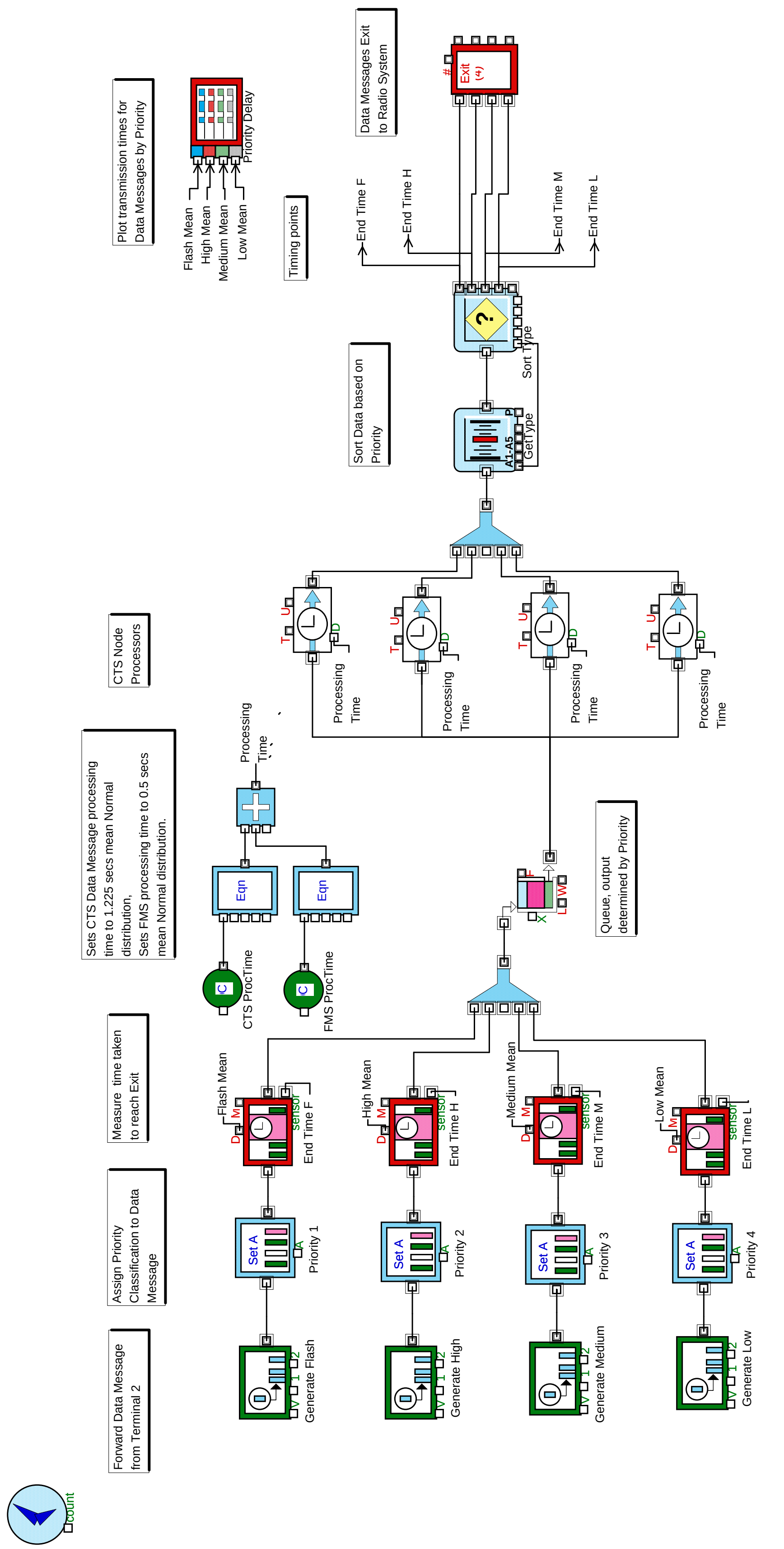

Figure 3 - Process Model Schematic for Functional Thread

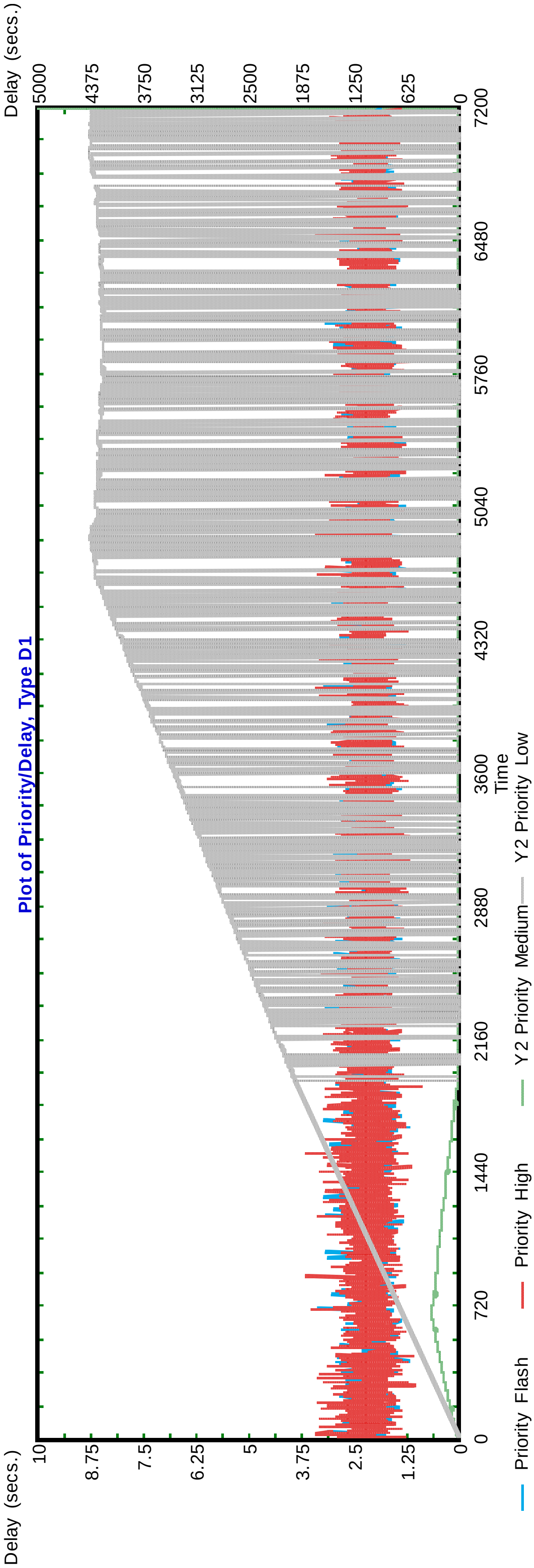

Figure 4 - Plot of Priority Type Delay against Time for Functional Thread

5 LESSONS LEARNT

5.1 R&M Modelling

5.1.1 From study of the results of the Network R&M model it can be seen that the elements of a Network can be classified into three types :

- Source and Destination Nodes : The nodes at which the interface devices for Message source and destination are connected to the Network;
- Communication Nodes : Routers/Switches that pass the data through and across the Network;
- Network Services Nodes : Servers providing Route selection, Re-configuration management, Node Addresses that enable the basic operation of the Network.

5.1.2 Given the presence of redundant paths through the network, increasing the level of redundancy does not give a corresponding improvement in overall availability as it is limited by :

- The availability of the source and destination nodes;
- The availability of the basic operating services for the Network.

5.1.3 Hence, the fundamental availability of a Communications Network, as perceived by the User, is determined by the Nodes at which the Users connect to it and the basic 'core' Management Services that allow the Network to operate, rather than the actual network complexity (number of routes).

5.1.4 Similarly, any constraints on the ability of a User to use different points of connection to the network (e.g. security) will also impact the availability.

5.2 Performance Modelling

5.2.1 At each Node, a message experiences transmission delay, according to the node function. Additionally, messages with higher priority are processed in preference to those with low priority. The result of this is that the message buffers at the nodes begin to fill up, primarily with the low priority messages. (This can be seen in both the delays estimated for each message type and the numbers of messages of each type successfully transmitted). As soon as the message buffers fill up, the behaviour of the Network changes significantly in that messages are processed not according to their priority, but on a 'first come, first served' basis. Hence both the assumed message input rates and the sizing of the Message holding capacity at the Network nodes can result in the compromise of any prioritisation scheme applied by the User.

5.2.2 Although only one thread is modelled in this paper, the Network can be used to carry 'real time' messages (e.g. video surveillance, voice conversations) as well as data. If these 'real time' messages are prioritised using the same scheme as for data messages it can be seen from the results that they could experience significant delays. While such a delay would not affect the content of a data message, it would a 'real time' message; e.g. a telephone message cannot be delayed by more than a few seconds or else the message content becomes unintelligible. Therefore if the Network is to a mixture of message media, including 'real time' messages, any prioritisation scheme to be applied must be two dimensional, accounting for both:

- Message content importance;
- Message media type.

6 ISSUES FOR FUTURE MODELLING

6.1 Based on the experience gained by FGS, it is considered that in order to accurately model a Network Communication System from the User perspective the following issues are crucial and so merit careful consideration.

6.2 Due to the multiplicity of functions and Users supported by the Network, a single model is inappropriate. R&M and Performance models need to be developed for the individual functions of interest.

6.3 The overall performance of a Network is governed more by the internal Network operating/management functions than by its routing complexity. The availability of such services affects all services and so is a crucial factor in the User perception of Network performance.

6.4 A single metric for message prioritisation is inadequate. Any prioritisation scheme must account not only for the message content, but also the message media. Consideration should also be given to an alternative prioritisation scheme, such as Guaranteed Time of Delivery for each Message Priority or Media. Such a scheme would enforce the passage of messages from each category through the Network, in ratio of priority or media, so preventing messages from the lowest category never being output or real time messages being rendered unintelligible.

6.5 The overall message input rate to the Network, together with the sizing of Message buffers at Network Nodes, are crucial factors and can significantly affect the performance perceived by the User.

6.6 Dependant on the duration of the operating scenario being considered, the Network performance model should incorporate the results of the R&M model (i.e. node failures affecting capacity) to correctly identify the long term behaviour of the Network and its behaviour while performing re-configuration.

6.7 Although not shown in this paper, it is known that the level of link utilisation, in some instances can affect message delays, well before the utilisation approaches the full technical capacity.

6.8 Many Networks operate on the transmission of data packets; messages are disassembled into discrete packets which are transmitted individually through the Network, intermixed with other packets (using Time or Frequency Division Multiplexing) and are only reassembled back into the complete message at the final destination. In order to correctly analyse this type of system the performance modelling tool used would need to be able to model discrete packages, as opposed to continuous flow of data through the Network.

6.9 Communications Networks can be used to provide ‘transparent’ connectivity to Users on different systems or who are remote from each other i.e. within a Network boundary, individual nodes may not be the source/destination points for messages, but access points to other communications systems or Networks (e.g. Satellite Datalinks, Wide Area Networks, PABX). From a User perspective, the source - destination path could therefore span across several datalinks or Networks that are outside the boundary of the System being considered. Confining the modelling of the Network to its ‘immediate’ boundary in this case would only provide a partial assessment of performance, being only the passage of messages between the Network and the external system and not between the actual Users. If assessment of the delivery of messages between Users is a critical factor, then the model must include these external elements, even if they lie outside the boundary of the Network being considered.

ANNEX B

R&M MODELLING ACCEPTANCE GUIDELINES

CONTENTS

1 INTRODUCTION

1.1 Purpose

The aim of this paper is to provide guidance to MOD R&M staff on what to look for when modelling is part of an R&M case. Obviously the information is applicable to contractors who are considering modelling as a technique to support their R&M activities. In this paper system is used as the generic description of any collection of items (hardware or software) that together perform a function and is equally applicable to a PC or a complex chemical plant. In general a system consists of a number of sub systems (which maybe considered systems in their own right).

1.2 Structure

1.2.1 This paper is divided into 3 sections:

a) Consideration of what Modelling can be used for at each stage of the life cycle. Note there are many different methods of thinking about the life cycle of a system; this paper uses the MOD CADMID cycle, although it could equally be applied to other life cycles;

b) What evidence is required to justify a model being used as part of a programme;

c) Definitions of types of models.

1.3 Limitations

1.3.1 This paper purposely does not recommend specific tools as the purpose of modelling is to shed light on a particular problem and there is no general-purpose solution.

1.3.2 This paper purposely uses generalities rather than specific, to make it widely applicable.

1.3.3 This guidance is aimed at staff trained to "expert level of R&M functional competency". If any of this paper is unclear or it is unclear how it applies to a specific situation, talk to the R&M modelling SME.

1.3.4 No specific solution is proposed, as it is necessary to build a solution that fits within the evidence framework of the project in question.

2 WHY MODEL

2.1 Generally

The prime purpose of any model is to provide a relatively cheap method of understanding and predicting the behaviour of a system or process without the need either to build the system or to conduct extensive testing.

2.2 Concept

2.2.1 By definition at the concept stage we are considering function rather than actual systems. It follows that the production of an R&M model may not be possible or practical although R&M should be considered in any OA work being completed, even if this is at an apparently superficial level. Just as anyone considering a "ship" would be foolish if they started OA modelling assuming that it could achieve 100MPH, it would be wrong to assume that the system will be 100% reliable.

2.2.2 Depending on the system, it may be necessary to do some modelling to get a feel for the major differences between areas or to understand obvious drivers. As an example, if we are considering a ship from a conceptual point of view some things will be the same what ever is selected.

2.3 Assessment

Model the proposed systems in their operational environment to identify the weak links, taking into account a sensible mission profile (80%tile). It may be necessary to construct more than one model to take account of differing mission profiles, or a single model may need to cover more than one operational mission. In the case of an aircraft it may be necessary to construct a model for high altitude cruising and another for take off / landing and then combine these smaller models into a typical 10 day scenario.

2.4 Development

2.4.1 During development, test results should become available. These test results should be compared to the model to confirm that the results from the earlier modelling are still valid. If the results are different it may be sensible to use modelling to assess the impact/Identify the key drivers.

2.4.2 As the design develops it may be sensible to expand the model to reflect the developing design; again modelling might identify R&M drivers.

2.4.3 Modelling offers the opportunity to consider the sensitivity of the proposed system to the manufacturing process. This may include using modelling to identify potential weaknesses in the process or to identify the impact of known component variability resulting from the selected manufacturing process.

2.4.4 Modelling of the support infrastructure can be used to optimise spares holdings and assist in optimising the location of repair facilities. This is applicable even for Contractor Logistic Support as the inability to repair failed items is a major availability driver, while the holding of excessive stock (either good or in a repair loop) is a major cost driver.

2.5 Manufacture

2.5.1 During the manufacturing phase the question which should be asked is "Does anything occurring lead us to consider that our assessment or development generated view are incorrect". Typically this could be following some sort of burn in where the failure rate is different to that which was expected, identification of differing failure modes, or non occurrence of expected failure modes.

2.5.2 Similarly a study should be undertaken to identify whether production problems are as identified in process FMECA, or alternatively are assembly difficulties occurring on the parts of the system which we expect top be highly reliable.

2.6 In Service

2.6.1 The first question to be asked is "Are the R&M characteristics in service as expected?" This may require modelling to transform from predicted usage to actual. (if this is the case this information should be fed forward to the people working on the next generation).

2.6.2 Do in-service results indicate our view is correct? This may require modelling to translate a trial under one set of conditions to another.

2.6.3 Modelling can also be useful in assessing the impact of a change of use. Does running the system at 110% capacity mean that the expected failure rate increases by -10%, 0% or 200%? Change of mission impact assessment. [Think about diesel generators (DG) running below optimum load - any increase in load is liable to increase the reliability, DG in redundancy may loose the redundancy due to poor load sharing].

2.6.4 It may be that it is felt that the system is not performing as well as it could, which in turn could lead to a Mid Life Update. (MLU) Modelling at this stage could be used to determine the likely improvement. Similarly it may be necessary to carry out a MLU of the system to enable it to stay in service. In this case modelling should be similar to that undertaken during the previous stages, although this time much of the original work should be available along with real data.

2.7 Disposal

If the decision is to dispose of the system by destruction then modelling is not applicable. If it is decided to sell the system to other users (either as a whole or in parts) then the thoughts on earlier stages apply.

3 MODEL VALIDATION AND VERFIICATION

3.1 No mater which stage you are at, and how simple your model, it should be validated and verified.

3.2 Model Validation is concerned with the truthfulness of a system with respect to its problem domain. In terms of this guidance, validation will seek to ensure that a suitable model/technique has been used and that the modelling process is carried out rigorously.

3.3 Model Verification is concerned with the correctness of construction of a model and must be judged against specific design requirements or scope.

3.4 Definition of Model Validation and Verification are similar to the definitions used in traditional software engineering as provided in Bohem's definitions of validation and verification (Bohem, 1981):

a) Validation: Are we building the right product?

b) Verification: Are we building the product right?

3.5 Validation and Verification can be split into 6 stages.

3.6 Is the algorithm/technique correct for this problem.

3.6.1 For instance Markov modelling is only applicable for equipment that exhibits an exponential failure distribution.

3.6.2 The algorithm/technique is correct for this problem if the assumptions contained within the algorithm/technique are acceptable and the outputs are sufficient to achieve the objectives of the modelling.

3.6.3 A model is always an approximate representation of reality, but there must be a balance between its authenticity and manageability. Therefore, if the prime purpose of a model is to provide a relatively cheap method of understanding and predicting the behaviour of the system, then an algorithm/technique will be selected which will be detailed and elaborate enough to represent the essentials of the system, but coarse enough to be tractable.

3.6.4 Selection of the appropriate technique should be documented in a context paper or similar document and should provide a reasoned case for the chosen technique including a critique of all options considered against the modelling objectives.

3.7 Is there sufficient confidence that the calculation engine implements the algorithm/technique correctly?

3.7.1 Validation of the algorithm/technique should establish confidence that the software is fit for purpose.

3.7.2 Confidence of a modelling tool may be assessed by considering factors such as:

a) Is it a MoD approved tool?

b) Is the tool widely used to analyse similar problems?

c) Are the user-defined algorithms correct?

d) If the software is relatively unknown can the supplier provide evidence of testing and validation of the algorithms?

3.7.3 The use of an “off the shelf” modelling tool does not necessarily provide assurance that the algorithms are implemented correctly therefore it may be necessary to test the tool against some models for which the levels of expected outputs are known, the main reasons for this are as follows:

a) There are many complex modelling tools commercially available that are of unknown providence, with no evidence that the calculation engine has been tested against hand calculations etc.;

b) A complex tool may be well validated for a certain use, but any change of use may reveal undetected systematic faults;

c) Some models, for example Arena, may appear to provide off the shelf validation of algorithms, however they provide such flexibility that the modeller may implement their own algorithms, which are not immediately obvious to the reviewer.

3.7.4 For self-developed tools (especially based on spreadsheets) it is important that it can be demonstrated that the calculations are correctly implemented in all cases and that in building the model it has not been corrupted.

3.7.5 Spreadsheets are notorious for having high failure rates as a result of poor design, inadequate testing and uncontrolled development; therefore evidence of an incremental validation process and a final in depth review is required. The incremental validation process should be documented in a validation plan, which should describe what testing is carried out, when and by what method. Testing should address the following:

a) Formula tests to check each formula in the model;

b) Numeric tests to trace calculations back through the model;

c) Robustness tests to perform boundary tests with required input values;

d) Macro tests to test the function of all macros.

3.7.6 The validation of spreadsheets can be a lengthy and resource consuming process and without the aid of validation tools may not give sufficient confidence that spreadsheet calculations implement the algorithm/technique correctly.

3.8 Has the problem been described correctly.

3.8.1 If an RBD is used are the two items that have been modelled as parallel redundant actually redundant? Often fall back modes are incorrectly considered to be redundancy i.e. the sidelights on a car are not redundancy for headlights although it might get you home.

3.8.2 Ensuring the problem has been described correctly is largely dependant on input from system Subject Matter Experts (SME's); therefore the data contained in the subject model should be assessed against available system knowledge for correct representation.

3.8.3 All data contained within the model including any assumptions made should be presented (with their source) in a context paper or equivalent document. There should be evidence that the document has been reviewed by the system SMEs and is written in a language the system SME's are able to understand and as a minimum includes:

a) System Description and Configuration;

b) Usage Data and Assumptions;

c) R&M Data and Assumptions.

3.9 Has the problem been represented correctly within the Model?

3.9.1 It is important to determine what level of validation is required. A full in depth review would validate the data of the complete model, whereas a sample-based review would provide the reviewer with reasonable confidence.

3.9.2 If a sample-based review is adequate there should be evidence that the model developed has been reviewed against the content of the context paper or equivalent document. However, if a full in depth review is required an independent audit may be required, which for complex modelling tools will require the reviewer to have in depth knowledge of the modelling tool.

3.9.3 As a guide it would take around 30 man-days of effort for an experienced modeller to conduct a full in depth review (including data validation) of a reasonably complex availability model; however, a sample-based review providing reasonable confidence would take around 5 man-days of effort.

3.10 Is the data used sensible/relevant to achieve the objectives of the modelling?

3.10.1 As with all modelling the data used is one of the key drivers. Data on the reliability of a computer in an air-conditioned computer room is not directly applicable to a computer fitted to a helicopter. Similarly data from early gas turbines has little relevance to today's aero-engines.

3.10.2 Is it truly possible to complete 50% of repairs in 20 minutes when the system takes 5 minutes to load windows and perform virus checking?

3.10.3 Whether the data used is sensible/relevant depends entirely on the objectives of the modelling. It is considered acceptable for the data contained in a concept model to be of low confidence, as it will be developed as the project progresses. However, if the model is required to define requirements or to provide a prediction of system availability in service then the data is expected to be of greater confidence. Contact the R&M modelling SME for further guidance on the acceptability of data confidence for the different stages of the procurement cycle.

3.10.4 Validation of R&M data requires careful examination by an experienced R&M engineer. The main issues concerning data validity are applicability of the data to the subject system and the source and likely accuracy of the data.

3.10.5 The context paper or equivalent document should identify clearly all assumptions made (and how they were derived) and provide references to data sources that are known or provided by the customer. These references should be reviewed to determine whether they are valid sources of information and whether the degree of accuracy in the data is acceptable.

3.10.6 If references have not been provided then the data contained within the model could be compared directly with other data sources, however, comparative data sources are not always available, therefore in some cases the reviewer will have to use engineering judgement to determine whether the data used is sensible.

3.10.7 Models can be highly complex and contain vast amounts of data; therefore assessing whether all the data is sensible or relevant is a time-consuming exercise. If the validation process is a sample-based review rather than an full in depth review, the reviewer will have to select the most important data to assess for example by assessing the data with high MTBFs to assess whether they are in the right ballpark or by concentrating on the R&M characteristics of the unavailability/reliability drivers or the most sensitive data.

3.11 Have sensible conclusions/recommendations been derived from analysing the sensitivity of the input data and assumptions?

3.11.1 One should always test a model to consider the impact of assumptions and data on the results. What is the impact of a 10% increase in maintenance time or a 10% drop in reliability?

3.11.2 Sensitivity analysis could be conducted on a range of options including the following:

a) How does the result change as a result of a 10% change in the R&M characteristics of the unavailability/reliability drivers?

b) How does the result change as a result of a 10% change in the assumptions?

c) How does the result change as a result of a 10% change in all MTBFs/MARTs?

3.11.3 As a model develops through the procurement process it is important that the confidence in the modelling data (especially for data which is sensitive to the model R&M result) is increased, this will include the resolution of important assumptions with known data. Therefore, ensure sensible conclusions/recommendations have been made from the sensitivity analysis e.g. data collection exercises are recommended for specified systems to increase the confidence of R&M characteristics data.

3.12 How credible are the results.

3.12.1 Having built a model, can the outputs be supported by other evidence, if current technology gives an 80% reliability why is a model output of 99% considered reasonable.

3.12.2 Caution is required when performing this analysis, as there are a number of reasons why credible modelling results could be significantly different from the comparative data being used. Therefore, the analysis should be supported by the assessment of the assumptions underlying the comparative data to determine whether the data is actually comparative. The reason for the differences may include the following:

a) Insufficient confidence in comparative data due to insufficient data being gathered;

b) Comparison of new but unproven technology against older technology;

c) Comparison not being like for like, in terms of system design, operating profile and environmental requirements.

3.13 Do you have sufficient confidence in the modelling team?

3.13.1 Confidence in the modelling team could be demonstrated by the modeller(s) demonstrating a full understanding of the model created and how the model influences the design, by demonstrating:

a) What has been gained through modelling, and providing evidence that all the important questions have been asked?

b) What is driving the modelling result e.g. what are the top unavailability drivers;

c) An understanding of how the assumptions are driving the modelling result and therefore understanding the importance of collating data to demonstrate assumptions to be correct;

d) Whether modelling trade-offs are being performed in line with the design process;

e) The correct conclusions and recommendations have been drawn from the modelling;

f) An acceptable modelling process has being followed.

4 TYPES OF MODELLING

4.1 General

4.1.1 It is convenient to think of 5 levels of modelling as we move from an overall scenario down to component level. When constructing a modelling strategy, it is necessary to decide at which level(s) the model needs to be built – too much detail increases the expense of modelling without proportionally increasing the "insight" given by the model. It may be better to build separate models at different levels rather than trying to include "detail" in a higher level model.

4.1.2 If more than one model is to be built then it is important to ensure that all models are coherent. This applies not only to "R&M" models but other associated models such as

a) Logistic Support Models;

b) Costing models;

c) Performance models.

The five levels of model are:

4.2 Campaign level

At this level models will take account of the interaction between different types of assets and demands from these assets on the same resources. It may consider how functionality from a number of different systems combine to deliver a robust capability.

4.3 Fleet management level

At this level the models are considering the impact at the fleet level, of reliability – many capabilities have R&M defined in terms of Availability, in order to understand what this means, it is often necessary to consider a number of platform operating to deliver the requirement.

4.4 Individual Platform

At this level models are used to consider the way that system R&M characteristics combine to give platform level characteristic. Modelling at this level will typically be used to set system level requirements.

4.5 System Level

This is the historic use of modelling to aid R&M, and typically consists of constructing a graphical representation of the system (RBD, FTA,…) and using data at the “component level” and a mathematical convention to calculate the R&M characteristics if the system.

4.6 Component level

At this level consideration of the “physics of failure” will allow the designer to optimise the design. Historic data from similar components being used in a similar way may give an insight into the R&M weakness of the component.

NOTES